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Application of UAS and Revit for Pipeline Design

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Abstract

The professionals in the vertical and horizontal construction have tested methods to enhance the quality, safety, environmental impact, delivery time and cost control in their works promoted in learning organisations. Automation strategies applying robots and technology has been a focal point in industry of manufacture by its benefits in productivity levels and quality of works, and in some cases, without affecting other factors in a long-term period. The construction industry is playing a predominant economic heading in certain countries. Therefore, the adoption of Unmanned Aerial System (UAS) and Building Information Modelling (BIM) methodology as an automation strategy represent in short and long terms positive economic impact. UAS or drones have been used for cargo and data capturing in the built environment. Nowadays, the construction of infrastructures is the most benefited project from UAS implementations by gathering visual data of cracks, obstructions, energy levels, traffic and current conditions of the projects fulfilling the gap of human risks reduction, speed on data collection, and digitalisation of the real-world along with BIM. However, there is a breach in reliability and awareness on the UAS application cases in the infrastructure sector.

The aim of this paper is to present the reasons and the application case of the UAS from the topography department of a Water Supply public organisation. The findings show that the UAS achieved a higher level of productivity and efficiency in the daily pre-construction works for designing pipelines. The case covers sewer identification and georeferencing in rural areas where the satellites were unavailable to show the state accurately. The tool used was an RTK DJI Phantom 4 to survey the site conditions in BIM format. The integration of UAS in BIM showed a higher level of productivity and efficiency in the employee's workflow in terms of data collection contrasting to old-fashion methods.

Keywords: survey, infrastructure, BIM, UAS, water supply

1. Introduction

Bridges, roads, railways, tunnels, water supply, sewers, electrical grid and telecommunications are infrastructures that underpin urban and rural services over a considerable period. Nowadays, infrastructure assets demand costly and extensive processes of construction, maintenance, inspections, rehabilitation, and restoration. The current workflows to survey the facilities involve high-risk exposure of the personnel, utilisation of site specialised machinery, exhausting walking distances, fastidious traffic diversion, and environmental impact which can significantly impact the productivity, quality, and cost of the projects. Therefore, automation strategy is required to provide trustworthy, durable records and resource maximisation of the public assets.

The built environment investments, in some nations, represent up to 50% of their national budget, indicating to be a sector to be optimised. However, tools and software have emerged to fill the gap in productivity as an Unmanned Aerial System (UAS) or drones integrated into Building Information Modeling (BIM). Several developed countries have applied automation strategies in the built environment through digitalisation. They are promoting efficiency in construction project data creation, storage and modification. Researchers well understand that on a long-term basis, construction digitisation presents positive evidence of increasing transparency levels, productivity and effectiveness on the projects schedules and cost management [1].

In the context of developing countries, the adoption of technologies can be reduced or minimal. The National Institute of Potable waters and Sewerage (INAPA) is a public institution in the Dominican Republic intending to consolidate an automation strategy utilising UAS. INAPA is responsible for meeting the needs and demands of the urban and rural population of the country with adequate non-potable water, sewers waters services, residual treatment plants and to develop and approve plans. Therefore, the department of topography is in charge of: gathering georeferenced terrain elevation data; locating pure water sources, ubicate the conditions of the sewer; calculate, design, inspect, and redesign parts or the entire infrastructure, the buildings concerned to the water supply source in the country. The department inspects, builds, rehabilitates, and redesigns aqueduct, sewerage system, water treatment and offices in the countryside division. The department manages a large number of projects and subsequently is seeking to incorporate an automation strategy throughout UAS and BIM application by the following reasons: facilitate easier and faster sharable visual data of the working process, Increment workers safety against hazard environment effects and climate change effects; boost the productivity in their workflows to achieve the annual institution's goals on budget; obtain a higher level of details and accuracy of the terrain models, project site and incorporate visual records of the progressed accomplishment; foment the reliability and transparency of the work process, site conditions and environmental concerns related to the external factors and impacts of the projects; implement innovation as a functional and creative approach for construction solutions to the quotidian works.

The traditional workflows in the institution operate in not-automatic for site condition inspections, surveys and 2D CAD design. These approaches inherently produce several delays in the water supply systems in the context of reparation and supply demands. The aim of this paper is to report a comparative analysis of the existing traditional methods of developing a water supply design against the case of UAS in BIM integration in the current workflow. By using a real-world project and data, the work seeks to contrast the productivity increase rate when UAS is used as opposed to traditional approaches.

2. Literature review

The application of aerial robots' has been explored in various industries to identify their effectiveness in the last 5 years. Most recently, aerial robots have been applied for spray disinfectant for COVID-19 in China, Cargo biological samples in the Dominican Republic, and determinate culture hydration levels in the agricultural field in Brazil. In contrast to the built environment, which the drone is mostly applied for visualisation and mapping. In any context, the UAS is applied with the aim to: reduce human risk exposure; use as a transport, digitiser and data record, then finally gather faster and numerous data from the environment that with the current instrument could not be possible to reach. However, the maturity in the UAs application relies on sensors and capabilities.

2.1. Unmanned Aerial System

The Unmanned Aerial System (UAS) or drone operates in three modes: manual, semi-autonomous and autonomous according to the manufacturer physical and software designs. The unpiloted aircraft is capable, *per se,* to transport sensors or goods. The sensors selection criteria perform a predominant role in infrastructures tasks assessments. Sensors such as GPS, thermal camera, RBG camera and LIDAR sensors enable crack inspections, energy monitoring, traffic monitoring and assets allocation in and around projects [2]. The visual data produced by RGB camera and thermal sensors endorse the tasks and data analysis compromising an adoption or not of a strategy. The UAS capture images that can be administered for the different department on the institution as the essential step and 3D reconstruction of the site for a more detailed and technical overview [3]. The integration of digital strategies based on emerging technologies pave the concepts of digital designs, processes, technologies, and finally, the shift paradigms of new workflows adoption as the integration of 3D models.

2.2. Infrastructure projects

In the infrastructure sector, the frequent applications of UAS are focused on bridge inspections undertaking cracks inspections and 3D reconstruction tasks [4] [5] [6] [7], in water supply quantification of damages by natural events and infrastructure maintenance [8] [9] [10]. In the case of roads pavement [11], electrical grids [12] [13], telecommunication, railway, tunnels [14] and sewers identification [15] there is a gap in scientific literature and maturity of the UAS operation. Furthermore, the current implementations are focused on reducing human risk exposure, gather and digitalise data for specific tasks and increase the amount and speed data in projects. The 3D reconstruction of the infrastructure allows generating a virtual representation of the geometry embedded in the infrastructure and compared with the actual designs. The UAS enables the Building Information Modelling data to be visualised in 3D, added parametric information, and provide as-built geometry. The role of UAS is filling the gap in automating reconstruction of the physical world into 3D digital format instead to be designing from 2D CAD or abstracts representations. Generally, the commercial software packages involved in 3D BIM are commonly Revit, Civil 3D, and Rinho, which drives the designs and monitor records during the construction project execution.

3. Research methodology

The aim of this paper is to present a comparative analysis of the existing traditional methods of developing a water supply design against the case of UAS approach in the current organisation workflow. The illustrative case of study investigates the contrast of productivity rate between traditional and digital survey method. The hypothesis was regarding UAS effectiveness to reduce time in the department. Therefore, the UAS approach can improve the accuracy and speed of designing process reconstructing visual data and adding to a digital platform or BIM.

3.1. Traditional methodology

The actual design method is carried out with an RTK station on site. Previous assessments used to be taken by google maps facing the challenges of accuracy and clarity of the sites. The google historical design data against the old storage images on the computer provoked productivity issues in the department. Therefore, the team of engineers used to travel to the site and identify the path segments to be surveyed. Manual sewers georeferencing is usually taken to locate the GPS coordinates in the map. Sometimes, the process gets confusing by the different stakeholders involved in the project. Then, the results were configurated into a spreadsheet file and exported into the 2D CAD designs in Civil 3D. As a result, the speed of the process created delays, communication issues and long waits for communities to receive the water services. Then, the idea of UAS was examined to improve productivity.

3.2. UAS workflow integration

The literature presents the cases of sewers location [15], road pavement [11], dams inspections [9] and the frameworks of UAS bridge inspections, [4]; undertaking a UAS 2D and 3D approach according with the task to be addressed [3]. Therefore, the framework of the automation process lies in the decision to adopt strategies thought digitalisation with- and without reality reconstruction. In the majority of the cases, the 3D reconstruction is used to provide a more significant amount of data that support site overview, measurements and capabilities. For this project, the approach was proofing the effectiveness of the UAS-imaging assessment to the department. The workflow presented in Fig. 1. express the process of UAS integration for infrastructure projects.

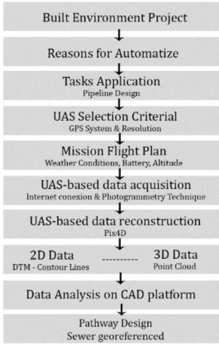

Fig. 1. Typical Workflow of UAS application

3.3. UAS data reconstruction

The pathway was delimited to 1.3km area where was needed the water pipeline supply. Seven ground control points were used as confirmation points between the model distances. Using the data captured from the UAS, a Digital Elevation Model (DEM) and a Digital Terrain Model (DTM) were generated to identify the field conditions (Fig. 2.) and extract the contour lines. Technical aspects of urban planning were considered for future site demands, land usage and human mobility—the point cloud generated with a 0.0018 distance between points allowed to produce 3D 0.2m distance contour lines. The DTM was passed to Qgis where the contour lines were generated and exported to Autodesk Civil 3D to reconstruct the terrain in Revit as a topography surface finally. The contour lines were superposed to identify the pipeline pathway line. Then, the contour lines were overlaid on the DTM appreciating the soft terrain pathway.

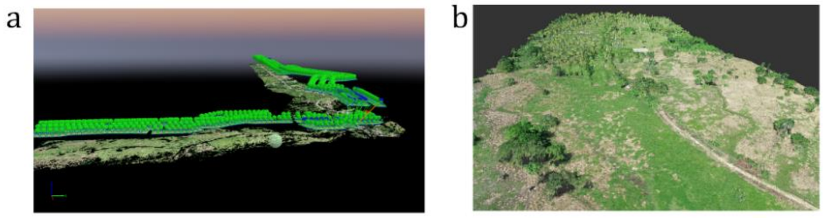

Fig. 2. (a) Photogrammetry 3D Reconstruction; (b) Site 3D view

The cross-section was extracted taking the civil 3D (Fig. 3. (d)) software and then, suggested to be reconstructed in Revit (Fig. 4. (c)) to visualise and quantify the material requirements. The 2D and 3D of the site allowed the engineers and architects to understand the irregularities of the area, identify current issues within the site boundary. Besides, the design contemplates the environment conditions, traffic congestion by the airport proximity and the impact on existing infrastructures.

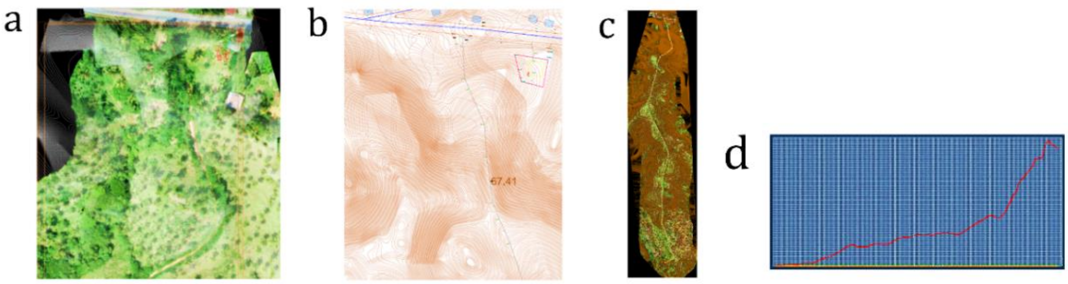

Fig. 3. (a) Segment of the 2D orthomosaic overlaid with the pipeline design; (b) Contour lines, altitude points lines, blue square are houses, the pink polygon is the main reservoir, black lines indications of street edges; (c) Overview of the pathway and high-resolution image;(d) cross-section of the path.

Furthermore, the Pix4D software was used to visualise and georeference the sewers and their conditions (Fig. 4. a, b). The 3D reconstruction of this element allowed the engineers to locate the conditions and step into rehabilitation if it was required.

Fig. 4. (a) Sewer identification status; (b) identification of possible obstruction of the sewers by construction works; (c) Point Cloud up to the Pipeline location

4. Comparative workflow

The workflow implemented to allow the organisation to present a significant amount of time and resources during the topography works. As shown in table 3 and 4, the major contribution of the implementation is observed in the initial stages.

Table 3. Traditional Pipeline Design Workflow

Project Phase	Description	Days	Personnel	Effort	Total
Data Capture	Field-based RTK survey	6	4	24	24
Survey Processing	Data arrangement for Cross-section development in Excel	1	1	1	
	Topographic point processing	1	1	1	4
	Contour line Generation	2	1	2	
Pipeline Design	2D Plan draughting	7	1	7	7

Table 4. UAS-BIM Pipeline Design Workflow

Project Phase	Description	Days	Personnel	Effort	Total
Data Capture	UAV Flight	1	1	1	1
Survey Processing	Point Cloud and Contour Generation	1	1	1	
	Topographic surface creation	0.5	1	0.5	3.5
	Cross / Long Section Creation	2	1	2	
Pipeline Design	Creation of the 3D Geometric Alignment and BIM	7	1	7	7

The results demonstrate an overall effort reduction of nearly 69% concerning the entire pipeline design process. A significant decrease of 96% in the effort is identified in the data acquisition. In addition to the initial, 25% in the overall process was reduced. Moreover, the new approach brought visual information regarding the conditions that routine survey works may not be carrying in.

5. Conclusion

The application of UAS workflow in BIM increases the productivity and quality of the pipeline design work. The implementation of the UAS improved the accuracy and speed of the design process. The surveying and 3D reconstruction of the site have been the biggest contribution to the automation strategy. The Cross sections used to be developed from the RTK survey, now are generated directly from either a point cloud or orthomosaic. It was permitted to manage a higher amount of data and facilitate information transfer between different departments. Furthermore, software as Pix4D allowed identifying the current conditions of sewers and their GPS location. Future works are focus on exploring the interoperability between software platforms and the integration of emerging technologies such artificial intelligence and the internet of things to enrich the UAS effectiveness in infrastructure projects, UAS photogrammetry techniques, sensors and economic feasibility according to the context applied.

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Automated State-Survey System for Monitoring Salt Damages on Plastered Wall Surfaces

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Abstract

Salt damage is a common problem at many heritage sites and historical buildings. The accumulated salt can aggravate moisture problems, cause inconveniences in use, and physical decay of the structures, most commonly the damage of the plaster layers. Internet of things(IoT-s) are becoming part of our advanced, contemporary toolset, which in case of proper establishment and settings enables us to collect data of the investigated facilities continuously, without a regular professional presence on site. In this research, an attempt has been made for continuous monitoring by the mean of a custom-designed single-board computer-based automatic survey station. The system records environmental (i.e., temperature, relative humidity) and visual data that enables state recording on a regular base in order to monitor historic buildings for preservation purposes.

Keywords: state survey, automated diagnostic system, surface condition monitoring, building health monitoring IoT

1. Introduction

1.1. Salt problems in historic buildings

Problems caused by moisture and salt are common at heritage sites and monuments. There are several reasons behind the appearance of damaging salts in structures, which issues have been discussed by many authors. [e.g. 1-4] Salt problems can be triggered by the missing or inconvenient damp proofing, the damage of water or wastewater pipes, de-icing activities, inappropriate use of building materials, etc. In some cases, even by the storing and preservation of historic artifacts in the museums can cause salt problems. [5-6]

Because of the numerous factors, sometimes it can be a challenge to reveal the exact source of the appearing salt and moisture or to answer the question when and at what climatic conditions the salt damage occurs. For a more profound investigation of the background of these problems, we need to improve our toolsets used for monitoring historic buildings.

Some previous research aimed to have a proper system for the diagnostics and the monitoring of the state of historic sites [1, 7-8]. Recently, the automation of some aspects of the monitoring has also been tested [9-12].

1.2. The goals of this study

In this research, an attempt has been made to monitor the behavior of salts (i.e. appearance of efflorescence) on a wall surface without continuous human presence. The solution could be an IoT-based automated inspection unit that later, according to our future development plans, can be part of a system for the regular remote monitoring of historic sites and building stocks.

The developed and demonstrated IoT is responsible for taking digital images and detect the temperature and relative humidity repeatedly and automatically in previously defined time intervals, replacing the continuous human presence on the site. It enables us to collect data and to analyze the surface state continuously.

2. Research method

For the purposes of the research, a test surface was produced, that was investigated with a uniquely designed automated survey unit.

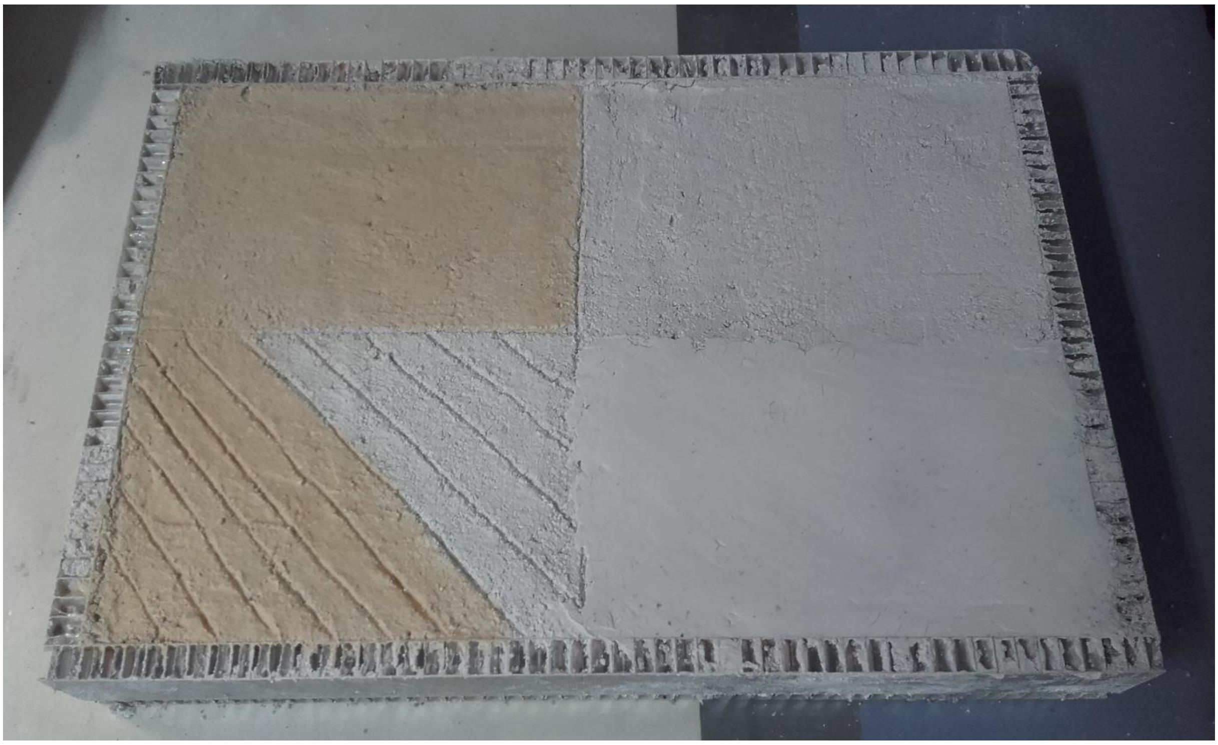

Fig. 1. The test substrate

2.1. The test substrate

As the subject of the investigations, a plastered test substrate was made in an aluminum frame. The material of the substrate was prepared from lime putty and quartz sand with a binder to aggregate ratio of 1:4. The plaster was applied in two layers. The surface finish of the substrate was prepared differently in the four quarters of the plaster (Fig 1.) to create altering optical environment for the expected efflorescence:

- upper-right corner in Fig 1. (upper-left corner in final position) - rendered surface
- lower-right corner in Fig 1. (upper-right corner in final position) - smoothed surface
- upper-left corner in Fig 1. (lower-left corner in final position) - rendered surface painted with yellow ochre
- lower-left corner in Fig 1. (lower-right corner in final position) - rendered, diagonally patterned surface partially painted with yellow ochre

Finally, we erected the frame, turned 90°counter-clockwise, and placed it in front of the state-survey unit.

2.2. The state-survey unit

2.2.1 The used hardware

The core of the hardware was a Raspberry Pi Zero W single-board computer, which was equipped with a Raspberry Pi V 2.1 camera module and a Grove Base Hat for the connection of the peripherals, like the sensors and the relays. The relative air humidity and the temperature are measured with an SHT31 Grove I^2C temperature and humidity sensor, and an analog moisture sensor (Grove Moisture Sensor v1.4) which was placed 20mm deep in the sample substrate. To ensure stable light conditions for the photos to be taken, an LED lamp was attached, that was supplied by electric power individually. Two relays were also used to switch a LED light and to switch off the power of the moisture sensor to reduce its corrosion during the time of the project. Finally, Raspbian Linux operation system was installed on the computer. The price of the survey unit was round € 130, which is an acceptable price; however, we aimed to reduce the costs by testing possible alternative hardware.

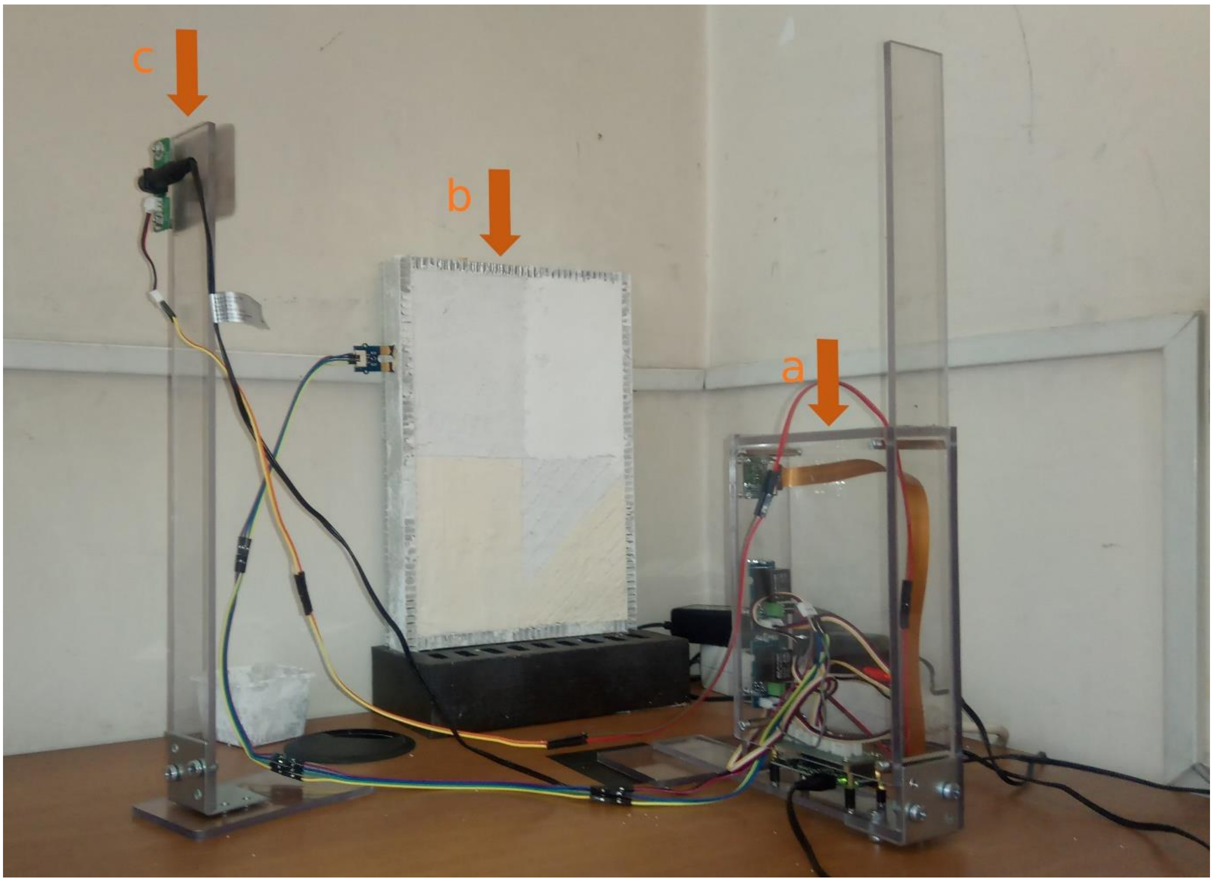

Fig. 2. The hardware - (a) state survey unit (b) test substrate (c) LED lamp

2.2.2 The possible alternatives

During the development time, we also took an attempt to create a smaller, cheaper, and more simple version of the state recording unit. The use of an ESP-32-CAM module with a DHT22 humidity and temperature sensor was considered as the first alternative. The unit was equipped with and USB lamp, which was switched from a 3.3V relay module. The price would be lower (round € 70); however, this development board seemed to have a too modest capacity to run the camera, the relay, and the DHT module together.

We also built a unit with a Raspberry Pi Zero W and Raspberry V 2.1 camera module again, equipped with a DHT22 temperature and humidity sensor, and a 3.3V relay, that was responsible for switching the USB led light. The light was fed from the same power supply as the Pi Zero this time. However, this second unit started to work only recently, so the experiences will be published later.

2.3. The performance of salt tests on the test sample

In the frame of the sample substrate, 45mm deep holes were bored sidewise, that were used to inject saline solutions and water into the substrate. Initially, we injected diluted sodium-chloride (NaCl), and diluted calcium-nitrate ($Ca(NO_3)_2$) several times in the system. Still, later we decided to use saturated sodium-chloride solution to increase the amount of the efflorescence.

Regularly, but on random days (altogether 58 times during the experiment), we also injected 6ml ordinary tap water to one or both top quarters of the substrate to have the salts transported towards the surface.

2.4. The activity of the unit

For taking photos, recording the measured values of the sensors, and controlling the relays of the system, a simple python code was written. The survey unit recorded the values of the sensors every second hour and took one photo every day. The data were recorded to a tab-separated text file; the photos were saved in a folder on the single-board computer. The system was running for preliminarily defined durations; however, after 30 to 45 days, we usually stopped and restarted it.

We used VCN Viewer application to control the unit, namely to manage the software and to up- and download data from the system. This remote control was really useful to reach the lab from a distance during the days of the COVID-19 epidemy in the spring of 2020.

We let the system run for 11 months from June 2019 to May 2020.

3. Discussion

3.1. Observations

3.1.1 Efflorescence

It was realized in the beginning already, that the effect of the diluted saline solutions would not turn out for a long time, neither in the case of sodium-chloride nor of calcium-nitrate. The reason is that the salt, which was stemming from the injections, did not make such amount of salt accumulation, which would cause efflorescence on the surface. Therefore, as far as we aimed a visible result, we decided to add a series of saturated saline solution injections, which were followed by efflorescence within a few days. This phenomenon can be observed in the photo series of Fig 3. With the help of the daily taken photos, we can follow the changes in the salt deposit on the surface of the sample substrate.

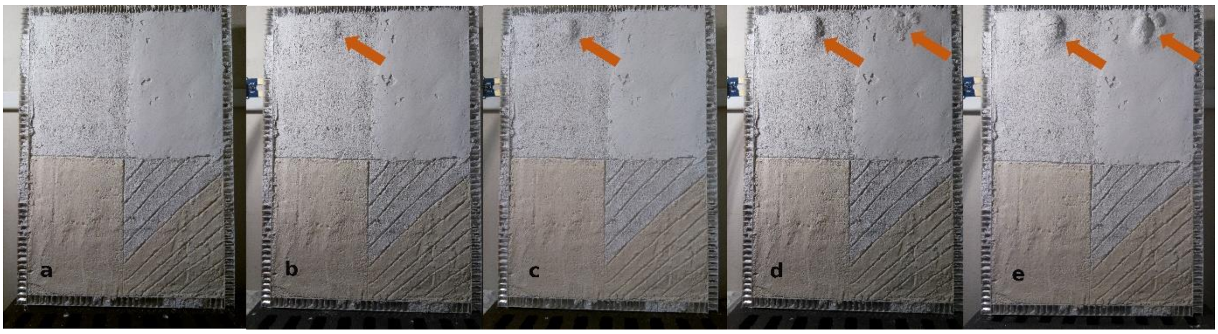

Fig. 3. Changing state of the plaster on some selected side-light pictures taken by the survey unit (a) June 2019; (b) September 2019; (c) December 2019; (d) Mach 2020; (e) May 2020

3.1.2. The work of the sensors

The SHT31 Grove I2C temperature and humidity sensor seemed to work well. The daily environmental circumstances were recorded properly without failure. The average values of the daily recorded data are demonstrated by the diagrams in Fig 4.a and Fig 4.b.

The applied contact moisture sensor, however, seemed to be idle, because of the low sensitivity to the moisture in the solid structure (Fig 4.c). While far from the injection (controlled with a Voltcraft MF-90 capacitive moisture meter unit) the moisture content of the sample substrate was approximately 29-33%, close to the efflorescence (at the place where the built-in sensor was placed) the value vas 42-48%, however, the sensor showed no relevant changes regarding the values.

Testing the sensor independently from the system, even round 100% percent of water/moisture content showed hardly any changes at its values, so this sensor type, which was developed to indicate soil moisture, was considered to be inadequate for our goals.

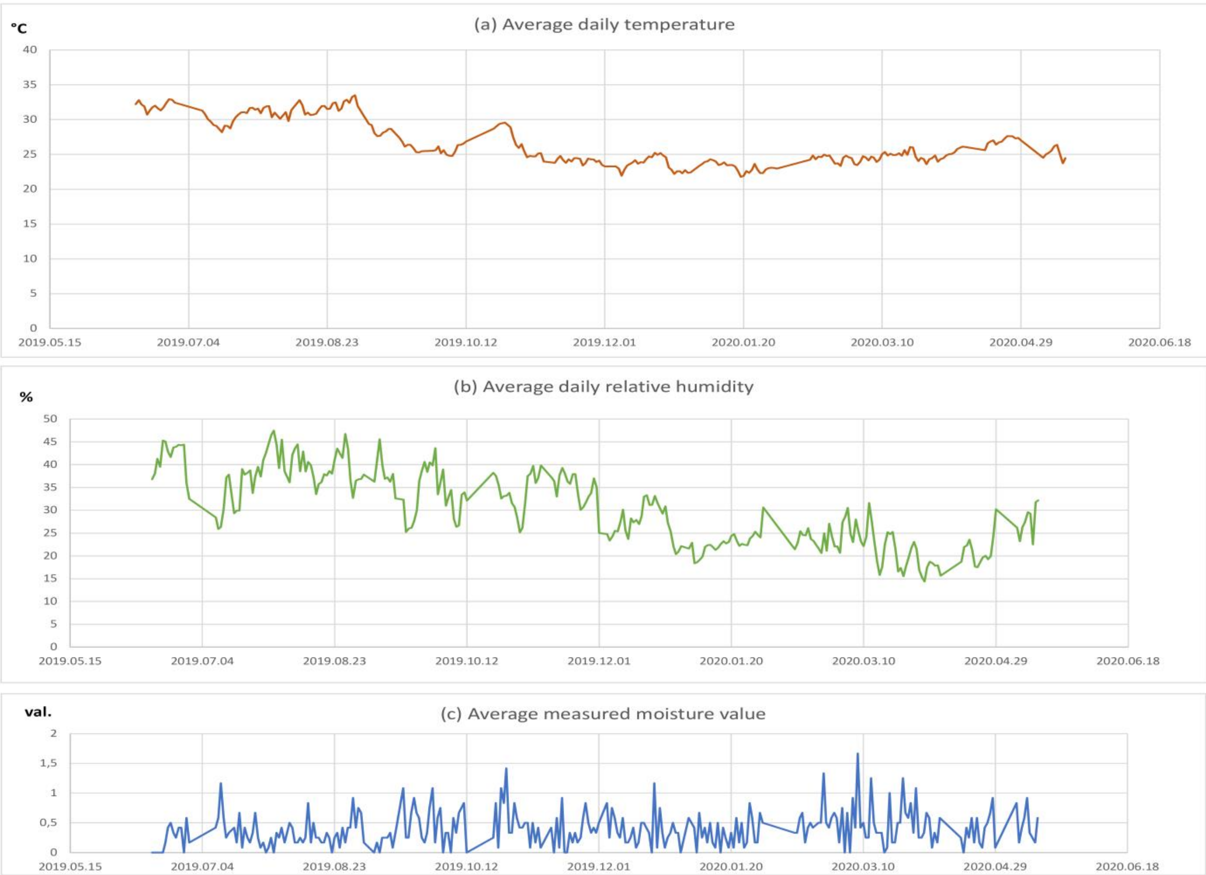

Fig. 4. Changes in the environmental circumstances (temperature, relative humidity) and the moisture

4. Summary

It can be stated that simple survey systems, like the one presented in this paper, are capable of recording the appearance of salts and the changes on plastered surfaces of historic masonry structures as a function of temperature and relative humidity. Salt damages triggered by climatic changes can thus be easily recorded as well as results may support conservators and maintainers to take appropriate actions to reduce the damage.

5. Future plans

As a next step, with the help of our set of state recording units, on-site surveys will be done at salt-laden historic masonries. The second alternative mentioned above seems to provide a feasible solution for our future plans.

6. Acknowledgments

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Development of a Digital Twin Model for Real-Time Assessment of Collision Hazards

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Abstract

The AEC industry is nowadays one of the most hazardous industries in the world. The construction sector employees about 7% of the world's work force but is responsible for 30-40% of fatalities. As statistics demonstrate, interferences between workers-on-foot and moving vehicles have caused several injuries and fatalities over the years. Despite safety organizational measures, passive safety devices imposed by regulations and efforts from training procedures, scarce improvements have been recorded. Recent research studies propose technology driven approaches as the key solutions to integrate standard health and safety management practices. This is motivated by the evidence that the dynamics of complex systems can hardly be predicted; rather a proactive approach to health and safety is more effective. Current technologies installed on construction equipment can usually react according to a strict logic, such as sending proximity alerts when workers and equipment are too close. Nevertheless, these approaches barely do make informed decisions in real-time, e.g. including the level of reactiveness of the endangered worker. In similar circumstances a digital twin of the construction site, updated by real-time data from sensors and enriched by artificial intelligence, can pro-actively support activities, forecasting dangerous scenarios on the base of several factors. In this paper a laboratory mock-up has been assumed as the test case, supported by a game engine, which is able to replicates the job site for the execution of bored piles. In such a scenario populated by an avatar of a sensor-equipped worker and a virtual driller, a Bayesian network, implemented within the game engine and fed in runtime by sensor data, works out collision probability in real-time in order to send warnings and avoid fatal accidents.

Keywords: artificial intelligence, building information modeling, digital twin, real-time system, real-time health and safety management

1. Introduction

The AEC industry represents nowadays one of the most hazardous productive sectors [1]. In fact, it employs only about 7% of the world's work force but is responsible for 30–40% of fatalities. Statistics, referred to different countries, demonstrates that the construction safety is a perennial global problem. In United States the census data from the U.S. Bureau of Labor Statistics (BLS) showed that a total of 774 workers died from injures they suffered on construction sites in 2010, accounting for 16.5% of all industries. The fatality rate (9.8 per 100,000 full-time equivalent workers) ranked the fourth highest among all industries. Within the two decades 1990 and 2000 more than 26,000 U.S. construction workers have died at work. That equates to approximately five construction worker deaths every working day [2]. Over six hundred construction worker deaths, occurred in the United States during the inclusive years of 2004 to 2006, were related to construction equipment and contact collisions [3]. The statistic can be explained by the dynamic work tasks which take place in construction sites and involve multiple resources, such as personnel, equipment and materials. These resources are often in motion and can come in close proximity to each other; because of the unstructured and almost random movement of the manifold of resources involving different trades on job sites, available space can be temporarily limited or constrained. If not coordinated and organized properly through optimized work planning, spatial interference can lead to incidents. One of the main safety problems in construction has been identified as the proximity of workers-on-foot to heavy construction equipment. Lower awareness and loss of focus due to fatigue, task repetition and blind spots affect the totality of construction sites' actors. Current technologies installed on construction equipment can usually react according to a strict logic, such as sending proximity alerts when workers and equipment are too close [3], and provide an estimation of working areas in order to prevent collision accidents [4]. Nevertheless, these approaches barely do make informed decisions in real-time, e.g. including the level of reactiveness of the endangered worker.

The current research develops a twin model of the Digital Construction Capability Centre (DC3), using Unity 3D, to simulate the execution of bored piles. The serious game application implements a Bayesian network which, fed by data from sensors, provides in real-time the linear, rotational and overall collision probability affecting workers-on-foot. This paper is organized as follows. Section 2 provides a description of applied technologies and introduces the developed system architecture. Section 3 reports the experiments and the related results. Section 4 is devoted to conclusion.

2. Materials and methods

2.1 Development of the digital twin in a gaming environment

The digital twin concept, that is the real-time virtual representation of a physical entity across its life-cycle, originates from the manufacturing industry in the early 2000's [5]. In the near future, digital twins will take a center stage in the Architecture, Engineering and Construction (AEC) industry as an instrument to support better informed decisions [6]. Sensors data will be delivered from the real environment, such as a construction jobsite, to its virtual mirror; here, fast forward simulations based on AI technologies can help to predict future scenarios. The development of a building's digital twin requires to model the environment, which includes physical space, sensors and mechanical physics. For the purpose of this paper, a serious gaming platform, namely Unity 3D, has been adopted. The physical space of the digital twin, assumed as case of study, can be directly imported within Unity 3D as an IFC project with its structure. To this end, the IFC Loader, based on the IFC Engine DLL library, has been developed in order to import topological information, materials properties and all semantic information from the digital model. This tool models the environment using one of the most powerful technique in solid modelling: boundary representation (B-REP). B-REP represents a solid as a collection of connected surface elements, that is the boundary between solid and non-solid. The digital twin, in order to mimics reality, requires the implementation of human and artificial sensors, known as agents. The sense of sight, for example, must be implemented in digital twins to give humans' avatars the awareness about what is happening around them. In Unity 3D, this can be done modelling the field of view (FOV) as a collider; a user can see an entity simply if her/his FOV collider intercepts the entity itself. The mechanical physics is a native functionality of game engines; hence, in the game scene every object is affected by gravity just like in reality. To conclude, Unity 3D hosts the digital twin and can work as a hub able to trigger co-simulations related to some specific discipline and receive back results. In this way, multiple simulators (e.g. fire scenario, plants' functioning, etc.) can be coupled, by means of the models exchange standard FMI.

2.2 Bayesian networks

Bayesian networks (BNs) are a computational tool for the development of qualitative probabilistic models. They are oriented graphs whose nodes represent random variables that are linked by arcs which correspond to casual relationships among previous nodes. BNs make use of probability theory and graph theory to make decisions in conditions of uncertainty. The potential of the BN instrument lies in its dual structure. The first one is a set of nodes representing system variables. Each variable may be given two or more possible states which can be of numerical (i.e. discrete), interval (i.e. subdivision into ranges), label or

Boolean type. The second one is a set of links representing the casual relationships between nodes. An arc from any set of *n* variables, called a_i, to another variable *b* denotes that the set a_i causes *b* and a_i are said to be the parents of *b* (*b* is their child). The graphical part illustrates and communicates the interactions among the set of variables through a Directed Acyclic Graph (DAG). Furthermore, Bayesian networks represent the quantitative strength of the connections between variables, allowing probabilistic beliefs to be updated automatically as new information becomes available, by applying the principles of the Bayes' theorem [7]. The strength of these relationships is quantified by conditional probability tables (CPTs), where the probability of observing any state of the child variable is given with respect to all the combinations of its parents' states. These probabilities are usually labelled $P(b|a_1, a_2, \ldots, a_n)$, where any variable a_i is conditionally independent of any variable of the domain that is not its parent. Thus, it is possible to obtain a conditional probability distribution over every domain, where the state of each variable can be determined by the knowledge of the state of its parents only, and the joint probability of a set of variables *E* can be computed by applying the "chain rule" [8]:

$$P(E) = P(E_1, E_2, \ldots, E_n) = P(E_n|parents(E_n))$$

The joint probability of a set E_n of variables is equal to the conditional probability of the variable, given only its parents. Other relevant benefits are: the DAG provides a clear understanding of the qualitative relationships among variables; every node can be conditioned upon the acquisition of new information; belief updating of nodes is supported from consequences to causes, also known as diagnostic reasoning. Finally, CPTs can describe the relationships among variables of different types (e.g., Boolean nodes, interval node, etc.), even within the same network.

In H&S management BNs can be applied to compute the probability of a hazardous scenario to occur, on the base of real-time sensors data. For the purpose of this paper, a Unity 3D tool, namely Discrete Bayesian Network, has been applied for the implementation of BNs inside the serious gaming platform. This tool provides a C# library that facilitates the definition of BNs' structure and parameters regulating Bayesian inference.

2.3 Digital Construction Capability Centre

The Digital Construction Capability Centre (DC3) is a hologram room of about 240 m^2 situated at the Polytechnic University of Marche in Ancona, Italy; the facility is dedicated to digital twin applications such as construction scenario simulation, innovative teaching approaches and operations scenario simulation. To make it possible, a twin model of the DC3 has been developed as a mock-up which, continuously updated by real-time data from sensors, constitutes a virtual replica of reality.

The DC3 mock-up is based on the system architecture shown in Fig. 1 and composed by the following technologies: a set of UWB position sensors, Node-RED programming tool, Arango DB database and Unity 3D game engine. In the DC3 environment, workers simulating field activity can be located by means of an UWB localization system. This technology leverages Time of Flight (ToF), which is a method for measuring the distance between two radio transceivers by multiplying the Time of Flight of the signal by the speed of light; thus, knowing the position of fixed UWB anchors and operating a trilateration, the position of moving UWB transceivers (tags) can be determined. For the purpose of this paper, five anchors have been installed in known positions, whereas two UWB tags have been applied to the safety jacket in order to track position and heading of the worker-on-foot who wears it. In order to wire together hardware devices (IoT) with the database and then with the Unity 3D game engine, the flow-based graphical programming tool Node-RED has been adopted. It provides an open-source browser-based graphical editor that allows to build complex flows using a wide range of nodes provided in the palette and by the community. In this research, a dedicated Node-RED flow wires together the position data coming from the UWB localization system with a database for their storage. This flow interfaces with the UWB localisation system (MDEK1000 by DecaWave) by using the MQTT protocol. When building a digital twin, different types of data have to be stored and linked together in an emerging way. Therefore, ArangoDB has been selected here as native multi-model NoSQL open-source database also for storing the complete data history from sensors. In order to allow Node-RED to access ArangoDB, a specific Node-RED node has been developed for writing JSON documents into a collection of an ArangoDB database by using the ArangoJS language. The hearth of the developed architecture is the serious game engine Unity3D, which hosts the digital twin and enables AI-based simulation to predict dangerous scenarios. On the base of sensors data stored in ArangoDB, the continuous update of the Unity3D scene has been made possible by SignalR software library, which sends asynchronous notifications to client-side web applications. As a consequence, position and rotation coordinates of the monitored worker-on-foot are delivered to a virtual avatar in order to mimic her/his behavior. In this research study, the AI component, implemented inside the serious gaming platform, is represented by a Bayesian network designed to predict collision hazards between workers-on-foot and moving equipment, such as a drilling machine. Finally, a dedicated web application, installed on the equipment's on-board computer, can make results from AI-based assessment available to the driver. The aim of this field application is to make the driver aware about oncoming risks, affecting vulnerable users in the job site, in order to prevent fatal events.

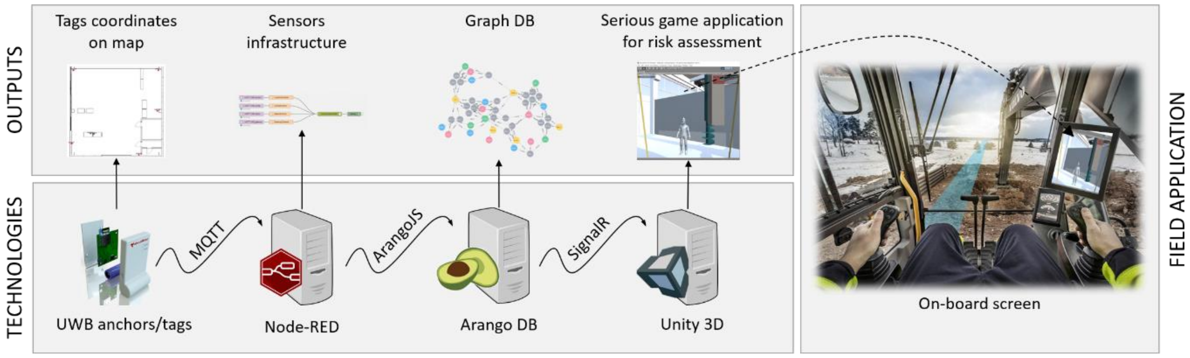

Fig. 1. System architecture

3. Experiments

3.1 Development of the mock-up and design of the experiment

For the purpose of this research study, the execution of bored piles has been assumed as test case scenario, since it represents one of the most hazardous construction procedures. In fact, a worker-on-foot is called to work close to heavy components, such as the drilling machine, during each phase. To make a few examples, the workers-on-foot leads the positioning of the bucket at the exact drilling point, assists the insertion of the reinforcement cage, opens the bucket to unload the extracted soil and supervise the concrete filling. During the described operations, a momentary lapse could lead to injuries and fatal events. For this reason, AI applications could greatly benefit real-time H&S management.

In this paper, the digital twin of the DC3 has been applied to develop a serious game application which support real-time H&S management. To this aim, a DC3 mock-up which replicates drilling operations has been implemented using Unity 3D. As introduced in section 2.1, the real environment has been recreated loading the IFC model of the DC3. The implementation of the UWB localization system, described in section 2.3, makes it possible to track the position of the workers and equipment. A worker-on-foot, wearing a sensorized jacket, can be monitored and replicated by an avatar who lives the virtual scene. The mock-up is completed by the virtual model of a drilling machine, which is controlled by a joystick in order to simulate a real working scenario. The BN shown in Fig. 2 assesses the probability that the drilling machine runs over the worker-on-foot given, as evidences, the linear distance driller-worker, the angle between the driller's forward direction and the line driller-worker, the driller's linear and angular speed and, finally, the mutual visibility. Being the BN implemented in Unity 3D by means of the Discrete Bayesian Network tool, as mentioned in section 2.2, the twin model receives real-time data from sensors and feeds BN's variables. The pseudocode shown in Fig. 3 describes the implementation of a portion (see the red dashed line in Fig. 2) of the Bayesian network, developed for collision risk assessment, inside the serious gaming platform; the resulting linear collision probability is the probability that the drilling machine runs out the worker-on-foot. The rotational collision probability is instead the probability that the rotating body of drilling machine hits the worker-on-foot. Finally, the overall collision probability summarizes the two previous variables providing an overview of the hazards affecting the worker-on-foot.

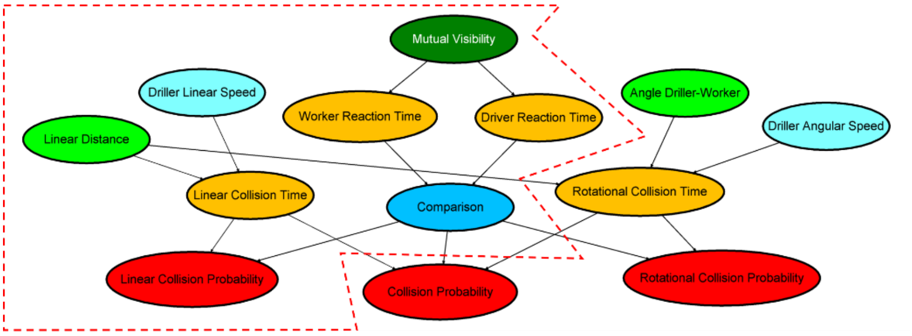

Fig. 2. The Bayesian network developed for the collision risk assessment

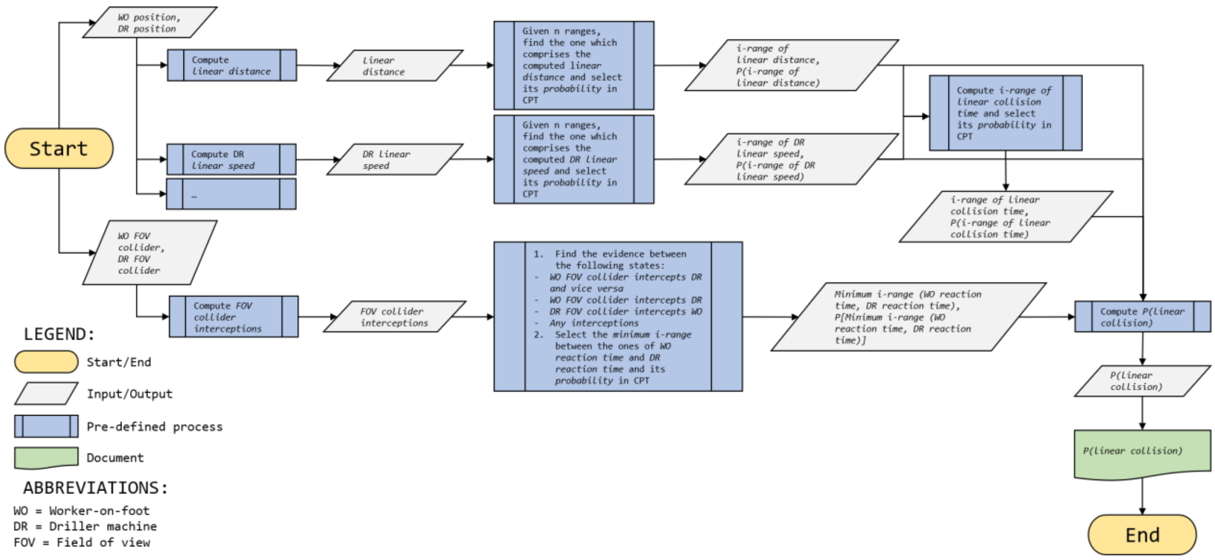

Fig. 3. Pseudocode describing the implementation of a portion (see the red dashed line in Fig. 2) of Bayesian network in Unity3D game engine

3.2 Experiments and results discussion

In this paper, drilling operations for the execution of bored piles have been simulated by two researchers. The first one wears the sensorized safety jacket and moves around the construction site in order to mimic the support activities accomplished by a worker-on-foot during drilling operations. The other researcher controls the virtual drilling machine by the joystick. This scenario is mirrored by the DC3 mock-up in Unity 3D on the base of real-time data provided by sensors. According to this data, the BN implemented in the serious game engine computes and updates linear, rotational and overall collision probabilities in real-time. In Fig. 4.a, the ground worker can see the drilling machine (see FOV colliders represented by green lines in Fig. 4.a), while the driver has a reduced visibility; nevertheless, the BN does not point out risks due to the distance between the worker-on-foot and the drilling machine. In Fig. 4.b, the visibility conditions keep unvaried whereas the linear collision probability rises from 0% to 24.51%, since the linear distance has decreased. In Fig. 4.c the worker-on-foot turns her/his back to the drilling machine; since the worker and the driver cannot see each other (see FOV colliders represented by green lines in Fig. 4.c), the linear collision probability increases up to 51.09%.

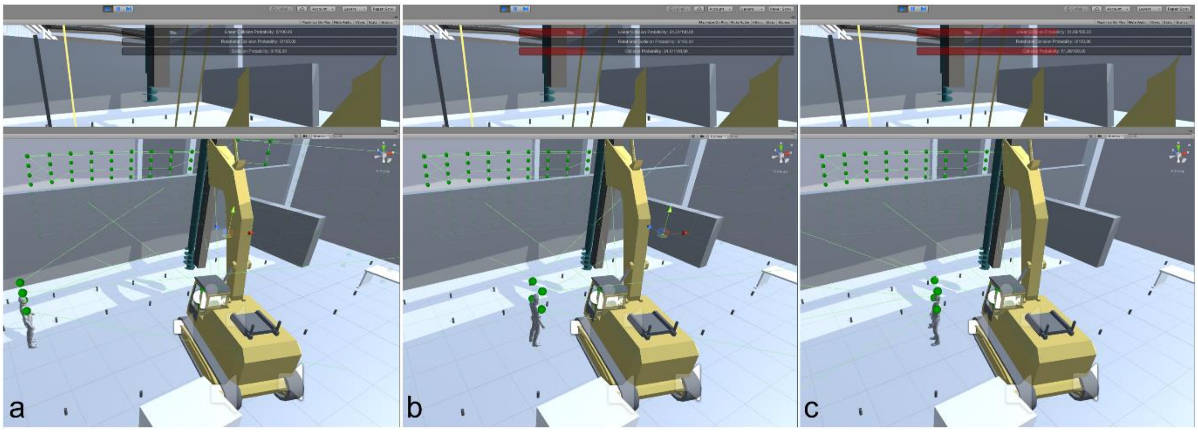

Fig. 4. The BN updates of the linear collision probability according to the changing environment conditions

4. Conclusions

The complex nature of construction sites makes it difficult to predict hazardous scenarios affecting workers. In similar circumstances, a digital twin of the job site, automatically updated by real-time data from sensors, can pro-actively support activities and forecast dangerous scenarios by means of AI technologies.

In this paper, the twin model of the Digital Construction Capability Centre (DC3) at the Polytechnic University of Marche (UNIVPM) has been developed as a mock-up using a gaming engine. The result is a serious game application which implements a Bayesian network to compute collision probability during drilling operations, based on several relevant variables. This technology can be applied to inform the equipment's driver about oncoming risks in real-time; hence, it aims to improve her/his awareness in order to avoid injuries and fatal events.

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Feasibility of Using Physiological Signals from a Wearable Biosensor to Monitor Dehydration of Construction Workers

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Abstract

Among major industries, due to the labor-intensive nature of most of the construction tasks, the construction industry has some of the highest numbers of heat-related illness claims. The leading cause of these illnesses is the repeated exposure of workers to heat stress, which adversely affects productivity, safety, and health. A biophysical interpretation of the body's responses to heat stress is a promising way to continuously measure the likelihood of heat stress exposure of workers. Such a method surpasses current metrics such as Wet Bulb Globe Temperature and Heat Index. The others do not account for variations of individual physiology and biometrics (e.g., age, gender, and metabolism) in response to heat stress. Also, environmentally based methods cannot be used to continuously monitor heat stress in the workplace. This study aims to examine the effect of heat stress exposure on the flux of three different physiological signals: photoplethysmography (PPG), electrodermal activity (EDA), and skin temperature (S.T). To facilitate capture of workers' physical responses to acute heat, these are acquired from a wristband biosensor. To that end, physiological data were gathered from 10 workers performing construction tasks under three climatic conditions, each with a different likelihood of exposure to heat stress – conditions of caution, extreme caution, and danger, as defined by the National Oceanic and Atmospheric Administration (NOAA)'s National Weather Service. Heart rate, heart rate variability, electrodermal activity, electrodermal response, and mean skin temperature were extracted to examine the potential of these signals for measuring workers' heat stress. The results indicated statistically significant differences in the metrics of heat stress exposure. The findings demonstrated the feasibility of PPG, EDA, and S.T. in capturing physiological changes during heat stress exposure and dehydration.

Keywords: dehydration assessment, wearable biosensors, physiological monitoring

1. Introduction

The construction industry is beleaguered by extensive health and safety issues. At labor-intensive construction sites, workers perform physically arduous tasks under hazardous working conditions all day [1–3]. Frequently done in scorching and unmonitored environments without enough of a break to recover physiologically from overexertion, tasks are often performed with limited or lack of shade or water [4], and workers can suffer dehydration, as well as heat stress.

In fact, enough exposure to heat can cause acute illnesses, such as dehydration, and chronic diseases, such as brain damage, both of which can adversely affect workers' productivity, safety, and health [5–8]. Between 2000 and 2010, construction was responsible for 36.8% of heat-related deaths, highest in the United States [9], a risk of heat-related fatalities 13 times greater than other industries [10]. Therefore, monitoring worker's heat stress exposure should be diligently implemented in health and safety management at construction sites.

To prevent heat-related illnesses, systematic heat stress measurement is of the utmost importance. There have been several efforts to gauge such. Some use answers to questionnaires [11,12]. However, survey-based methods interfere with ongoing tasks and are prone to biases. Other heat stress measurements rely on environmentally based metrics, such as Wet Bulb Globe Temperature (WBGT) and Heat Index (H.I.) [11,13]. Despite their use in measuring the state of heat stress in the field, these metrics cannot assess the full variation in a worker's physical characteristics and personal physiology [14,15]. Therefore, there is a need for objective and non-intrusive ways to evaluate heat stress in the field.

Biophysical responses to a workplace stimulus can offer valuable information about a worker's health, mental state, and other work-related responses [16–19]. Recent advances in wearable technologies offer an unprecedented opportunity to do non-intrusive, objective, and continuous real-time monitoring of workers' physical activity and processes [17,18,20,21]. These aspects of physiology can be monitored easily using photoplethysmography (PPG), electrodermal activity (EDA), and skin temperature (S.T.). The responses can be promptly processed and effectively analyzed to infer health conditions [16,22,23]. Specifically, this analysis can pave the way for continuous heat stress assessment in the field. In this vein, this study attempts to investigate various features of PPG, EDA, and S.T. signals as mechanisms of heat stress exposure.

2. Current methods of heat stress assessment and their limitations

Construction practitioners and researchers have mainly relied on subjective techniques (survey-based methods) to assess heat stress at work sites. The Heat Strain Score Index (HSSI) is a widely used subjective technique for heat stress assessment. In this method, heat strain experienced by an individual is evaluated by a questionnaire that contains 17 items related to the assessment of heat stress, such as questions about the experience of thermal and humidity conditions, the intensity of sweating, and intensity of fatigue [11]. While this method has broadened our understanding of the heat-stress of construction workers, it is prone to biases of self-report inherent in subjective scales. Also, doing the survey will interrupt the workflow because workers are required to participate during work hours. In addition to subjective assessment, heat stress has also been understood in terms of meteorological (climatic) parameters. Metrics such as H.I. and WBGT can monitor heat stress at construction sites. By assessing two common meteorological values, temperature, and relative humidity, H.I. reveals the climatic condition as experienced by the human body [13]. This index ignores other meteorological parameters (i.e., wind speed, air pressure, and sunlight) to evaluate the climatic conditions affecting heat stress accurately. WBGT is an efficient assessment of the thermal environment (ambient temperature, relative humidity, wind, and solar radiation) [13]. It is the most widely used index in assessing heat stress and has been adopted by the U.S. occupational safety and health authorities and other national and international agencies as the basis of heat-stress standards [24]. Although WBGT is a convenient method, the chances of heat stress exposure being different from environmental conditions and the reliability of the worker's judgment of his/her metabolic rate reduces its viability. More importantly, along with other environmentally-based techniques, WBGT suffers from generalization, representing only one value for heat stress exposure. Workers' responses to such exposure are different due to variations in physiological status such as age, gender, chronic or pre-existing diseases, fitness, hydration, and use of alcohol and medication. Different types of physical activity, body size acclimation, and clothing vary across workers [24–28], pointing to the importance of physiologically based techniques as a solution to heat-stress assessment.

3. Knowledge gaps and research objectives

As mentioned above, current techniques mainly rely on subjective evaluation, and environmental assessment for measuring heat stress exposure, a more in-depth evaluation of workers' physiological conditions in the field is necessary for efficient and pragmatic monitoring. With current advances in non-intrusive wearable biosensors, several physiological responses to heat-related stimuli can be captured by a physiological sensor. These biosignals contain valuable information regarding physiological functioning and changes, and they can be extracted with advanced signal processing and machine learning techniques. However, the extent to which the biosignals can reveal the correct fluxes in human physiology depends on the type of stimulus.

Previous studies suggested PPG, EDA, and S.T. could capture information about the body's thermoregulation and be used as physiological signals [29–31]. PPG is a noninvasive way to measure blood volume changes in microscale vessels just under the skin [23]. When individuals are in a highly stressful environment, the brain innervates the heart via the sympathetic nervous system. Changes in the heartbeat (H.B.) mechanism will result in variations in blood volume; these can be measured by PPG [32]. Metrics obtained from PPG signals (e.g., H.B. variation) have the potential to measure workers' exposure to heat-related injuries (heat stroke and exhaustion) [33,34]. As a result, PPG can provide an opportunity for understanding workers' bodily responses to thermal stress.

The sympathetic nervous system controls the sweat glands. EDA measures the changes in the electrical properties of the skin in response to autonomic sweat gland activity [35]. If the sympathetic branch of the autonomic nervous system is activated by external stressors, the number of active sweat glands increases, reflecting a higher EDA measurement [36], several features can be extracted from it, such as mean value, median value, variance, electrodermal level [EDL], and electrodermal response [EDR]) to measure these changes. To this end, EDA can be introduced as a reliable signal of the sympathetic nervous system when thermally stressful environments produce dehydration. When the body is subjected to intense, acute thermal conditions, the thermoregulation system adjusts skin temperatures through vasodilation and -constriction to maintain thermal homeostasis [37–39]. The dynamic between these two mechanisms controls skin blood flow, resulting in skin temperature adjustments. S.T. has the potential to be a quantitative and objective indicator of likely illness and injuries [33,39,40]. Features like mean skin temperature (MST), mean frequency, and median frequency can be extracted from S.T. to assess the heat shock experienced by workers during ongoing work.

As mentioned above, the stimulation of the sympathetic autonomic nervous system results in significant changes in EDA, S.T., and PPG [16]. Nevertheless, the feasibility of using these measures to understand workers' heat stress under various conditions has not been well studied. Therefore, this paper aims to investigate more precisely the potential of these biosignals in unfolding the responses of construction workers to levels of heat stress exposure.

To this end, the authors recruited ten healthy subjects to perform two physical activities under three climatic conditions, namely low, medium, and high exposure to heat stress. During the experimental procedures, the subjects' physiological signals were collected from wearable sensors. A wide variety of metrics were extracted from the signals, such as heart rate (H.R.), heart rate variability (HRV), EDL, EDR, and mean skin temperature (MST), to name a few.

By statistically analyzing these features, a more in-depth understanding of the potential responses of a worker's body to heat stress can be achieved. Furthermore, such comparisons can reveal the underlying effect of heat stress on various aspects of PPG, EDA, and S.T. biosignals. Also, future studies can exploit the findings of this one to more suitably select relevant biosignals to develop predictive models.

4. Experimental design

4.1. Subjects

Experimental procedures were established to collect physiological signals from 10 able-bodied adults recruited among students at Pennsylvania State University (PSU). The data collection protocol was approved by the Institutional Review Board (IRB) at PSU. All subjects were provided with informed consent forms explaining the confidentiality of the data and participants' rights. After the consent form was signed and received, all subjects were asked to provide demographic information (i.e., age, gender, height, and weight). To exclude unhealthy subjects, participants were also asked for any history of health problems. None of the subjects reported any. Among ten subjects, seven were male; the remaining three were female. No subjects had any clinical conditions.

Fig. 1. Experimental setup: (a) roofing task; (b) materials handling task; (c) chamber room; (d) control station for simulating temperature and humidity at conditions labeled caution, extreme caution, and danger; (e) wearable biosensors measuring PPG, EDA, and S.T. signals.

4.2. Chamber room

The study was performed in an environmental chamber room with three different climatic conditions to simulate exposure to heat stress at the three levels of caution, extreme caution, and danger. The climatic conditions were simulated by controlling the temperature and humidity level. Such categorization was performed using the Humidex scale. This index calculates the temperature and humidity required to induce various levels of heat stress exposure. In this vein, for a condition of caution regarding heat stress, the temperature and humidity were set to 84.2 F^{O} and 40%. Correspondingly, for extreme caution, temperature and humidity were set to 87.8 F^{O} and 45%. Likewise, to simulate the condition of danger, the temperature and humidity were set to 89.6 F^{O} and 55%, respectively.

4.3. Data collection procedure

All the subjects were asked to wear a non-intrusive wristband sensor (i.e., Empatica E4 wristband). They were instructed to perform roofing and materials handling tasks in the environmental chamber room. The roofing task involved nine minutes of hammering nails into a roofing surface angled 30^{O} from horizontal, as well as attaching and adjusting shingles. The materials handling task required subjects for six minutes to move concrete blocks from a wheelbarrow, place it on the roofing surface, and put it back in the wheelbarrow. Each subject was asked to perform the tasks in the chamber room for 15 minutes. Between the tests, they rested for 10 minutes. During each task, S.T., EDA, and PPG biosignals were captured at a sampling rate of 4 Hz, 64 Hz, and 4 Hz, respectively. The sensor promptly transmitted the data to a portable device. By using the sensor's application programming interface (API), the device was able to upload the biosignals onto an online server in near real-time.

5. Data analysis

5.1. Noise removal

Interpretation of the signals can be affected by several kinds of noises. These come from changes in the body (i.e., excessive movement, etc.) and extrinsic changes (i.e., electrodes popping, environmental noises, ambient light, thermal noises, etc.) [41–44]. Robust noise removal decontaminated the biosignals of the major artifacts. Such an approach smooths the way for precise inferences of metrics based on the physiological signals. To better eliminate the adverse effects of signal noises, this study selected noise removal techniques based on the sources and modality of capture.

The PPG sensor determines the changes in blood flow by calculating the differences between the wavelengths of the original lights and the one reflected from the subject's tissue [45]. Environmental factors such as ambient light, thermal noise, and electromagnetic sources are more likely to induce high-frequency artifacts [45]. To remove them, a frequency-based filtering technique (i.e., bandpass filter) within the range of 0.5-4 Hz was applied. An EDA sensor records the signals by passing a minuscule amount of current between the electrodes in contact with the skin [41]. Hence, the measurement is vulnerable to different types of noises, namely electrode artifacts, excessive movement, and adjustment of sensors due to disruptions in the skin-electrode interface [41–44]. A high pass filter with a cut off frequency of 0.05 Hz was applied to the EDA signals. Furthermore, a rolling filter was used to remove large magnitude noises caused by excessive movement and electrode pressure. Different filtering methods (e.g., a Hampel filter and a finite impulse response filter) were applied to remove artifacts from S.T. signals. To remove outliers, a Hampel filter was used. A finite impulse response filter was applied to smooth the S.T. signals and to avoid aliasing in the data.

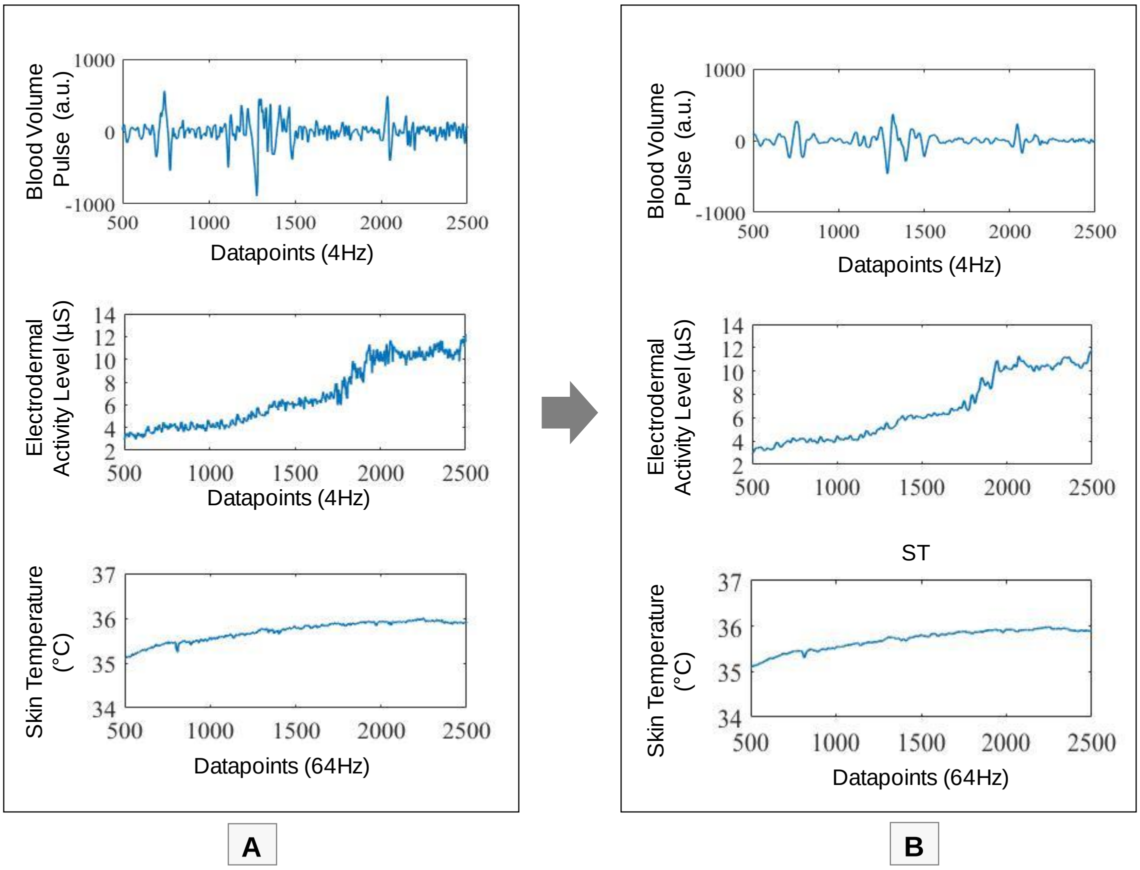

Fig. 2. PPG, EDA, and S.T. signals noise removal: (A) Raw signals; (B) Filtered signals

5.2. Physiological metrics

Several metrics were calculated after removing signal noise. From the PPG signals, three metrics were extracted, heart rate (H.R.), mean frequency, and median frequency. H.R. was determined from the processed PPG signal by counting the number of peaks in the alternating current of the signals. Also, the median value and mean frequency were extracted in the frequency domain to examine the changes in the subjects' cardiac activity.

Similarly, several metrics were extracted from EDA signals. These results included mean value, median value, and variance. EDL and EDR were extracted from the EDA signals to more achieve more precise results. EDL has been regarded as a suitable measure of sympathetic activity induced by long term stress [46,47]. On the other hand, EDR reflects short term responses to external stimuli [48,49]. In this regard, a deconvolution approach was applied for decomposing EDA signals into continuous signals of tonic and phasic activity to measure EDL and EDR, respectively. The metrics from S.T. in time and frequency domain included mean skin temperature (MST), mean frequency, and median frequency. These values were calculated after applying a finite impulse response filter to monitor skin temperature changes working under different exposures to heat stress.

5.3. Statistical analysis

To analyze the statistical differences among levels of heat stress exposure, the Wilcoxon signed-rank test was performed on the metrics. Specifically, this non-parametric comparison was used to determine the statistical differences across climatic conditions because the data did not satisfy the normal distribution assumption (Shapiro-Wilk test [50]). This lack was probably due to the low sample size [51]. In this study, the statistical comparison tests were performed with a 0.05 level of significance.

6. Results

Fig. 3 represents the distribution of the calculated metrics pertinent to the PPG, H.R., median frequency, and mean frequency, for all the subjects across all heat stress exposure. There were no statistically significant differences among the metrics computed for low, medium, and high climatic conditions.

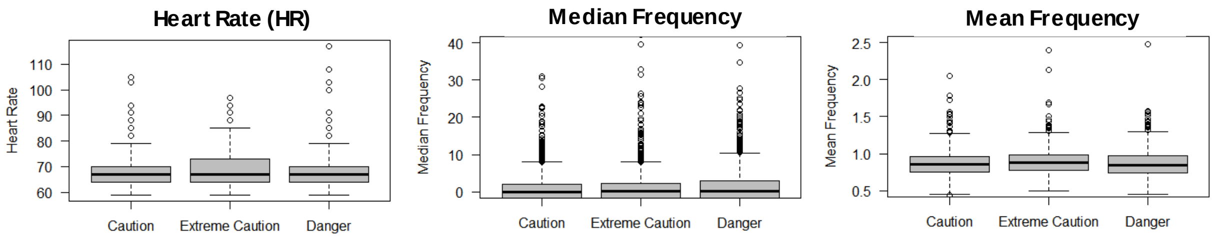

Fig. 3. Metrics values derived from PPG.

On the other hand, there were significant differences (P-value < 0.05) between the mean value, median value, and variance of EDA in the time domain. As seen in Fig. 4, as the heat stress level increases, these metrics exhibit a significant increase. More specifically, the Wilcoxon signed test indicated that the mean value for the EDA signals is significantly higher under medium heat stress than low heat stress (z= -5.05, p<0.05). Likewise, the test revealed a significant difference in the mean value of EDA signals between medium and high levels of heat stress (z= -6.56, p<0.05). The test also corroborated a significant difference in the median value (z= -5.05, p<0.05) and variance value (z= -6.69, p<0.05) of the EDA signals across low and medium heat stress conditions. Similarly, the test showed that these metrics were significantly higher in high heat stress conditions than under medium heat stress (z= -6.53, p<0.05 for the median value and z= -4.39, p<0.05 for the variance value). As for the EDR and EDL values, a similar trend can be observed among levels of exposure to heat stress (Fig. 4). The Wilcoxon signed test substantiated that the EDR values at medium heat stress are statistically higher than the values at low heat stress (z= -5.0649, p<0.05). The results of the non-parametric test demonstrated that EDR changes from medium to high heat stress (z = -4.136, p<0.05). Similarly, EDL values exhibit a significant increase as the condition changed from low to medium heat stress (z= -4.91, p<0.05), and from the medium to high heat stress (z = -6.5277, p<0.05).

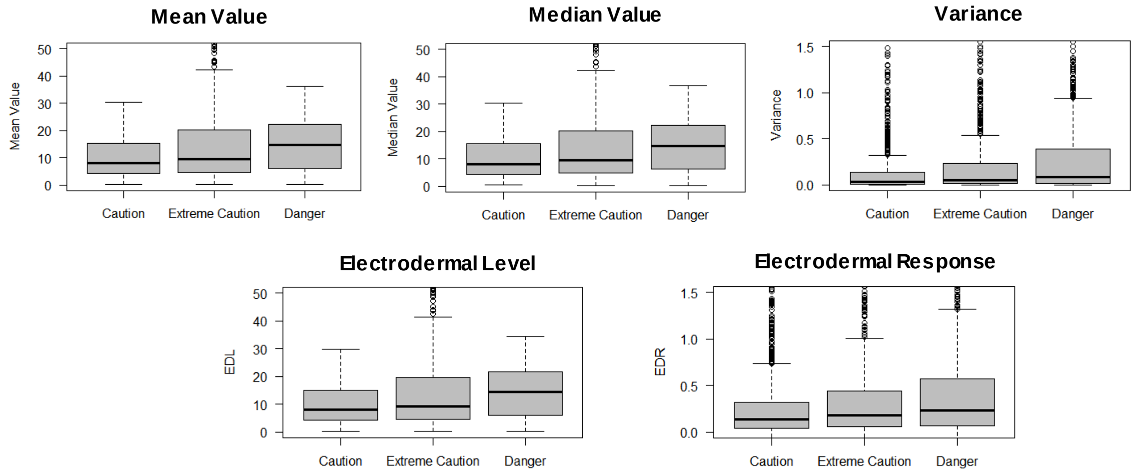

Fig. 4. Metrics values derived from EDA.

Meanwhile, differences in MST extracted from S.T. signals were captured while subjects were working under different levels of heat exposure. As seen in Fig. 5, the MST value is higher in the conditions with high heat stress. The Wilcoxon signed-rank test indicated that the MST value is significantly higher under medium heat stress conditions than in low heat ($z = -12.9$, $p<0.05$) Also, the test stated that MST values significantly increased from medium to high heat stress conditions ($z= -21.3$, $p<0.05$). On the other hand, metrics extracted from S.T. in the frequency domain (mean frequency and median frequency) failed to show any clear difference across levels of heat stress.

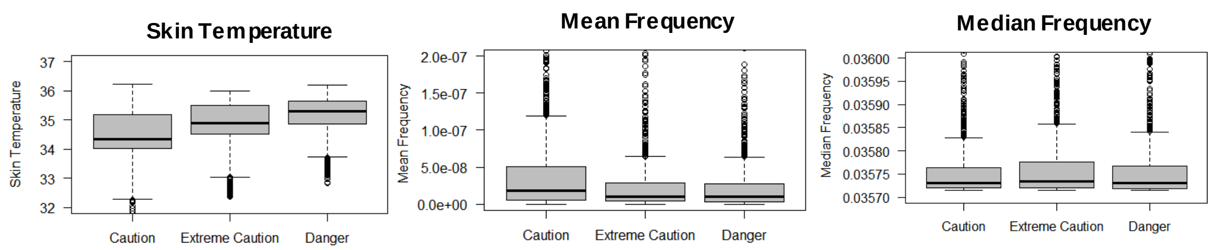

Fig. 5. Metrics values extracted from S.T. (MST, mean frequency, and median frequency)

7. Conclusion

This study was designed to investigate the capability of using physiological signals collected from a wristband sensor to capture the responses of the body due to exposure to heat stress. Metrics from PPG, EDA, and S.T. signals were collected from 10 healthy subjects performing two construction tasks under different environmental conditions. The results showed there is a significant difference in the metrics of EDA and S.T. among different levels of heat stress exposure. While the subjects performed the two tasks, roofing and materials handling, in thermally high stress conditions, the values of metrics from the EDA signals in the time domain (mean value, median value, and variance value) generally increased. The results indicated that EDL and EDR values increased with elevation in heat stress. Also, the findings revealed that MST extracted from S.T. signals exhibited significant differences under different climatic conditions. This pattern of the increase can be an appropriate criterion for the selection of relevant biosignals and the development of interpretive models for heat stress prediction and assessment. Such an attempt also augments our understanding of workers' physiological mechanisms under acute environmental conditions. As a critical step toward safer workplaces, this deeper understanding of human physiology can lend itself well to the design and development of wearable sensor-based health monitoring systems for a near real-time and objective assessment of worker heat stress in the field, which provides good opportunities to improve construction safety management. In addition, this study provides a promising avenue for personalized heat stress monitoring from wearable sensors by exploring the impact of heat stress exposure on key physiological responses. Future investigations can be more accurately performed through additional experiments with more significant numbers of subjects, physical activities, and naturalistic working environments.

8. References

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Investigating a 24 GHz CW-Radar for Non-Contact Vital Sign Sensing in Construction Machine Cockpits to Increase Safety on Building Sites

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Abstract

The US-construction industry sector in 2018 had about 4.5 % of U.S. workers, but 19.1 % of the fatalities - the largest number [1] of fatalities reported for any industry sector [2, 3]. In this context, transportation incidents with heavy vehicles and aging workers over 55 years have the highest fatal event accounting in respect to selected events and demographic characteristics [3]. Therefore, research is underway to measure the health condition of the driver in the construction machine cockpits unobtrusive and non-interfering with their activities. Generally, in research this attempt can be divided into those based on image analysis of camera images, those equipped with wearable sensors, and the method of incorporating sensors in the workers environment, e.g. chairs, controllers, steering wheel, etc. There are various ways to incorporate sensors into the chair [4]. E.g. one of the authors is also trying to extract the driver's heartbeat and respiration information with capacitive electrodes and a pressure sensor built into the seat [5]. This paper focuses on a biometric driver seat concept based on Vinci and Leonhardt [6] using a 24 GHz CW-Radar sensor module to monitor the driver’s health status. The radar sensor signal carries information about the respiration, heartbeat and motion signals of the driver by evaluating the phase-shift of the reflection wave. To separate the respiration-signal from the heartbeat-signal a digital low-pass filter with a cutoff frequency at 0.5 Hz is used. The driver’s respiration rate (RR) is determined by a maximum peak detection in the frequency-domain of the radar signal. The heart rate (HR) is obtained in the time-domain by a heartbeat count estimation. The elimination of random body movement artefacts was not examined in this work. The authors’ objective by this work is to improve safety on construction sites, via the proposed biometric driver seat concept, by early identification of potential health hazards of the driver. For this objective, it is necessary that the detection of human vital signs inside of the cockpit of construction machines will become a part modern driver assist and safety systems in future.

Keywords: biometric driver seat, unobtrusive driver health state monitoring, non-contacting vital sign sensing, CW-Radar Sensor

1. Introduction: A biometric driver seat concept

Working on construction side safely, means according to Haslam et al. [7] to work efficiently. Therefore, it is important that construction works are well rested and healthy. However, Haslam et al [7] confirms that for operatives are only rarely any effective pre-employment health surveillances or screenings.

Also [8] found that there is only little possibilities given for health monitoring on construction side and that there is the link between “occupational health” and “health and safety departments” is missing. Therefore, in this paper, the authors present the concept of a biometric driver seat for contact free measurement of the vital sign parameters of construction machinery drivers. This approach can enable a health data screening in order to increase safety on construction side. For this purpose, a capacitive electrocardiograph for ECG, HR, HRV detection and a 24 GHz CW-Radar for the detection of the RR and PTT (pulse transit time) are used. The sensors are arranged as shown in Figure 1. The cECG electrodes (green) consist of a conductive silver-coated fabric and are sewn onto the backrest of the driver seat.

The electrodes are placed according to the Einthoven 1 arrangement in order to obtain the largest possible amplitude signal of the QRS complex. The seat under the driver's buttocks acts as a ground plane. A conceptual implementation of the ECG unit is presented in Pehr et al. [9] . The 24 GHz CW-radar (yellow) is installed at the chest level of the backrest to monitor the driver's respiration frequency and heartbeat signal. Radio signals in the 24 GHz range can penetrate foams and clothing with low attenuation and get reflected/absorbed by the human body. A second 24 GHz CW-radar sensor is attached at the end of the biometric driver seat for pulse wave detection at the artery in the thigh. In combination with the cECG sensor, the PTT can be determined, which allows an indirect conclusion about the driver's blood pressure.

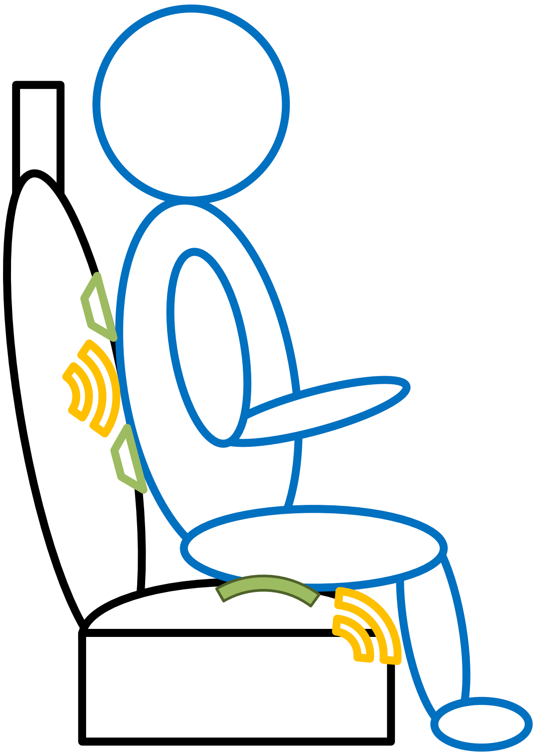

Figure 1: cECG electrodes (green) and Ground plane (green) place at the backrest and biometric driver seat bottom to measure ECG, HR and HRV through the drivers clothing according to Einthoven 1. Cardio Radar Sensor (yellow) is placed at the biometric driver seat backrest to measure RR and HR. Pulse Radar Sensor (yellow) is place at the end of the biometric driver seat to measure the PTT and BP in combination with the capacitive ECG.

2. Material and methods

The implementation of RR and HR detection of the proposed biometric driver seat is carried out by a 24 GHz CW-radar sensor. Therefore, we used the IPS-154 sensor from the company InnoSenT as shown in Figure 2. It provides an EIRP output power level of 16dBm/40mW (average) and 20 dBm/100mW (maximum).

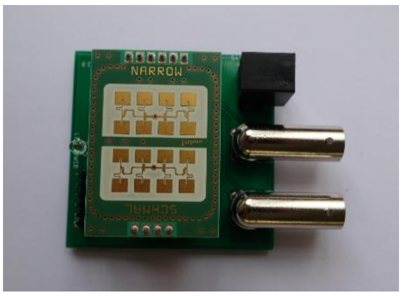

Figure 2: IPS-154 CW-radar sensor from the company InnoSent.

The concept of the CW-radar sensor is shown in Figure 3. The transmitted wave of the 16-element patch antenna array is reflected from the back of the driver, which movements induced by the heartbeat, breathing and random movement artefacts generate a phase shift Δφ in the incident wave. The phase shift is a result of the doppler effect which comes into account by the thorax lift, due to the respiration of about 1 cm and the heartbeat motion at the skin surface in µm to mm scale. The reflected wave is now carrying the information about the driver's vitals consisting of RR, HR and random movement artefacts. Because of the small cardiac body movement, the HR signal comes with a lower SNR-ratio than the RR signal. The incident wave from the surface of the driver's skin is picked up by the same 16-element patch antenna array and gets mixed in the IQ-modulator of the sensor. The analogue I-Q output signal of the radar sensor gets digitized in a 24 Bit ADC of the type ADS1256 at 500 SPS. To receive the phase difference Δφ between the I and Q-channel of the radar sensor, following formula is used:

$$\Delta\varphi(t) = \tan^{-1}\left(\frac{I(t)}{Q(t)}\right) \quad (1)$$

The phase difference gives an indirect measure of the body movement of the driver. Therefore, the HR and RR can be extracted by DC removal, digital filtering, Fast Fourier transform and peak detection in the time- and frequency domain as shown in Figure 3. To separate the respiration-signal from the heartbeat-signal a digital low-pass filter with a cut-offs frequency at 0.5 Hz is used.

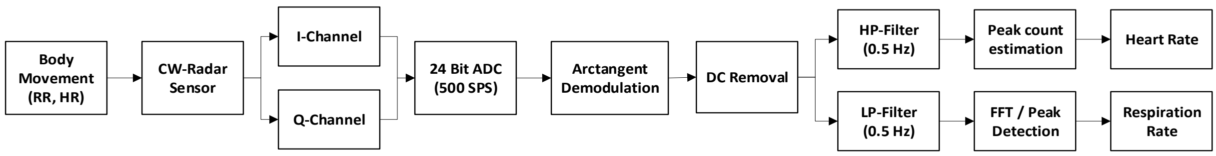

Figure 3: CW-Radar sensor workflow.

3. Results: Radar sensor signal analysis

The radar signal shown in Figure 4 was measured through a cotton T-shirt at the sternum level of the test person at a distance of 5 cm. The large amplitude peaks in the time domain characterize the respiration and the small peaks are associated with the heartbeat of the person. In the frequency domain of the signal two clear peaks at 0.19 Hz and 0.77 Hz show up. The driver's respiration rate (RR) is determined by a maximum peak detection in the frequency-domain of the radar signal. In the power spectrum the peak is located at 0.19 Hz which is equal to a respiration rate of 11.4 breaths per minute. This result is corresponding to the peak count in the time domain with 11 breaths per minute. The second maxima peak in the power spectrum is located at 0.77 Hz/46.2 beats per minute and does not correspond to the correct HR of 54 beats per minute measured with a pulse sensor. Therefore, the HR signal is partly superimposed by the RR signal in the frequency domain.

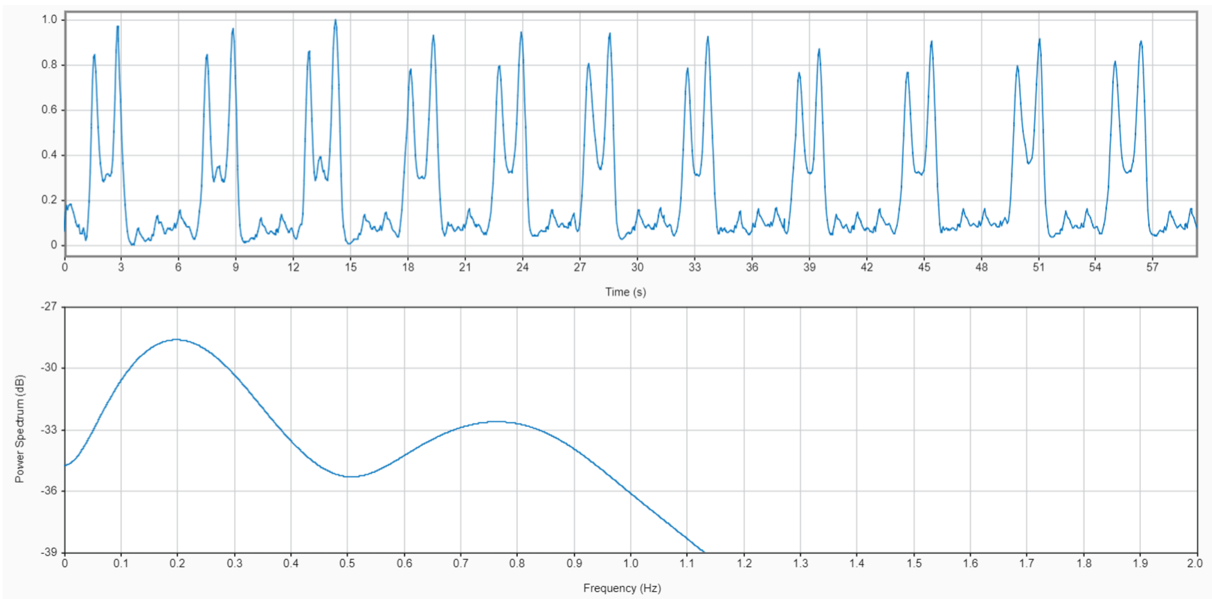

Figure 4: Microwave reflectometer data analysis. Up: Time domain. Down: Frequency domain.

As a solution, a more accurate heart rate (HR) is obtained in the time-domain by a heartbeat count estimation. In this method all local maxima peaks of the high-pass filtered microwave reflectometer data set were considered and giving a more accurate HR of 48 peaks per minute. Compared to the correct HR of 54 beats per minute this method gives better results than maximum peak analysis in the frequency domain.

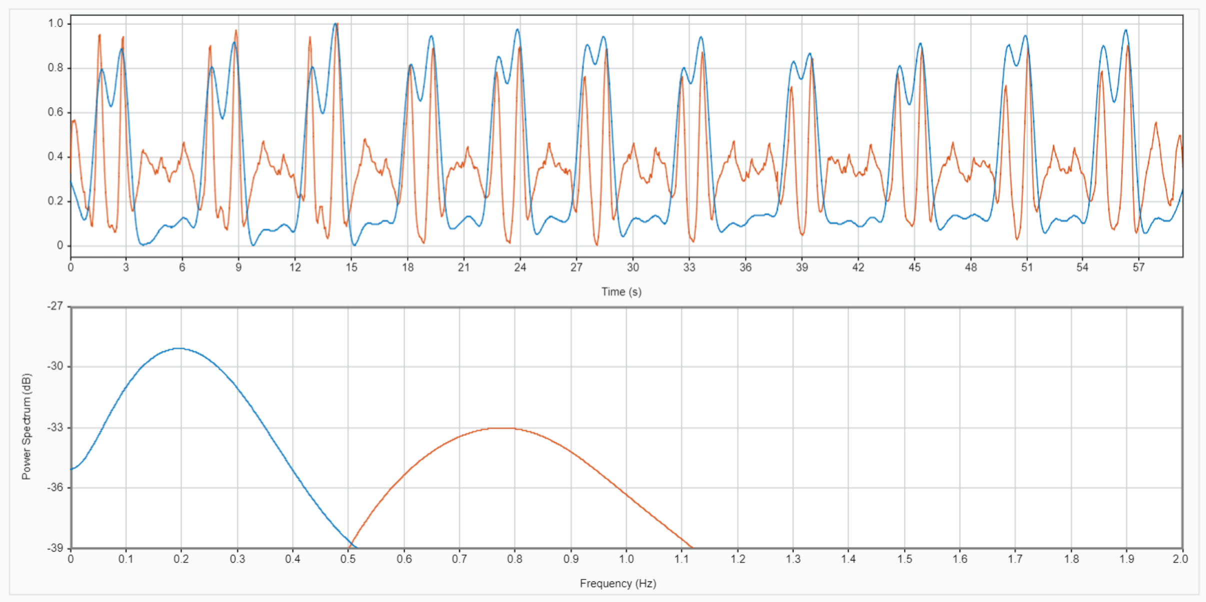

Figure 5: Microwave reflectometer data analysis. Up: Time domain of filtered signals. Down: Frequency domain of filtered signals.

4. Discussion

This paper introduced the innovative concept of a biometric driver seat using a capacitive ECG and radar sensors in construction machine cockpits to increase safety on building sites. The results of the 24 CW-radar sensor data set analysis proves that it is possible to measure the RR of the driver in an accurate and HR of the driver in a sufficiently precise way through a T-shirt and without direct skin contact. We are looking forward, that the concept of this biometric driver seat and the first realisation step by testing its feasibility in our 24 GHz CW-radar sensor study will become a part of modern driver assist and safety systems in future.

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6. References

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Nested Network for Detecting PPE on Large Construction Sites Based on Frame Segmentation

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Abstract

Safety is a main concern for the construction industry because of the high rate of accidents and casualties on construction sites. Personal Protective Equipment (PPE) is a major part of safety regulations to prevent accidents. However, workers may neglect to wear the required PPE while working, which subsequently increases the potential risk for accidents. Currently, safety managers and inspectors on construction sites are responsible for monitoring safety regulations, which is a time-consuming task. To facilitate safety monitoring, a large number of research studies applied computer vision for detecting PPE on construction sites. Nevertheless, detecting workers and PPE is still a challenge in far-field videos. This research proposes an approach for detecting if anyone on the construction site is wearing the required PPE, even when he or she is far from the surveillance cameras. This method uses a frame segmentation technique and a nested network with two Faster R-CNN models to detect safety noncompliances. The first model detects the human bodies on the construction site, and the second one detects if the detected person is wearing a hardhat and a safety vest. The proposed method is applied to videos from a construction site. The experimental results demonstrate the practicality and robustness of the proposed method to detect PPE in far-field videos. Based on three different test videos, the average precision and recall for the worker detection model were 99.67% and 92.92%, respectively. The PPE detection model had the average precision and recall of 91.25% and 94.77%, respectively.

Keywords: computer-vision, construction safety, far-field surveillance videos, faster R-CNN

1. Introduction

Safety regulations are not always followed on construction sites, which is the main reason for accidents. According to [1], more than 450 workers were killed, and over 63,000 workers were injured on construction sites in Canada in 2017. These accidents cost nearly $19.8B each year. Based on the statistics from the Association of Workers' Compensation Boards of Canada (AWCBC) [2] in 2017, 951 workspace fatalities were recorded in Canada with an increase of 46 from the previous year [3]. One of the most crucial ways of preventing accidents is to use personal protective equipment (PPE). In addition to fatal injuries and casualties, there are other consequences of accidents [4]: time loss of project execution, damaging the reputation of the firm, mental illness of workers, cost of medical care, cost of recruiting and training new workers, compensation cost, cost of repairs and additional supervision, productivity loss, and cost of accident investigation. Safety inspectors are responsible for ensuring that safety regulations are followed by contractors to avoid accidents [5]. Hardhats and safety-vests are the most fundamental PPE. "Employees working in areas where there is a possible danger of head injuries from impact, or from falling or flying objects, or from electrical shock and burns, shall be protected by helmets" [6]. Canadian Centre for Occupational Health and Safety (CCOHS) emphasizes the importance of wearing High Visibility Safety

Apparel (HVSA) for different lighting conditions and working close to moving vehicles [7]. Due to the nature of the construction industry, detecting workers and their PPE from surveillance videos is a challenging task for the following reasons: (1) bad weather conditions, (2) low lighting conditions, (3) low camera resolution, (4) camera height, (5) narrow field-of-view of the camera, and (6) occlusion [8]. Among these challenges, occlusion is the most significant barrier to object detection. To facilitate safety monitoring, a large number of research studies applied computer vision (CV) for detecting PPE on construction sites. Nevertheless, detecting workers and PPE is still a challenge in far-field videos. This paper proposes a novel nested network based on frame segmentation that consists of two Deep Neural Networks (DNN) to facilitate safety monitoring on construction sites. The first model detects the human bodies on the construction site, and the second one detects if the detected person is wearing a hardhat and a safety vest. The proposed method is validated based on the videos collected from a real construction site. The results show the effectiveness and practicality of the proposed method for detecting the workers far from the camera as well as detecting compliance or noncompliance with the PPE regulations.

2. Methodology

In this research, surveillance cameras are installed at a height to reduce the occlusion and cover most of the construction site. Fig. 1 shows the projection of workers on the image plane under these conditions, where the center of projection (COP) is the center of the surveillance camera, and three workers are at different locations. Based on the angle of view of the camera, the worker far from the camera is captured on the upper part of the image plane. The angle of projection for this worker becomes smaller and makes him appear smaller on the image plane because of the perspective view [9]. As will be explained in the case study, the worker in far-field could be about 1/3 the size for workers in near-filed on the image frame. A novel frame segmentation nested network is proposed to overcome the challenge of detecting workers and PPE. The proposed method consists of two nested Faster R-CNN models that are applied sequentially. These models are custom-trained using the transfer learning approach. Fig. 2 shows the overall flow of detection for every frame in the surveillance video.

2.1. Worker detection module

The state-of-the-art Faster R-CNN [10] is a robust object detection algorithm that uses a Region Proposal Network (RPN). Faster-RCNN has an input frame size of 1024×600, which has an aspect ratio of 1:7. High Definition (HD) surveillance cameras used in construction sites have the resolution of 1920×1080. This resolution is larger than the input frame size of the Faster R-CNN model, and the network resizes frames in order to fit the input size in both detection and training stages. As shown in Fig. 1 a worker in the far-field is captured in a small area on the image frame. Additionally, as a result of resizing, the worker becomes even smaller, which makes the detection more challenging and also affects the training performance. The worker detection module has four main steps: frame segmentation, worker detection, detection refinement, and removing duplications. The objectives of the worker detection module are: (1) detecting far-field workers, (2) eliminating the resizing effect, and (3) covering all workers with segments. Fig. 3 shows the components of the worker detection module.

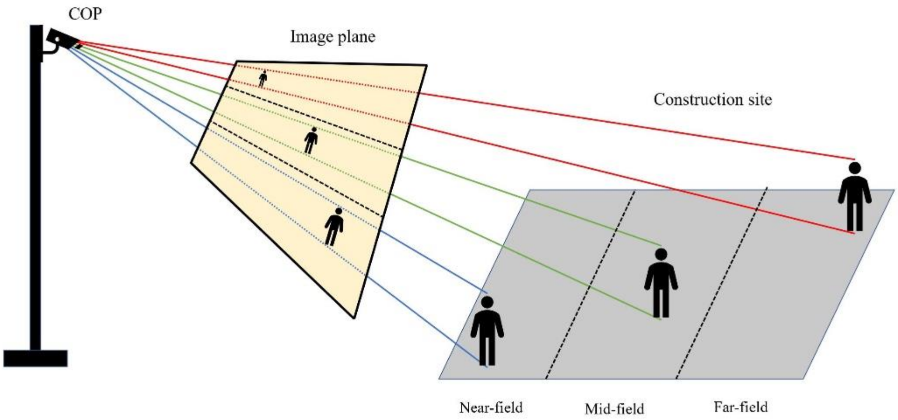

Fig. 1. Projection of workers on the image plane under the real-world condition

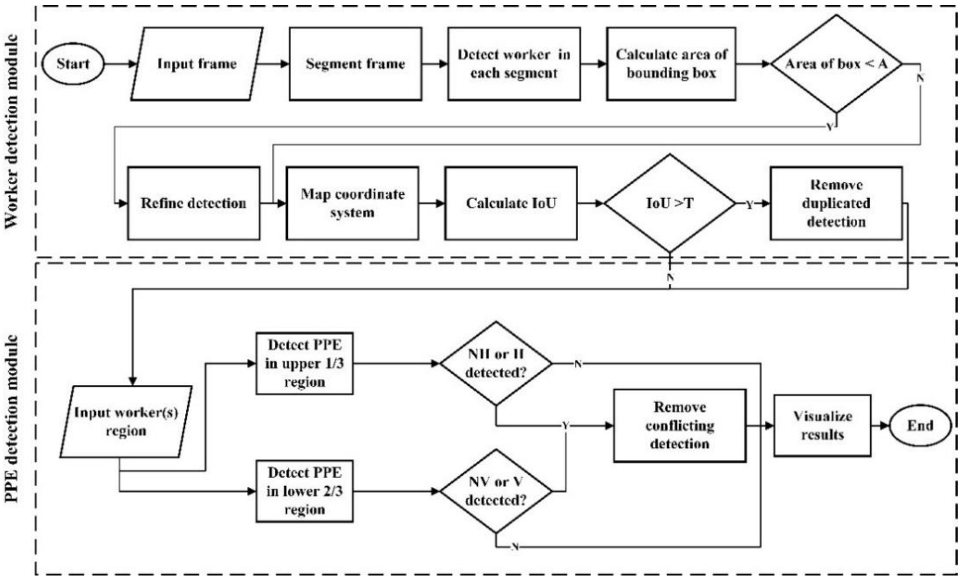

Fig. 2. The overall frame segmentation based nested network detection approach

Three main segments are defined parallel to the horizontal axis of the image frame. I is the near-field strip where workers are captured in the largest size compared to the whole frame, K is where workers are captured in medium-size (mid-field) and J, where workers are captured at the smallest size on the image plane (far-field). Additionally, sub-segments are needed within each main segment to meet the input size and aspect ratio of the network. Workers' width on the image plane is the smaller dimension of a worker and is used to calculate the sub-segments' width. Equation 1 is used in order to get the number of the non-overlapping sub-segments where N is defined as a number of workers fitting into a sub-segment. Different values of N are considered to get the best detection results and compared with the aspect ratio of the Faster R-CNN network. In order to make sure that the detection fully covers workers intersecting with the borders of the main segments/sub-segments, overlapping main segments and sub-segments are defined.

$$\text{Number of sub-segments} = \text{Ceiling}\left(\frac{\text{Frame width}}{N \times \text{Average width of worker}}\right) \quad (1)$$

$$\text{Sub-segment width} = \frac{\text{Frame width}}{\text{Number of sub-segments}} \quad (2)$$

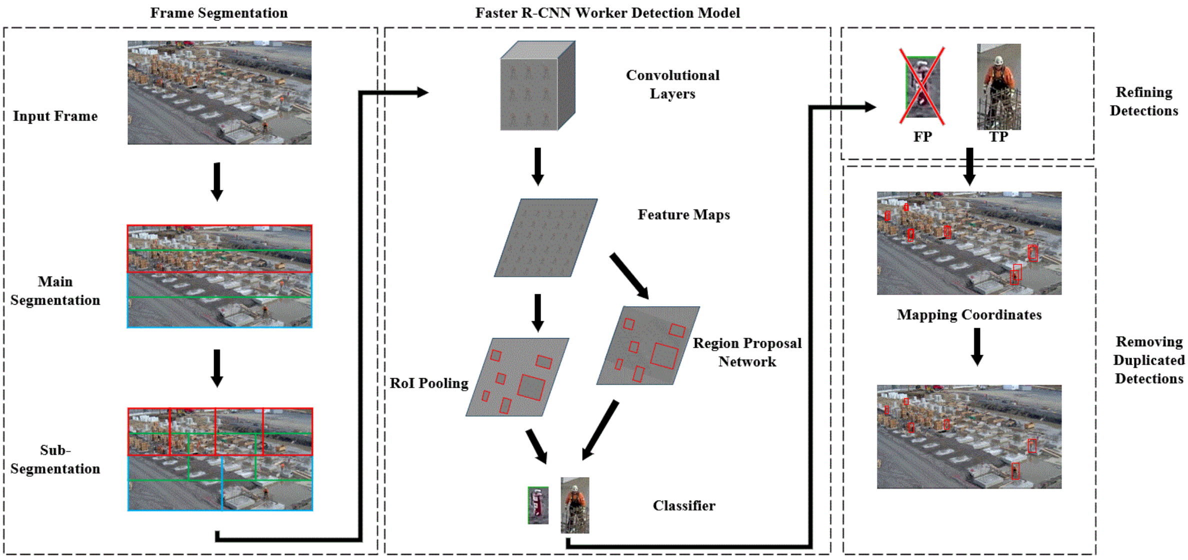

Fig. 3. Components of the worker detection module

In some cases, some objects (e.g., detecting traffic cones) might be detected as a worker. In order to refine the detection results, this study considers the average area of workers in each main segment to remove the false detections from the detection lists. In addition, the detection of workers in overlapping segments results in double counting of workers. The proposed solution is to first map the detection coordinates in the segments to the uniform frame coordinates and then using the IoU cost function to remove duplications. IoU represents the intersection of the ground truth bounding box with the detection bounding box divided by the union area, and is calculated between all the detected objects in the same frame. A threshold (*T*) is defined to remove the duplicates when the IoU is higher than *T*.

2.2. PPE detection module

The next step after detecting workers is to detect whether they are wearing the required PPE (i.e., hardhat and safety-vest). Detecting hardhats and safety-vests is a challenging task, especially under the far-field area with a small angle of view. Therefore, a nested Faster R-CNN model is used, which relies on the detection outputs from the worker detection module. The PPE detection dataset considers the labels H (hardhat), NV (no-safety-vest), NH (no-hardhat), and V (safety-vest). If NH (no-hardhat) or NV (no-vest) are detected, it will be considered as dangerous behaviour. Then, potential regions are defined for each object of interest, where H or NH must be detected in the upper 1/3 region of the detected worker bounding box and V or NV in the lower 2/3 region. In addition, this research considers conflicting detections, where the PPE detection model returns both wearing and not wearing a hardhat or a safety-vest at the same time, based on the confidence level of the detections.

3. Implementation and case study

Surveillance videos from a construction site are used to validate the proposed method. The construction site is a power substation. The construction site is located in Montreal, Canada, where Axis P1425-E surveillance cameras with HD resolution (1920×1080) installed on four poles at about 10 m height. The training for worker detection and PPE detection was done using two primary datasets containing 2200 and 1000 images, respectively. In the worker detection dataset, the main object of interest is human. Since the region of interest for the PPE detection model is the human body, the PPE dataset contains cropped images of persons. The PPE dataset is created by combining the CUHK01 dataset [11] that contains people captured from a high angle of view, as negative examples of workers with no PPE, and the image dataset of workers with PPE from the site. The images in both datasets are annotated using open source software LabelImg [12] using PASCAL (pattern analysis, statistical modelling and computational learning) format [13]. Examples of worker and PPE annotations are shown in Fig. 4.

Fig. 4. Examples of workers and PPE annotations

The three main segments of *I*, *K* and *J*, are defined with an equal size of 1920×540 parallel the horizontal axis of the image frame. However, the size of the main segments does not fit with the input size of the Faster R-CNN network. As explained in Section 2.1, in order to find the optimum number of sub-segments considering the accuracy and detection time, using Equation 1, three values of 5, 15 and 25 are considered for *N*. The average width of workers is measured on the image plane. The average width is 55 pixels in the main segment *I*, 35 pixels in main segment *K*, and 20 pixels in the main segment *J*. The total number, size, and aspect ratio of sub-segments with different *N* are summarized in Table 1.

Table 1. Number of sub-segments with overlaps for detection based on different N

N	Sub-segment information	Main segment I	Main segment K	Main segment J
5	No. sub-segments with overlaps	13	21	39
	W x H (pixels)	274×540	174×540	96×540
	Aspect ratio	0.51	0.32	0.17
15	No. sub-segments with overlaps	5	7	13
	W x H (pixels)	640×540	480×540	274×540
	Aspect ratio	1.19	0.89	0.51
25	No. sub-segments with overlaps	3	5	7
	W x H (pixels)	960×540	640×540	480×540
	Aspect ratio	1.78	1.19	0.89

Three 5-minute validation videos recorded with 30 frames per second are selected from different phases of the project, and detection is performed every one second. Precision, recall, and accuracy are calculated to evaluate detection results. The results are based on assuming the value of 50% for the IoU. Based on the results of the worker detection model, the best detection results are for N equals 25, where the image frame is divided into a total of 15 sub-segments that fit input dimensions and aspect ratio of the Faster R-CNN person detection model. The average precision and recall for the worker detection model are 99.67% and 92.92%, respectively. The proposed method based on frame segmentation improved workers detection on large construction sites compared to the literature [14]. In order to evaluate the PPE detection model, 200 images were gathered, with half of them for workers wearing PPE and the other half for cases where PPE is not used. Precision and recall are calculated to evaluate the PPE detection module, which are summarized in Table 2. The PPE detection module achieved higher precision and recall compared to [15], which similarly detected the PPE within the worker's bounding box.

Table 2. PPE detection results

Classes	Precision (%)	Recall (%)	Accuracy (%)
H	94.06	95.96	90.47
NH	97.93	93.14	91.34
V	80.00	96.97	78.05
NV	93.00	93.00	86.92
Average	91.25	94.77	86.70

4. Summary and conclusions

This paper proposed a nested network for detecting workers and PPE on large construction sites based on frame segmentation techniques. The framework combines two Faster R-CNN models in order to detect workers and PPE. Three main segments of near, mid, and far-fields of view are defined. Sub-segments are defined for each main segment to meet the required input size and aspect ratio of the worker detection model. Detection results are first refined based on comparison with the average area of workers in each main segment; then, the results are mapped from sub-segments to the original frame. Duplicated detections are removed from the detection list of workers. Moreover, the PPE detection module defines potential regions for each type of PPE to be detected. Detection results are compared based on the confidence level of the detection to remove any conflict (e.g., detecting *H* and *NH* at the same time). The final output of the nested network indicates if a worker is wearing a hard and safety vest or not. Based on the case study results, the proposed method improved the detection for far-field workers and PPE.

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Providing Proximity Safety Alerts to Workers on Construction Sites Using Bluetooth Low Energy RTLS

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Abstract

Struck-by equipment is one of the main reasons of accidents on construction sites. In order to improve construction safety, previous research proposed using Real-Time Location Systems (RTLS) to track the location of workers and equipment on construction sites. However, using ultra-wideband RTLS on large sites is difficult because it needs many timing cables to synchronize the data of the sensors surrounding the site. Furthermore, providing safety alerts to workers within dangerous proximity to equipment has not been addressed in previous research. Instead, the alerts were sent only to the safety manager. This paper aims to develop a method for providing proximity safety alerts to workers on construction sites using Bluetooth Low Energy (BLE) RTLS. BLE RTLS can provide acceptable accuracy coupled with large coverage and without the need of timing cables. In addition, with the support of two-way communications between the tags and sensors, it is possible to provide vibro-tactile alerts to the workers using wristbands. A prototype system is developed to filter the location data and remove outliers using averaging over time and averaging over tags of the objects. A case study is applied on a construction site to demonstrate the feasibility and performance of the proposed method.

Keywords: Bluetooth Low Energy (BLE), Real-time Location System (RTLS), construction safety, wristband, vibro-tactile alert

1. Introduction

Struck-by equipment is one of the main reasons of accidents on construction sites [1]. In order to improve construction safety, previous research proposed using Real-Time Location Systems (RTLS) to track the locations of workers and equipment on construction sites. However, it is important to find the balance between positioning quality and cost of the RTLS. For methods using the low-cost radio-frequency identification (RFID), the accuracy is too low for safety management on construction sites [2, 3]. Technologies such as ultra-wideband (UWB) and the surveying-level Global Positioning System (GPS), on the other hand, are accurate but expensive, which reduces their applicability in construction sites. Moreover, UWB RTLS requires timing cables to synchronize the data of the sensors surrounding the site [4, 5], which is another difficulty for construction projects since more cabling means more cost. In addition, in previous research, alerts were sent only to the safety manager, or risk events were recorded in reports which can be reviewed by the safety manager on a daily or weekly basis. To prevent struct-by accidents more effectively, a method that can warn workers in near real-time is needed.

This paper aims to develop a method with less cabling using Bluetooth Low Energy (BLE) RTLS based on the angle of arrival (AOA) technique, which provides sub-meter positioning accuracy with a relatively lower cost compared to UWB [6], to provide near real-time proximity safety alerts to workers on a construction site. The research has three objectives: (1) Testing the feasibility of using a wireless scheme of RTLS on construction sites; (2) Developing a method which effectively detects proximities in near real-time; and (3) Testing vibro-tactile alert patterns sent to workers which can be easily perceived.

2. Purposed method

The method focuses on data processing to define proximity events, and generating near real-time alerts and weekly proximity reports. First, the BLE system setting is configured to meet the requirements according to the constraints. Then, data processing is discussed to illustrate how to define the proximity. At last, the method of generating near real-time alerts and events recording is presented.

2.1. BLE RTLS setting for meeting requirements

Five requirements are identified for BLE RTLS in order to get good positioning performance: (1) Field of view (FOV) of sensors: FOV of sensors is the most important factor affecting the performance of the system. To guarantee good performance, the sensors should be installed where they have line of sight to as many tags as possible. (2) Data handling capacity of sensors: The RTLS sensors have limited capacity for handling tags data, which depends on the specific type of the sensors. For the BLE RTLS used in this project, the maximum capacity that the sensors can handle is 250 packets/s [6]. (3) Network environment and power supply: The sensors should be connected to the same network of the server computer. One solution to reduce the need for long ethernet cables is to build a wireless network environment using antennas as shown in Figure 1. (4) Visibility of tags: Although setting sensor at a high position can help increase the visibility of tags, there are occlusions which are inevitable. Since the construction site is a dynamic place, tags can be occluded for short periods by different construction resources. To address this issue, several tags are attached on the same object, so that even if data of one tag is missing, the position of the object can still be calculated by using data from the other tags. (5) Reflective materials: Signals can be reflected by the metallic surfaces on the construction site. Since the BLE RTLS uses AOA to calculate the position of tags, reflections of the signals will generate more errors in the results.

Figure 6. Using Antenna to Connect Sensors to Server in Site Office

2.2. Data processing

Although filters are embedded in most of RTLS systems, the smoothed data still have many errors. Therefore, extra processing is applied to reduce errors. The steps of data processing are shown in Figure 7: (1) Identifying the tags attached to the same object; (2) Averaging position data of the same tag over a period of time d_t to get position at time T_i; (3) Estimating the pose and the velocity of an object based on the known geometric relationship between tags on that object; (4) If the data of an object at time T_i is missing, the position of the object at time T_i is calculated using extrapolation.

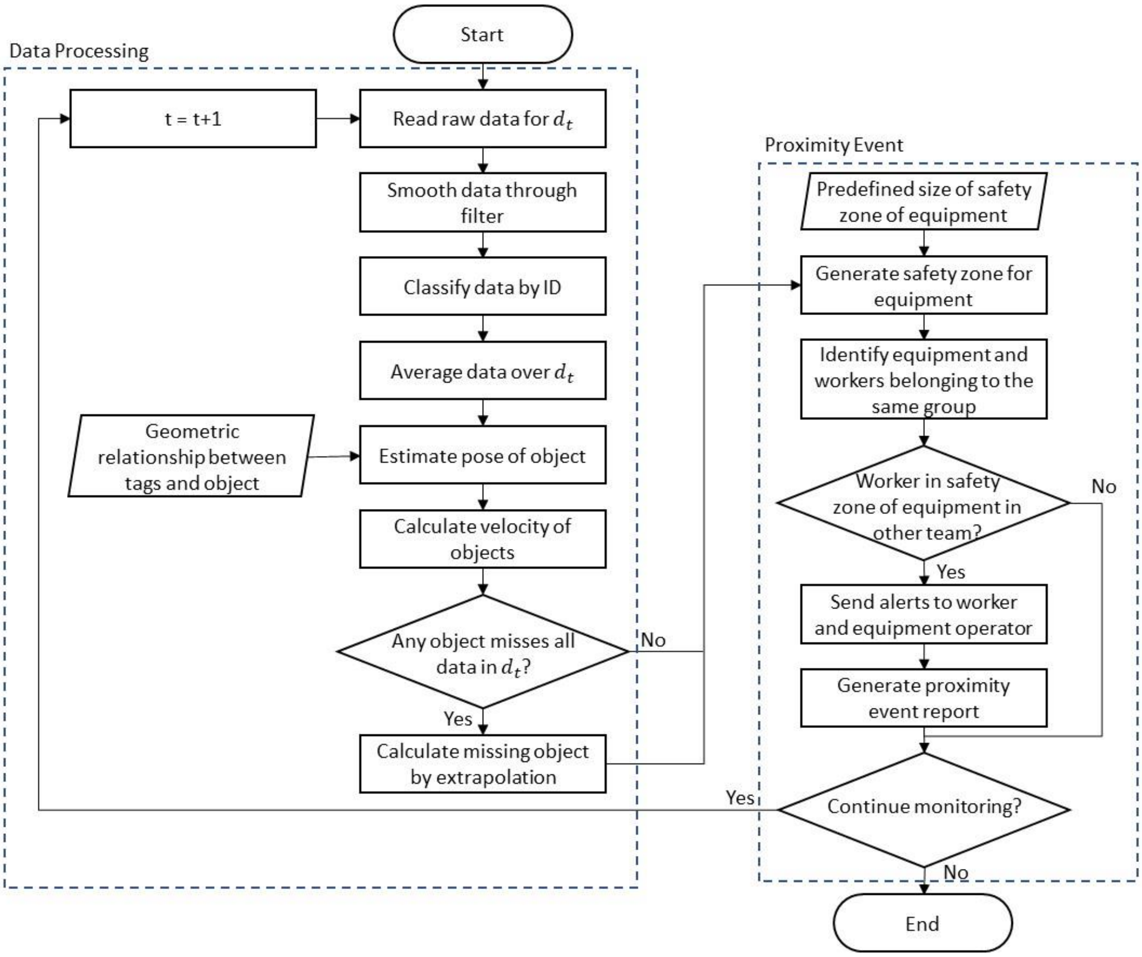


Figure 7. Data Processing and Proximity Event

2.3. Proximity events

Using the positions of workers and heavy equipment, proximity events can be detected. The size of the safety zone for each equipment is selected at the planning phase. In this paper, safety zones are designed to have a circular shape with a radius corresponding to the size of equipment as shown in Figure 6. After getting the position of equipment, dynamic safety zones are generated. In the proximity detection step, whenever a worker enters the safety zone of an equipment not belonging to the same group, this is considered as a proximity event. In this case, alerts are sent to the worker and equipment operator through vibro-tactile signals. Information of this event, including the time, ID and position of involved the worker and equipment, are also recorded in order to generate a daily/weekly safety report.

2.4. Generating alerts

Three tactile signals are designed to be sent to workers and equipment operators. Based on the results of Saket et al. [7], the user's feelings and perceptions are different for different vibration patterns. With the same vibration strength, a rapid pattern produces a more urgent feeling to the user. Three vibration patterns are designed to represent three different cases of proximity. The three patterns are shown in Figure 8. When a worker enters a safety zone, Pattern 1 is generated. If the worker continues approaching the equipment, then Pattern 2 is generated. If the worker enters a very dangerous zone (i.e. very close to the equipment), Pattern 3 is generated.

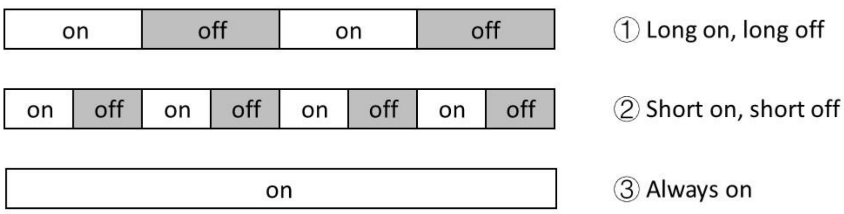


Figure 8. Vibration Patterns

3. Case study

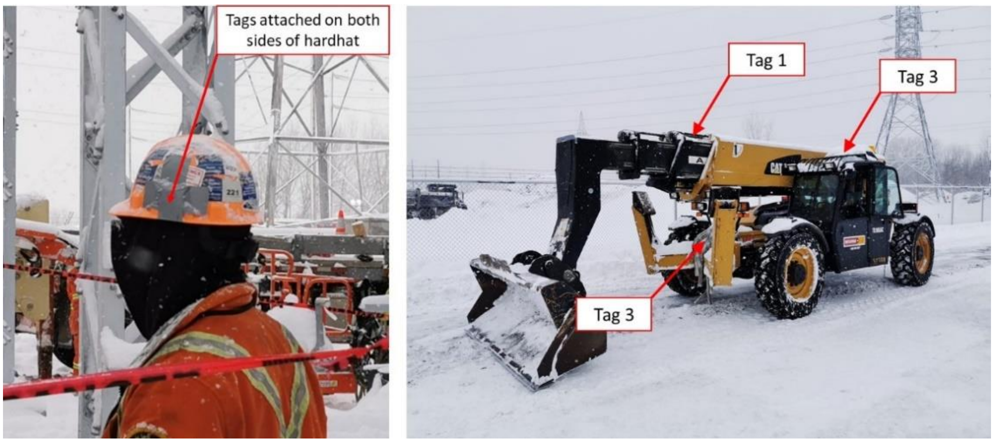
In the case study, tests are conducted to evaluate the feasibility of the proposed method on a construction site of an electric substation. The area of the construction site is about 110 m × 70 m. The RTLS sensors and antennas are installed on four poles at the corners of the construction site. Another antenna was installed on the pole near the site office. The site office is located at a distance of more than 100 m away from the construction site.

3.1. RTLS installation and setup

The BLE RTLS used in the case study is Quuppa [6]. The sensors are of the model LD7L, which is suitable for outdoor positioning and can achieve sub-meter accuracy within the range of 150 m. A total of nine sensors are installed on the four poles. Antennas are installed at the top of poles and sensors are connected to the antenna on the same pole. On each pole, a camera is also installed to capture the video of the site. The videos are used to visually compare with the results from RTLS. The positions of sensors are measured using a total station. The setting of the RTLS is configured to optimizing outdoor positioning performance according to Quuppa's recommendations. Two-dimensional (2D) tracking mode is chosen in the RTLS because the accuracy in the height direction is lower than in the x and y directions.

3.2. Proximity detection and alert generation testing

Five anonymous volunteer workers joined the test. They were asked to attach tags on the sides of their hardhats. In addition, three tags were attached on the body of an equipment as shown in Figure 4. Tapes are used to reinforce the attachment of all the tags. In addition, the workers were asked to wear wristbands for generating vibro-tactile alerts [8]. The Workers and the equipment operators were asked to complete their tasks according to their schedule. The system recorded the data and detected proximities. After applying the RTLS system on daily activities, the system could show the position of workers and equipment as shown in Figure 5. In this figure, the proximity between Equipment-2 and Worker-D are indicated. The system monitored the distance between workers and equipment not belonging to the same group. Whenever the distance is less than 2 m, the ID of the equipment and the worker are shown on the user interface. An initial test was done for alert generation. The generated vibro-tactile alerts were received by the respective workers within 1 s.



(a) (b)

Figure 9. (a) Tags on Hardhat; (b) Tags on Telehandler

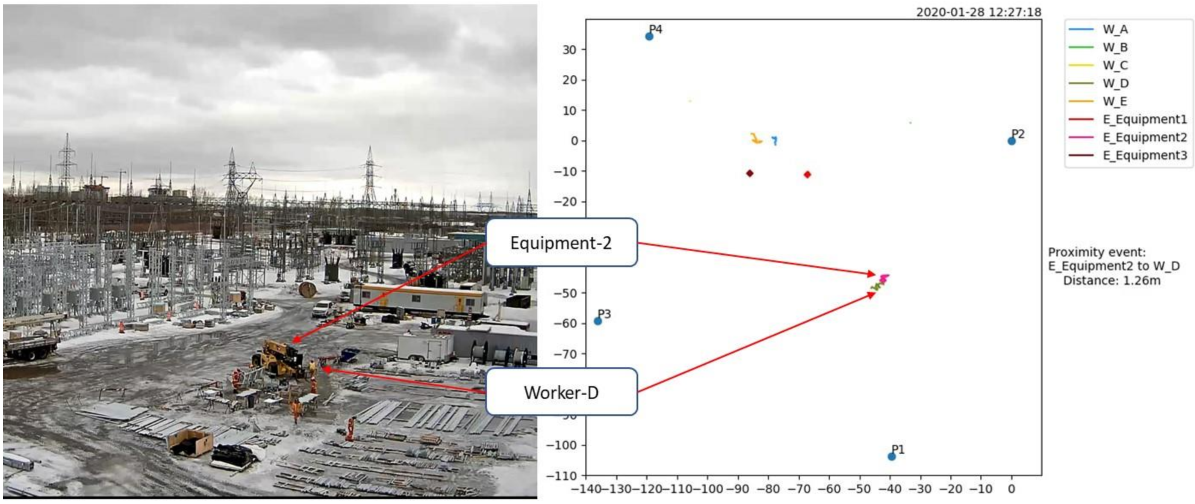


Figure 10. Monitoring Position of Equipment and Workers

4. Conclusions and future works

The paper proposed a method to generate near real-time alerts to both workers and equipment operators by applying a wireless scheme of BLE RTLS on a construction site. The method estimated the poses and velocity of objects by considering the positions of multiple related tags during short periods. The estimated information of the objects is used to detect risky proximities. A test on a construction site was conducted. The results were compared with the ground truth data. The BLE RTLS is able to provide accurate positioning in a large site. The method is able to monitor the position of equipment and workers and detect unsafe proximities. Furthermore, vibro-tactile alerts can be generated by the system and are perceived immediately within 1 s by the workers wearing a wristband.

Future work will focus on three aspects. First, more rules will be added to the method when estimating the pose and motion state of objects in order to reduce false alerts. Second, more tests will be performed during construction activities to test the feasibility of applying the proposed proximity warning system in the long term. Third, by considering feedbacks from workers, methods for improving the usability of the system will be developed.

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Structure Equation Model for the Successful Implementation of ICT / Automation in Construction Project Management in India

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Abstract

Each project is unique in nature and has its own complexities associated with it, and the management of construction projects requires effective and well-organized communication between all parties and stakeholders involved in the project. Coordination and collaboration between all stakeholders are the key to the success of any project. This is the sole importance among the team members of completing any given project on time and at the required cost. ICT is a technology that can be used to enhance communication between all the parties concerned working on specific or concerned projects, including stakeholders, etc. IT-based technology has many tools and software that have the tremendous ability to ease work related to the flow of information, data collection and storage, etc. The objective of current research is to identify and analyze the factors affecting the implementation of ICT / Automation in construction projects in India using structured equation modelling (SEM). The literature review has been carried out and some attributes have been identified regarding the benefits, barriers and enablers of ICT. These attributes were included in the questionnaire prepared to receive a response from industry professionals in the construction sector. The survey was conducted in the Indian construction industry and the response of various industry professionals from top-level management and middle-level management was recorded. The data collection was carried out and the response was further analyzed. Various factors affecting the use of ICT in construction project management have been analyzed using different statistical techniques (exploratory factor analysis, reliability analysis and structure equation model). The findings of the research provided a SEM model for the successful implementation of ICT in construction projects.

Keywords: ICT, automation in construction, construction management, project management, structure equation model

1. Introduction

Many building aspects reflect the significant benefits that the industry could reap from information and digital technologies: the vast quantities of knowledge to be handled, production focus and participant dissemination. Nonetheless, IT adoption in construction sector usually considered minimal and potential adoption predictions have proven optimistic (Fukao, Ikeuchi, Kim, & Kwon, 2016; Suryawanshi & Narkhede, 2015). While more champions were disappointed, the use of digital technology in construction has increased. The use of information and communication technology (ICT), also known as information technology (IT) has grown enormously in such areas as design and planning, cost control and budgeting, computer-aided facilities management, among others, thereby creating many opportunities for better and more efficient project execution within the industry. This study has the potential to offer some new insights into ICT in the construction and context creation. The explanation is, because in developing economies such as India, what a company may see as major challenges in implementing and using ICT would be significantly different from those in a developed economy such as UK where the ICT Industry with various regulatory frameworks and cultural constraints (Jayasudha & Vidivelli, 2016; Kenley, 2014; Koseoglu & Nurtan-Gunes, 2018).

1.1. Objectives of the study

The objective of current research is to identify and analyze the factors affecting the implementation of ICT / Automation in construction projects in India using structured equation modelling (SEM).

2. Literature review

The use of information communication and technology is simple to handle different resources, including human resources. New techniques, such as BIM (Building Information Modelling), have totally changed the architectural point of view of the global market. The Internet is used internationally, and the projects are debated in several ways (Arayici et al., 2011). (Gu & London, 2010) has stated that there is a lack of education of these technologies and professionals in construction industry find it difficult to use and learn these technologies. The ICT based technology can only be adopted in construction sector if these technologies are adopted by large and big name organizations of a nation and set a benchmark for other organizations. The lack of efforts made by these organizations are a big barrier in the adoption of ICT. The awareness of technology and user education is required in the industry to improve the acceptance and adoption of ICT. The top management should be aware of these technologies and should adopt and promote so that everybody at middle and lower management takes it seriously (Arnold, Javernick-will, & Asce, 2013; Kang, Brien, & Mulva, 2013; Son, Lee, & Kim, 2015). The quality of tools or ICT equipment made available to the construction companies are also one of the barriers. During the use of these technologies some organization are also not convinced regarding the security these software or tools provide [3]. The use on building project performance has been recently evaluated through best practice and the direct impact on the project cost growth of use of 3D CAD, which means the cost outcome has a negative impact as the associations of project output and technological use at project and process level. The results indicate that the link between the technical usage and the project findings has been explored and that the cost and the timeline of the project will be greatly influenced by the data / intensive data / knowledge and management functions. The IT utilization enhances time-bound productivity and has a relatively low cost-effective impact (Dixit, Mandal, Thanikal, & Saurabh, 2019; Dixit, Sharma, & Singh, 2020; Dixit & Sharma, 2020)

3. Research methodology and data analysis

The research methodology used in the analysis is the compilation of primary data for ICT adoption in the Indian building industry. For data collection, a standardized questionnaire survey is used. The study targets are consultants, clients, investors, contractors, government officials, architects and other key players in the Indian construction market. The Likert five-point scale is used to identify respondents where one has the least impact and five has the greatest effect. The survey was conducted in the Indian construction industry and the response of various industry professionals from top-level management and middle-level management was recorded. The data collection was carried out and the response was further analyzed. Various factors affecting the use of ICT in construction project management have been analyzed using different statistical techniques fig. 1 and 2. Approximately 350 questionnaires were circulated and 88 correct answers were returned (Dixit et al., 2020; Shah et al., 2019).

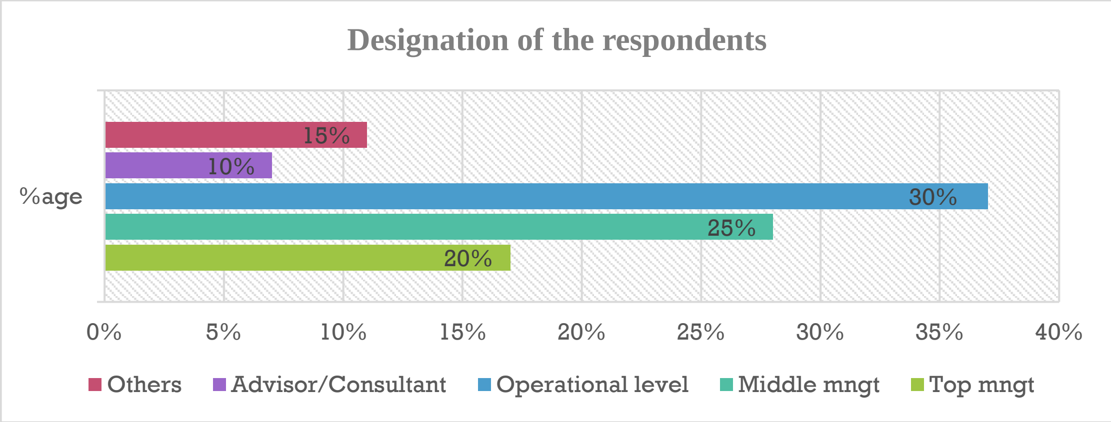

Figure 1. Position/Designation of the respondents

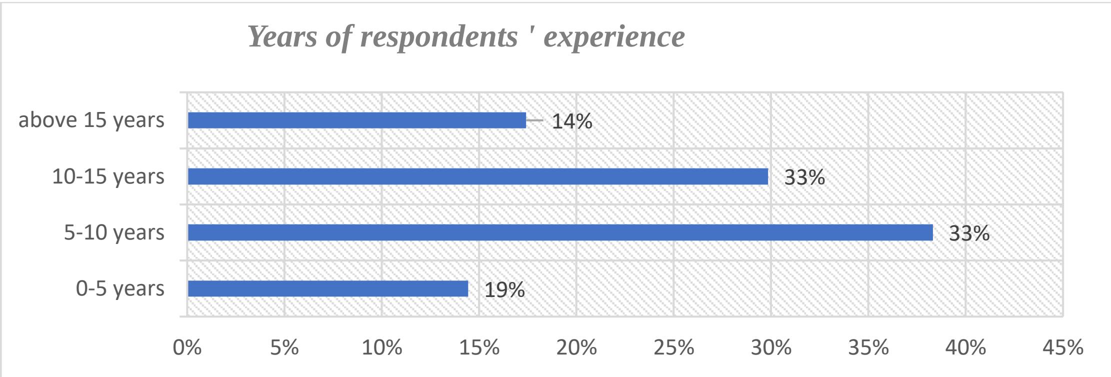

Figure 2. Years of respondents ' experience

3.1. Reliability analysis

Reliability refers to the degree to which a calculation provides accurate outcomes if measurements are replicated many times. The reliability analysis is called the reliability analysis. Reliability analysis is calculated by obtaining the ratio of the systemic variability by calculation of the correlation of the scores obtained from different administrations of the scale table 1. And, if the reliability measurement correlation is strong, the scale findings are consistent and therefore accurate (Hartmann, Meerveld, Vossebeld, & Adriaanse, 2012).

Table 1. Reliability analysis/Cronbach's alpha for different factors

Factors	Cronbach's Alpha	No. of attributes
Factor 1 (Site management)	0.82	06
Factor 2 (Leadership management)	0.81	05
Factor 3 (Project change management)	0.84	02
Factor 4 (Performance)	0.87	02

3.2. Exploratory factor analysis

Exploratory factor analysis is a statistical method used to decrease data to a smaller collection of summary variables and to investigate the theoretical framework underlying the phenomenon. The EFA has reduced the 19 attributes into 4 factors. All of the selected attributes have a factor load of more than 0.4. The cumulative quantity of variance explained by four factors are 57.25% which is above the minimum threshold (above 50%). All four factors from the EFA were shown in Table 2 below.

Table 2. EFA table

Attribute/variable name	Factor loading	%age of variance explained
Site management		21%
Less handling and managing charges	0.6	
Helps to improve collaborations and coordination	0.8	
Improve swift communication	0.8	
concurrent construction management	0.6	
Efficient procurement of materials	0.8	
Helps in contract management	0.6	
Leadership management		14.50%
Metadata information availability to the management	0.4	
Efficient query resolution mechanism	0.5	
Project change management		12.30%
Streamline flow of accurate information	0.5	
Project information is stored precisely in a better way	0.7	
ICT refines the productivity of organization		
Real time project information availability	0.6	
Effective project change management	0.6	
Performance		9.45%
On time completion of project	0.4	
Within budget completion of the project	0.6	
		57.25%

3.3. Structure Equation Modelling (SEM)

Structural Equation Modeling involves a number of mathematical models, computer algorithms and computational methods that are suitable for networks of data structures. SEM contains confirmatory factor analysis and composite confirmatory analyzes, path analysis and partly least square path modeling and latent growth modeling. Models of structural equation are also used to test 'latent' structures that can not be observed. The use of SEM in social sciences is generally justified because the relationship between unknown structures (latent variables) is defined by observed variables. The review of literature and CFA grouped the 19 attributes into 4 main significant factors are: Site Management (SM), Project change management (PCM), Leadership management (LM), And Performance (PR) of construction projects the following hypothesis are formed (refer conceptual model) fig. 3:

- Site management (SM) factors are having a significant impact on performance (PR) of construction projects
- Project change management (PCM) having a significant impact over productivity (PR) of construction projects.
- Leadership management (LM) is having a significant impact on productivity (PR) of construction projects.

3.4. Findings of the study

The findings of the SEM results concludes that the most significant factor impacts the performance of the construction projects is site management (SM) (Abbott, 2013; Allen, 2016; Bröchner & Olofsson, 2012; Rivas, Borcherding, González, & Alarcón, 2011) followed by Project Project change management (PCM) and Leadership management having a significant value of 0.03, 0.05, and 0.01 respectively (table 3 and 4).

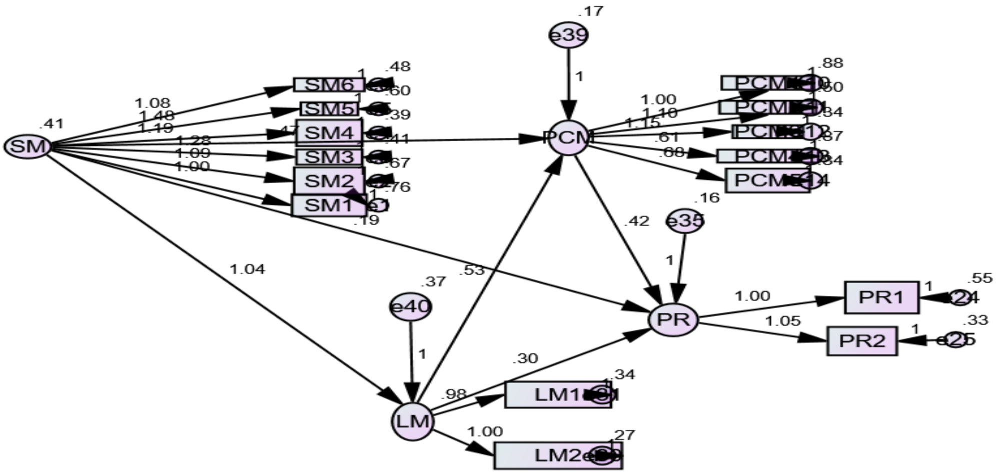

Figure 3. SEM model

Table 3. Measure for the goodness of fit (GOF)

Measure for the goodness of fit (GOF)	*Initial model values*	*Final model values*
χ^2/DOF	3.25	1.98
Comparative fit index (CFI)	0.62	0.85
Goodness of fit index (GFI)	0.58	0.84
Tucker-Lewis Index (TLI)	0.61	0.94
Root mean square error of approx. (RMSEA)	0.13	0.09
Incremental fit index (IFI)	0.65	0.79
Normal fit index (NFI)	0.73	0.80

Table 4. Hypothetical path and their influences

Hypothetical path and their influences	Path coefficient	Sig. (p)	Interpretation
H1: PR ←PCM (expected -ve impact)	0.42	0.05	Accepted
H2: PR ←LM (expected +ve impact)	0.30	0.01	Accepted
H3: PR← SM (expected +ve impact)	0.53	0.03	Accepted

4. Discussion and conclusion

The progress of any project depends on good communication and understanding between all project participants and stakeholders. Good communication is the secret to the success of any project. In the construction sector, projects need very good communication management between all parties which can be accomplished through the adoption of ICT or ICT technology. The study identifies various attributes affecting the adoption of ICT in the Indian built environment. Large organizations and policy agencies have to take care of that, and guidance and regulations are needed to make the best use of these technologies, which definitely will help other professionals, our services, our organizations and companies. In order to compete world-wide and to aspire to be an established construction industry and nation in the eyes of the global world (Aguilar & Hewage, 2013; Forcada, Fuertes, Gangolells, Casals, & Macarulla, 2013; Kim, Park, Lim, & Kim, 2013; Zeng, 2020), the industry will have to accept change and with the new age we will welcome these optimistic changes with open hands. In this regard, the governments and big corporations in our industry need definite help, so that small businesses can see them as a model and follow their footsteps (Fadiya, Georgakis, & Chinyio, 2015; Ikediashi, 2014).

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Validation of a Formal Framework Model to Improve On-site Construction Productivity: Indian Scenario

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Abstract

Validation can be carried out in many ways, as with most of the research work model validation is usually carried out in five main ways: retrospective project analysis, use of archival data, alternative data collection methods, replication of studies, and experimental implementation. Given the complexity of the data used to propose a framework model for on-site construction productivity, three separate validation methods have been used to verify accuracy and reliability. The validation of the framework model (structure equation model) and the hypothesis using statistical validation measures (quantitative experimental studies are ideal testing tools such as GOF, TLI, and CFI), secondly the validation of the model is by validating the seven main hypotheses using an expert panel of top management industry professionals from the Indian construction industry (using an expert panel of project managers from 13 different construction project in India). The results of the accuracy and effectiveness of the framework model were compared in both different validation processes and the findings of the study suggest that the framework model developed using the structural equation model is valid and that the model could be used by the Indian construction industry.

Keywords: validation process, framework model, construction productivity, construction management, structure equation model

1. Introduction

Each construction project is unique and complex. Each project begins with unique parameters, massive investment with good effort and planning(Abdul Kadir, Lee, Jaafar, Sapuan, & Ali, 2005). But as planned, only a few projects succeed. Poor productivity performance is the main problem with the unsuccessful project. Growth and improvement in construction productivity are not constant over time and tends to be low compared to productivity growth in other sectors, such as manufacturing, services, etc(Bröchner & Olofsson, 2012; Kuykendall, 2007). The construction sector is considered to be the engine of growth for a country's economy, providing links and job opportunities to other industries. On average, the contribution of the construction sector to the global economy has been around 7-10 per cent over the last five years(S. Dixit, Pandey, Mandal, & Bansal, 2017). Whereas the contribution of the construction sector to Indian GDP has been around 8-9% over the last five years. "India's economy is one of the fastest-growing economies in the world(Olomolaiye, Wahab, & Price, 1987). Productivity has been one of the most critical and significant issues in the Indian construction industry in recent decades (Saurav Dixit & Sharma, 2020; Saurav Dixit, Sharma, & Singh, 2020). Factors affecting productivity may have a short-term or long-term impact on the company, with productivity being affected for a short time. Productivity consists of different attributes such as labour, capital, utilities, services, plant and equipment, etc. Various experiments have been carried out in different countries to determine the factor affecting labour productivity"(Abdel-Wahab & Vogl, 2011; Gatti, Migliaccio, Schneider, & Fierro, 2010; Ma & Liu, 2014; Moselhi & Khan, 2012).

The Indian construction industry has an average annual turnover of 3.85crores(Loganathan & Kalidindi, 2015). But every year the industry faces huge revenue losses due to a variety of issues, conditions, and delays due to poor productivity are one of the main challenges (Rami Huges 2014). Nevertheless, productivity losses in India are still more than 30%, which is a major area of concern for construction workers(Loganathan & Kalidindi, 2015) (S Dixit, Mandal, Thanikal, & Saurabh, 2019; Shah, Dixit, Kumar, Jain, & Anand, 2019). Successful completion of any work in time generally depends on the quality of the projects, resources and processes involved. Authorized bodies such as CPWD, Bureau of Indian Standards, etc. have made several standards to set the quality guidelines for various construction-related activities. The Construction Industry in India is very complex, fractured, and largely unorganized. The professional and productive labour force has always been one of the most complex issues for the construction industry(Guntuk & Koehn, 2010; Kirmani, 1988; Mani, Kisi, Rojas, & Foster, 2017; McKinsey and Company, 2010). The objective of the study is to validate the SEM framework model using expert judgement analysis and respondent's data analysis to check the applicability of the factors affecting the construction productivity in the Indian construction industry fig 1.

2. Research methodology and analysis

The methodology adopted for the study is to validate an SEM model for improving on-site construction productivity using an expert panel of respondent's (Beguería, 2006; Hallowell & Gambatese, 2010; Patt, 2004). And for this purpose, a two-sheet handout of the conceptual model and final framework model and seven statements about the impact and effectiveness of the hypothesis and findings of the SEM model was asked on a Likert scale of 1-5. Please provide your inputs for the below-mentioned statements on a scale of 1 to 5. Where,

- 1= Agree but perceive the impact to much lesser than the assigned value in the model.
- 2= Agree, but perceive the impact to lesser than the assigned value in the model
- 3= Agree, and perceive the impact to equal the assigned value in the model
- 4= Agree, but perceive the impact to higher than the assigned value in the model.
- 5= Agree, but perceive the impact to much higher than the assigned value in the model.

The received responses were collected and stored in excel spreadsheets. And the final data analysed using the mean, standard deviation, and standard error of the data.

Figure 11. Factors selected for the study

2.1. Hypothesis

- Project change management (PCM) having a significant impact over productivity (PR) of construction projects.
- Leadership & Financial management (LF) is having a significant impact on productivity (PR) of construction projects.
- Project coordination & Claim management (CS) is having a significant impact on productivity (PR) of construction projects.
- Site management (SM) factors are having a significant impact on productivity (PR) of construction projects.
- Project Risk management (PRK) factors having a significant impact on the on productivity (PR) of construction projects fig. 2.

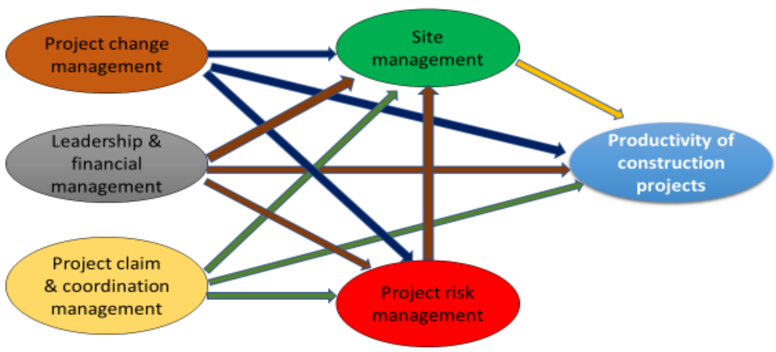

Figure 2. Causal model derived from the hypothesis

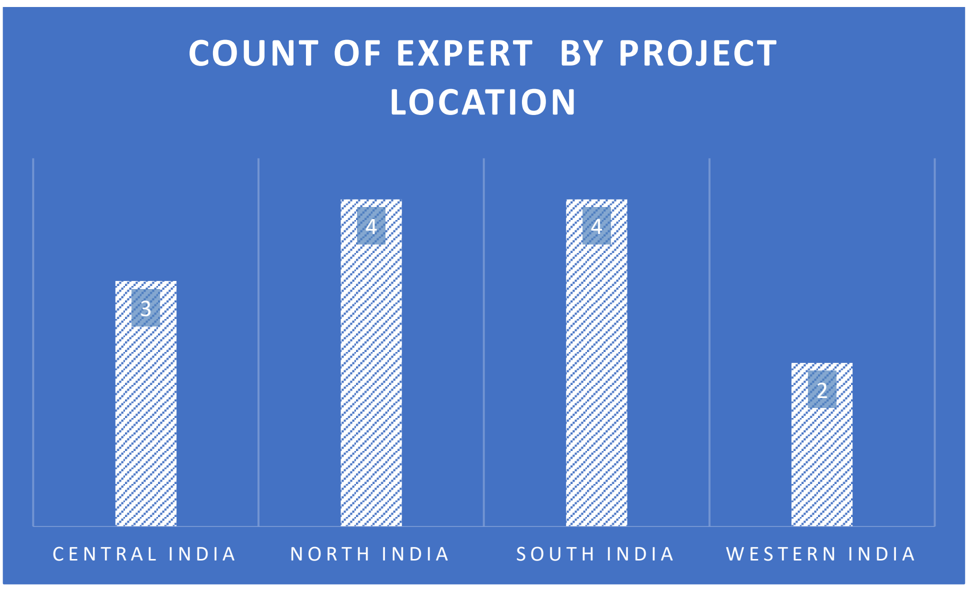

Figure 12. Location of the projects of the respondent

3. Research findings

Table 1. Respondent main data analysis table

	Designation	Senior Manager	ADGM	PM	AGM	Senior Manager	Senior Manager	AGM	Senior Manager	Project Incharge	PM	AGM-Construction	AGM-Projects	
Sr. No.	**Statements for the validation of Model (Factors affecting construction productivity)**	**Expert 1**	**Expert 2**	**Expert 3**	**Expert 4**	**Expert 5**	**Expert 6**	**Expert 7**	**Expert 8**	**Expert 9**	**Expert 10**	**Expert 11**	**Expert 12**	**Expert 13**
1	Project change management (PCM) having an impact on the productivity (PR) of construction projects.	4	1	4	3	2	4	1	4	3	1	2	4	3
2	Leadership & Financial management (LF) is having an impact on the productivity (PR) of construction projects.	3	2	5	2	3	2	3	5	4	2	5	3	2
3	Site management (SM) factors are having an impact on the productivity (PR) of construction projects.	4	5	5	4	3	5	4	4	3	3	3	2	4
4	Project change management (PCM) is having an impact -on Site management (SM) factors projects.	4	2	3	3	2	4	2	4	4	2	4	3	4
5	Leadership & Financial management (LF) is having an impact on Site management (SM) factors projects.	3	4	5	3	3	5	4	1	3	3	2	3	3
6	Leadership & Financial management (LF) is having an impact on the Project Risk management (PRK).	2	1	5	4	3	1	2	3	4	3	3	2	3
7	Project change management (PCM), Leadership & Financial management (LF), and Project coordination & Claim management (CS) is having an impact on the productivity (PR) of construction projects mediating Site management (SM) factors.	4	3	4	3	3	4	2	1	4	3	3	3	3

The majority of the responses were in the average range of 2.8 to 3.2, with one exception in case of site management factors having an impact on the productivity of construction works (shows a value of 3.8), which is on the higher side. The standard deviation of the data is in the range of 0.9 to 1.2 for all the seven statements. The cumulative average value of all the seven statements and 13 expert responses is more than 3 i.e. (agree, and perceive the impact to equal the assigned value in the model) table 1. The respondents selected for the study represents the major and significant construction zones of the country fig. 3. The findings of the study conclude that the main significant factors affecting construction productivity are site management (SM), Project change management (PCM), Leadership & Financial management (LF), Project coordination & Claim management (CS), and Project Risk management (PRK) factors having a significant impact on the on productivity (PR) of construction projects. Furthermore, the study also validates the conceptual model developed by the authors and validates its applicability in the Indian construction industry.

4. Discussion and conclusion

This study provides a new insight towards the validation of SEM framework models and conceptual models using the participation of industry expert panel. The findings of the study also demonstrate the significant importance of site management and project change management practices on the productivity of construction projects. Productivity in the construction sector is less due to various difficulties and factors affecting the industry's growth and economic growth. Analysis cannot focus only on one customer point of view, as the building industry is a multiparty business, the customer, the contractors, the subcontractor and the contractor also need to be examined. In this study, the authors have validated the conceptual model is a first step towards the more detailed analysis of different SEM models and their applicability on the construction projects.

Furthermore, Validation is a comparison of the proposed model predictions with a set of real-world data to assess their accuracy and to predictive their effectiveness (Ghanem, Doostan, & Red-Horse, 2008; Henriksen et al., 2003; Lucko & Rojas, 2010; Pesämaa, Eriksson, & Hair, 2009). Validation enables the trust of the model to be developed, which is extremely important for the transmission of the findings to the final users. Results for effective decision-making should be monitored before research that may have an impact on health, cultural, political climate, economy, and the environment (Thorne and Giesen 2002).

5. Acknowledgement

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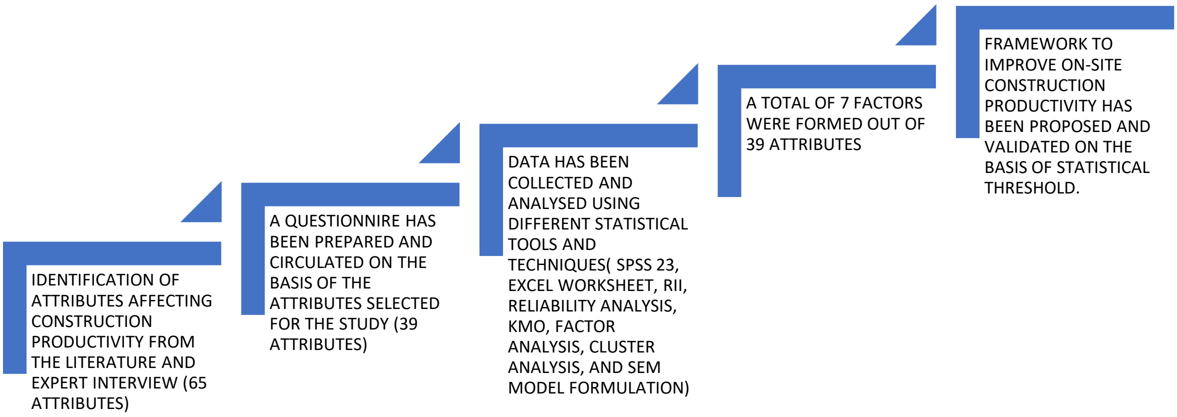
Appendix A. VALIDATION OF FRAMEWORK TO IMPROVE ON-SITE CONSTRUCTION PRODUCTIVITY: INDIAN SCENARIO



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Grouping of attributes into Factors

Productivity of construction works (PR)	RE	Rework
	C3	Cost
	C4	Quality
Project coordination and claim management (CS)	CS1	Site clearance/availability
	CS2	political and economic environment
	CS3	Interest and inflation rates
	CS4	Working hours
Leadership and financial management (LF)	L1	Project coordination meetings
	L2	Regular budget update
	L3	Leadership qualities
	L4	Timely payment of completed works
	L5	Availability of training and development for enhancing of skills
Project change management (PCM)	P1	Obsolete construction equipment's, methods and technology
	P2	Human resource and labour strike
	P3	Supply chain
	P4	Social environment
	P5	Climate conditions
	P6	Social skills of key team managers
	P7	Interpersonal skills
	P8	Top management support to pm
Project risk management (RK)	RK1	Conflict of interest among team members
	RK2	Selection of pm with proven track record
Site management factors (SM)	S1	Use of inappropriate planning tools and techniques
	S2	Willingness to adopt change
	S3	Urgency emphasized by the owner while issuing tender

	S4	Inadequate project formulation in the beginning
	S5	Coordination between all stakeholders
	S6	Contractual disputes
	S7	Design capability and frequent design changes
	S8	Ability to delegate authority
	S9	Project managers authority to take financial decisions and selecting key team members
	S10	Availability of resources

Please provide your inputs for the below mentioned statements on a scale of 1 to 5. Where,
1= Agree, but perceive the impact to much lesser than the assigned value in the model.
2= Agree, but perceive the impact to lesser than the assigned value in the model
3= Agree, and perceive the impact to equal the assigned value in the model
4= Agree, but perceive the impact to higher than the assigned value in the model.
5= Agree, but perceive the impact to much higher than the assigned value in the model.

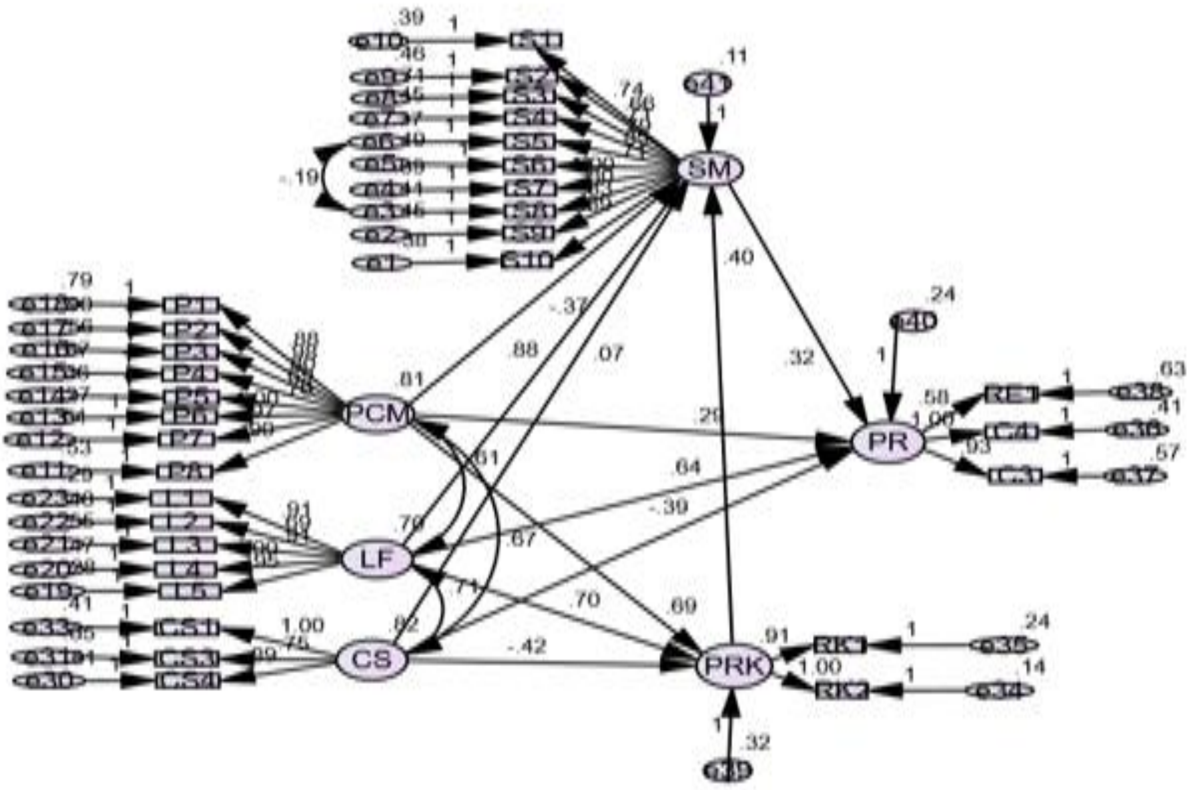
Sr. No.	**Statements for the validation of Model (Factors affecting construction productivity)**	**1**	**2**	**3**	**4**	**5**
1	Project change management (PCM) having an impact 29% on the productivity (PR) of construction projects.					
2	Leadership & Financial management (LF) is having an impact 64% on the productivity (PR) of construction projects.					
3	Site management (SM) factors are having an impact 32% on the productivity (PR) of construction projects.					
4	Project change management (PCM) is having an impact -37% on the Site management (SM) factors projects.					
5	Leadership & Financial management (LF) is having an impact 88% on the Site management (SM) factors projects.					
6	Leadership & Financial management (LF) is having an impact 69% on the Project Risk management (PRK).					
7	Project change management (PCM), Leadership & Financial management (LF), and Project coordination & Claim management (CS) is having an impact 32% on the productivity (PR) of construction projects mediating Site management (SM) factors.					

Final SEM proposed framework model to Improve on-site productivity of construction project.

Please share your comments on this framework:

I. I acknowledge that I have discussed in detail with the researcher, and all my concerns have been satisfactorily addressed.

II. I understand that my participation in this exercise is confidential and information gained through this group discussion/survey can be used for the researcher's academic work and can be published but my identity will not be revealed. And I am participating in this on my free will and can withdraw from this study at any time.



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Will Artificial Intelligence (AI) Take over the Construction World? - A Multidisciplinary Exploration

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Abstract

The late Stephen Hawking was reported to have said, "Computers will overtake humans with AI within the next 100 years. When that happens, we need to make sure the computers have goals aligned with ours." This statement is frightening to most, as very few people may like the idea of seeing computers take over the world. However, what can be more frightening is for those few people who like the idea to also make use of Hawking's suggestion and find a way to make sure the computers have goals that are strictly aligned with only theirs. There is a distinguishable apprehension among people of the role AI is set to play in the future of humanity, and this apprehension is transcending disciplinary boundaries. In the particular fields related to construction, there seems to be a genuine interest in integrating AI in each phase of a project to improve quality, enhance safety, and reduce costs, but this interest is countered by a legitimate concern that many types of jobs would be lost to AI-enhanced machines. In this paper, the authors tried to shed some light on how AI might change the face of the construction industry. The authors, spanning generations and disciplines in the industry, tried to answer the question "will AI take over the construction industry?" each from their own perspective including architectural, structural, and construction management. A synopsis of the status of the application of AI in construction and related fields is first provided, and then the authors offer their individual views with respect to how they expect AI to affect their side of the industry. This paper is an effort to gain insights into the perceptions of current and future construction related professionals of the role of AI and the impact it may have on the industry.

Keywords: artificial intelligence, construction automation, deep learning, future of construction, machine learning

1. Introduction

Charles Babbage, an English mathematician, inventor, and computer pioneer of the late eighteenth and early nineteenth centuries, was reported to have said that "At each increase of knowledge, as well as on the contrivance of every new tool, human labour becomes abridged" [1]. This assertion, which is still relevant about two hundred years after it was made, strikes at the heart of the subject of this paper. In a MarketWatch article that was published in early 2019 by Associated Press, the author quoted a Brookings Institution report that predicted that soon more than 30 million U.S. workers will lose their jobs to Artificial Intelligence (AI) [2]. And a briefing that was published about the same time quoted AI experts stating that automation could replace 40% of the world's jobs in as little as 15 years [3].

According to Makridakis [4], AI is set to bring about considerable change that will affect all aspects of society and life, just as the industrial and digital information revolutions did. How people will react to this change will mostly depend on their perspective and role. To researchers in the field, AI may just be a tool, or a set of concepts and tools, through which human thinking and decision-making processes are transferred to machines, which then can use their inherent capabilities to solve complicated problems faster and more accurately than any human would be able to do. But for many other people, the growing inclusion of AI in most areas poses a threat to their job security and, perhaps more importantly, the dreaded risk of losing control to the machine. However, would this latter group acknowledge those applications of AI that can assist people in achieving a better performance at their jobs instead of replacing them? Or are they more concerned that the services of architects, engineers, and construction managers may be at risk of being taken over by intelligent machines. Can AI enhanced machines be as creative as humans in solving problems? Do architects, engineers, and construction managers have the same expectations and apprehensions of the role of AI in their respective sectors? And who would assume the liability for any problems that may arise from, say, "machine error"? These are important questions that will need to be addressed by the industry as an increased integration of AI in the design and construction processes is inevitable.

This article is not meant to provide the answers to these questions but rather be a thought-provoking exposé to stimulate a comprehensive discussion about AI and its role in the construction industry. The authors hope that such a discussion will help in consolidating the directions of AI research in construction and its related fields or defining new ones.

2. Historic relevance of Artificial Intelligence

The idea of using other than human intelligence is not new and some researchers even trace the concept back to Greek mythology [5], although the name, Artificial Intelligence, of this now major area of computer science was not formally adopted until the middle of the twentieth century. A careful observation of the progression of humans' use of knowledge over time would ultimately reveal that the advent of AI was bound to take place and that its continued integration in all aspects of human life is unavoidable. Just as a carriage evolved into a car, a train, an airplane, and then a rocket that can transport people to outer space, and just as most of the people who were around when the first carriage in the world was made could not have imagined a rocket lifting off into space, the manipulation and undoubtedly further enhancement of human knowledge by machines will continue to evolve and will eventually reach levels that most people living today cannot even fathom or think about.

In the past fifty to sixty years, the world has witnessed an explosion of research and in-depth analysis of the human thought and decision-making processes in an attempt to create machines that can mimic those processes. If only one thing was to be inferred from all of the work that has been performed in the field so far, it would be the fact that intelligence cannot be restricted to one aspect or another of human cognitive abilities. This is an extremely important observation to consider moving forward because, whether knowingly or unknowingly, people typically use a combination of their cognitive and reasoning abilities to solve problems, and many of these abilities are yet to be adequately suited for automation. This, however, does not mean that those abilities will never be automated. The first person who attempted to fly did not succeed but persistence allowed mankind to eventually land a rover on Mars. So, if history is a measure, AI is coming to stay, and people will adapt to it just like they have adapted to the use of engines, electricity, phones, and computers.

3. AI for architectural design

Architectural design (AD) is a creative and iterative problem-solving approach whose purpose is to organize living spaces for any kind of human use [6]. Rather than an aesthetic position, architecture is based on an ethical position (i.e. environmental approach), spatial practice (ways of living and mores of a society), and a working progress (methods and tools used to pursue the design) [7]. Past cases help the designer to refine solutions [8]: this is called case-based design. Research in the design cognition field has demonstrated that designer's background and the immediate design environment also influence the emergence of solutions [9]. These can evolve from general environment to details (top-down approach) or from basic elements to general ones (bottom-up). It appears that the thinking of human designers simultaneously works both ways [9].

Generative Architectural Design (GAD) refers to the use of algorithms (i.e. cellular automata, genetic algorithms, shape grammars, etc.) to support architectural design [9]. These algorithms have been around for decades and are part of the history of AI. The first uses of AI techniques for AD date back to the 1960s [10], even though the idea that an algorithm could "creatively solve problems" [6] was not new at the time. The Architecture Machine Group at MIT has been a pioneer in this field; its leader, Nicholas Negroponte, considered that the AD process can be "assisted", "augmented", and eventually "replicated" by the computer [11]. More generally, two visions of AI coexisted: the first postulates that the role of AI is to be able to mimic human intelligence; the second assumes that its goal is to make the computer more useful to humans by performing tasks that require intelligence [10]. The second vision largely prevails.

Some very recent work using AI for AD will now be examined. Several AI applications are intended to stimulate designer's creativity in very early stages of design, by generating images (street ambiances in the GAN Loci project [12]) or 3D models [13]. Classification possibilities of CNN are often exploited to retrieve examples that match a design, for assisting a designer in a situation of case-based design to find relevant cases of previous designs (like for example the DANIEL project [14]). This type of operation is now often associated with evaluation and optimization algorithms [15].

Architectural solutions have also been generated with AI algorithms. Here are a few examples of very different approaches. Spacemaker [15] is an ML-based software for urban design that covers generation, evaluation and optimization of urban designs. AI-generated solutions maximize indicators as sun exposure, noise reduction, etc. Habx [16] is a property development company that developed an ML-based algorithm that draws apartment plans (partitions and room assignment). Based on reinforcement learning, the algorithm does not use a database (training set), but design constraints had to be made explicit in order to train the algorithm to make consistent floorplans. Stanislas Chaillou [17] has developed for his PhD a GAN-based algorithm that generates apartment floorplans with furniture in an exclusively top-down approach. The algorithm generates building footprints, partitions apartments, and positions furniture. The designer can intervene at each stage to provide input and choose the most suitable design for the next step. While the Spacemaker algorithm is mainly based on performance, Chaillou's algorithm rather offers options to the designers.

As generation algorithms can quickly generate large amounts of possibilities, classification algorithms are generally used complementarily, in order to give the opportunity to the designer to browse through the large range of solutions. AI has also made it possible to drastically optimize simulation durations to real-time simulations approximations, by projecting the results of previous simulation cases on new similar ones. This introduces a kind of "intuition for decision making" [18] for designers.

Digital design has four main components that AI algorithms can already realize: generation, representation, evaluation (analytical and judgmental processes) and performance (programmatic, performative and contextual considerations) [19]. While some solutions let algorithms manage a large part of the design process, others, on the contrary, aim at giving the designer the possibility to master the algorithm itself, in order to combine the sophistication of a human design process with the power of algorithm generation. Algorithms are limited by the solutions that can be found in their learning set, or by the constraints they have been given. Some initiatives give the designer control over the algorithm itself, making it easier for him to access it without having any particular machine learning skills (i.e. Lobe.ai, a visual programming tool). AI solutions will probably gradually be integrated into professional design tools to enhance designer's creativity (*via* solutions generation, retrieval and classification), "intuitions" (*via* real-time analysis) and constraints integration (*via* optimization). But as any other innovation in the construction sector, AI adoption will probably be slow. Human intervention will still be necessary and desirable although it may be reduced for certain types of projects.

4. AI in structural engineering

The field of structural engineering is a fertile ground for applications in AI. In general, civil engineering problems are multifaceted and usually require a variety of solution techniques that go well beyond deterministic computations. In structural and other civil engineering disciplines, these may include past experience, judgment, and creativity: traits that require respectively increasing levels of difficulty to automate. Moreover, the role of a structural engineer is very central to the successful completion of a project and carries a sizeable share of liability. A successful structural design not only must meet the strength and serviceability requirements as stipulated in the applicable building and design codes and standards, but it also must accommodate the needs of other disciplines, such as mechanical, electrical, plumbing, and specialty trades, in addition to meeting architectural requirements. Additionally, there may be numerous options to consider during any one particular design in terms of materials and construction methods to achieve most benefit.

Research related to the use of AI for structural design goes back to the mid 1960's [20], but to the best of the authors' knowledge, there has never been an attempt to produce a comprehensive AI-based tool for the design of a structural system. What is meant by comprehensive here is the ability to produce a detailed design of structural system starting from an architectural model and without human intervention at any stage of the design process. When one considers all the intricacies and implications of the structural design process, it becomes evident that if an AI-based tool is to be developed to comprehensively address structural engineering problems, it must have a number of necessary abilities that will allow it to tackle the various aspects of the problem in a reliable and consistent way, namely, and just to name a few:

- Access to all applicable building and design codes and an inherent ability to interpret and apply their provisions to the problem at hand
- Ability to produce conceptual models of possibly feasible structural systems based on architectural or other relevant information
- ability to produce structural modeling information from conceptual models
- Ability to execute the design process and interpret structural design information
- Ability to perform a holistic assessment of the integrity of the designed system

Each one of these items can be the subject of the implementation of an AI-based application of its own, and many of them may be amenable to the production of a number of AI-based applications for the same item. For example, the ability to execute the design process and interpret structural design information can be integrated in different tools that deal with different types of structural systems and materials. As a matter of fact, the literature is rich with examples of uses of the various AI tools, such as expert systems, neural networks, deep learning, fuzzy logic, and others to assist structural engineers in specific aspects of the design process. However, the availability of commercial software that makes serious use of AI for design is still lacking. This could be due to a number of reasons including the lack of software developers who are well versed in structural design as well as AI, the lack of comprehensive platforms for the development and maintenance of AI-based engineering applications, and the prohibitive cost of developing and maintaining AI applications in the absence of such platforms.

Will AI take over the structural engineering world? The answer to this question will depend on what is actually meant by "take over." If taking over means that the world will see the demand for structural engineers plummet because designs will be completely automated using AI-driven software, then the most likely answer is no, or at least not in the foreseeable future. Other than the absence of the required AI technology to allow for that to happen, there are also serious liability implications for letting a machine be responsible for independently producing a design. Consequently, any advances in AI that will lead to the development of such a system will have to be accompanied by changes to the legal system. The most likely scenario though is that the effect of AI on the practice of structural engineering will be similar to the effect that the introduction of computer technology had on the industry some forty years ago or so. Computers did not replace structural engineers. Instead, engineers became able to design larger and more complex structural systems using more computationally intense analysis and design methods that found their way into applicable building and design codes. The authors anticipate that AI enhanced design tools will start finding their way into the structural engineering practice as add-ons that would be designed to work with established commercial software, and the expansion of web and cloud-based computing will play a big role in allowing such tools to thrive.

5. AI in construction management

Construction is a high-risk industry with countless opportunities for accidents, miscommunication, and running over budget or behind schedule. From front end planning to construction documentation, preconstruction to handover, many stakeholders and changes can overwhelm even the most organized project managers. Artificial intelligence (AI) can significantly improve construction project management effectiveness. The potential applications of AI in construction are vast. AI applications in the construction industry are forecasted to reach $4.51 Billion by 2026 [21]. The easy risk mitigation of quality and safety, coupled with saving the time and cost of the construction projects, will drive the growth of the market.

Most construction projects run over budget [22]. AI could help to predict cost variance based on aspects such as project size, contract type, and the experience level of project managers. Historical data such as project start and end dates are used by predictive models to predict accurate timelines for future projects. AI helps staff get training material remotely, which helps them enhance their skills and knowledge rapidly. This reduces the time taken to train new resources, and consequently, project delivery will be expedited.

Today, 3D modeling and Building Information Modeling (BIM) transformed the buildings' design process significantly. To accurately plan and design the construction of a building, the BIM models need to consider all project systems such as architecture, structural, mechanical, electrical, and plumbing (MEP) systems and the sequence of activities to build these systems. The main challenge is to ensure that the different systems do not clash with each other. Machine learning, which is a branch of AI, could help to create 3D models of MEP systems while concurrently making sure that the routes for MEP systems do not clash with the building architecture/structural components.

Construction projects are exposed to countless forms and degrees of uncertainty and risk [23]. The larger the project, the more significant the risk, as multiple teams are working on different trades in parallel on the job site. AI could be used to monitor possible risks on job sites so that the contractors can come up with more effective contingency plans. Project managers can also prioritize on mitigating high risks when AI determines one.

Many construction firms are investing in AI and data science to boost the industry's low productivity and solve the labor shortage problem. Construction companies could boost productivity by as much as 50% through real-time analysis of data according to a 2017 McKinsey report [24]. Construction companies are starting to utilize AI and machine learning to improve resources allocation and resources leveling. An AI-based application could continually evaluate job progress and the location of resources to enable project managers to tell which job sites have enough resources to complete the project on time, and which might be falling behind where additional resources could be deployed. AI could help robots to perform repetitive tasks more efficiently than their human counterparts, such as pouring concrete, bricklaying, welding, and demolition, etc. [25]. This releases up human workers for other construction activities and reduces the overall time required to complete the project.

Laborers are killed on construction sites five times more often than other industries [26]. The leading causes of deaths in the construction industry were falls, followed by struck by an object, electrocution, and caught-in or between machinery [27]. AI-based applications that utilize visual processing algorithms are a vital risk monitoring and prevention tool for safety managers. Safety monitoring solutions that use AI scan large amounts of photos and quickly identify workers and instances that are not following safety protocol. For example, AI could help identify safety hazards, such as workers not wearing appropriate PPE gear.

6. AI in construction from a student's perspective

We can do it, but should we do it, when deciding whether to allocate cognitive and physical labor from humans to that of artificial intelligence. The consequences of our decision on outsourcing our cognitive labor to AI will only be fully understood in hindsight [28]. And at the moment, there is a terrifying amount of work automation in warehouses and labs around the world. From a student's perspective, it is reasonable to believe that AI poses the ability to improve quality, enhance safety, and reduce cost within the construction workflow. How will AI impact the quality, safety, and cost, and how will the impact be measured to ensure that AI's goals are aligned with the good for humans? The following sections describe how AI will impact construction.

The construction industry has been through economic revolutions before, but the robot revolution is different. Universal robots are requiring minimal maintenance with a minimum lifetime of 35,000 hours and a return on investment that outperforms the meat-based competition [29]. Construction companies constructing complex buildings, large scale projects, and demanding deadlines may feel the need to adopt robots to stay competitive against other companies. Currently, Boston Dynamics has made a construction robot named SPOT that can inspect progress on construction sites, create digital twins, and compare as-built conditions to building information models [30]. Spot can perform quality management of workmanship, and, a key area focused on during an undergraduate degree in construction management; the robot performs the task autonomously. Will AI take over all of the construction managers' roles and duties? Only time will tell. Currently, construction managers can keep their employability by continuing education and finding ways to adapt and work next to artificial intelligence instead of being replaced by machines [31]. In the meantime, while humans are still the majority of the construction workforce, Artificial Intelligence and digital transformation will swiftly creep into the workforce by providing convenience to the people it serves. Enabling/Empowering people to accomplish more work with the help of computers has established a lasting presence for computers within the construction industry.

Safety in construction is a collective priority and has improved significantly since the early 1900s. Many lives have been saved and injuries prevented from job safety analysis and safety programs established to keep workers aware of the risks present while completing work. As Job Safety Analysis becomes digitized, it will become behoove of the companies to utilize the data for safety inference. Such inference will help ensure EMR rates remain low and help keep workers aware of the risks present while performing individual job tasks. AI will be coupled with big data to help determine unsafe acts, and statistics will be used to increase awareness of potential injuries. The most likely injury can sometimes be prevented by doing toolbox talks to cover the hazards seen most frequently. AI could take the form of a bot on a safety app that notifies workers of unique hazards while the user is filling out the form. The Job Safety Analysis is intended for workers to think about the dangers present. Safety is somewhat of a stochastic environment that concerns the occurrence of freak accidents and a safety manager will still need to be present to ensure that people are complying with the program and give human intuition on safety concerns.

AI can also play a significant role in reducing construction costs. Intelligent systems were initially discovered in the 1960s when Allen Newell, Herb Simon, and John McCarthy were questioning what human-level intelligence is [32]. The researchers broke down human-level intelligence into three pieces: perception, deciding what to do, and then acting, today known as the decision loop [32]. Machine learning has contributed to the decision portion of the loop; before machine learning became fashionable, humans wrote the predictions of what happens next which was limited to decision making such as chess and instead had computers observing historical data to predict what happens next through making artificial neural networks [32]. The key here is that during the decision-making process, advanced intelligent systems can accomplish planning by weighing possible sequences of actions and finding the probability of the outcome. Then the system chooses the most likely one and acts based on the choice, followed by the perception of a new situation. AI poses the ability to reduce cost by giving inference on what potential outcomes are possible and helping humans make decisions with less time by providing information faster than traditional construction information gathering.

7. Conclusions

Every creature in the world is born with a Knowledge-Base, to use an AI term, that allows it to perform the required functions it needs to be able to survive. What sets humans apart is their ability to simultaneously use the different types of the knowledge they already have and in unpredictable different ways to create new knowledge that may be of a completely different nature that what they started out with. It may be this ability that defines a large portion of what is referred to as intelligence, of which creativity, intuition, and, to a certain extent, inspiration.

AI offers powerful tools that can outperform humans in many areas of design and management, but so did computers when they were first introduced to help in computationally heavy professions, such as accounting, for example. The fact is that the advent of computers did not kill the need for accountants. To the contrary, and although computers did take over the world of accounting, there may be more accountants per capita in the US today than there were 50 years ago. Moreover, computers created new opportunities for computer savvy accountants to find rewarding careers in software development and consulting while allowing practicing accountants to focus on the specifics of the information at hand, rather than on performing arithmetical operations.

AI will inevitably take over the construction industry by becoming more integrated into the software and equipment that is being used by the industry and its related disciplines. AI will also most likely trigger a big change in the way the industry conducts its business by introducing more automation and robotics and affecting design methods and the means and methods of construction. AI may not end up reducing the need for architects, engineers, and construction managers. Instead, these professionals of the industry and others may see their roles and the way the perform their duties permanently changed to become aligned with the new reality of an AI driven world. How this will play out will be an interesting thing to witness but the industry will have to make a choice between riding the wave on the front or being dragged by the tide.

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An Investigation into the Integration of Building Information Modeling with Pre-Construction Industry in the Developed Countries and Iran

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Abstract

Modern methods of construction buildings to improve the quality, reduce the time and cost, and increase their productivity have always been desirable for architectural, civil and construction engineers. In the 21st century, any evolution in technology was achieved with advancement in computer science. Building information modeling is actually a simulated multidimensional model related to building geometry, spatial relationships, geographic information, the amount and properties of all building components, and their intelligent communication with each other. This technology is a new approach to building design, implementation and management at the same time with great quality and coordination. Now days with the advancements in digital architecture, prefabrication and all kinds of building design optimization, it can be seen the growing use of building information modeling system in the construction industry. For this reason, building information modeling can have a significant effect on pre-fabrication. Also, by examining the building model, planning to install prefabricated components of the building and identifying executive interfaces will also be present. This paper examines the advantages and disadvantages of building information modeling, as well as the need for this type of software for the construction industry in the world and Iran.

Keywords: building information modeling, prefabrication industry, modern methods, construction industry

1. Introduction

The modeling of building information: in the last decade, building information modeling (BIM) is noticed significantly that points to the executive problems in building industry (ASHRAE,2009 & Eastman, 2011). The modeling of building information includes real building information and is not just two _dimensional drawn plans of building that is drawn commonly by CAD software (Becerik-Gerber, 2009& Krygiel, 2008). The complete description of BIM: a three dimensional simulated model consist of parametric elements that every element has special detailed concepts and includes demanded information of architecture and structure concepts and how they are made and its price and purchase and installation date, that information is being implemented in model by all the project stakeholders while model designing. This model is demonstrated as a four, five and multi dimension model regard to the cost and time information. This is a remarkable help for correct understanding of work by small contractors and is transferred the expectation of designers and engineers (Golabchi, 2016). these problems are associated with the relatively slow adoption and integration of advanced information technologies and industrialization principles such as mechanization, automation, robotics, standardization, modularization, and information- driven construction. Prefabrication Housing Production (PHP), asan innovative solution in the construction industry, uses the principles of industrialization in the lifecycle of construction projects, includingdesign, manufacturing, transportation, on-site assembly, maintenance, and deconstruction stages(Li et al.).

2. Generation

The prior reasons for BIM generation are the existence of several problems in traditional system of plan presentation that its usage lead to fix these problems and the workability improvement in construction process (NIBS, 2007). BIM process is not a progress or a development of work process, it is a fundamental evolution in work infrastructure (Azhar et al, 2008a,2008b& Beck, 2011). For the first time, BIM was defined like this: it's a series of processes that includes production and processing of digital profiles to describe spaces and performances. The result of building information modeling, help practitioners from the first stages of brainstorm in design to construction stages and at last the operation along whole the project (Golabchi, 2016). National standard building information modeling forums NBIMS, defined BIM as: a complex process in relationship of planning, designing, construction, performance and facility management through a standard information model that is readable by devices and new and old programs, that includes all appropriate produced or collected information in relationship with that facilities in usable opportunities from all stakeholders in the cycle of project (NBIMS, 2007). BIM concept in BIM handbook is this: new modeling technology and the related series of processes for production, relationship and analyzing the building models (Eastman, 2011& EASTMAN,2012). The BIM concept includes the infrastructure of IT devices that integrates design into one. Also, supports the construction and building operation. (Merschbrock,2012). BIM is it's a series of processes that includes production and processing of digital profiles to describe spaces and performances. The result of building information modeling, help practitioners from the first stages of brainstorm in design to the construction stages and at last operation along whole the project. (Lloyd,2009& Golabchi,2016). the available tools in BIM are divided to three separated parts:

- 3D – Modelers
- Viewers/ surface modelers
- Analyzers

Three-dimension modeling: it's a real tool for BIM that the parametric things with adequate details are used imaginary in it through solid materials to build a structure.

Viewers/ surface modelers: all the aspects of project don't need to have the same details. Although the financing provider may like to see how the building would be like and for this you just need to a superficial modeling that all the objects are empty in it. The only thing that is defined, is in work surface and is used to demonstrate the idea. This demonstrates the contracts in first stage and is so valuable.

Figure1. Design and coordination process of the conventional method[37]

Analyzers: normally it's a supplementary software that plays the role of the main BIM tool. It means that it can receive information from three-dimension model and estimates and analyzes the energy efficiency and how to lightening in different seasons accomplished by so many things. While so many companies are active in the BIM area and the production of software, like any industry each has a market share that as a sample, the following chart demonstrates the download rate of BIM different companies in UK that Bently BIM Suite, Vector works, IFC, Archi CAD, Revit are the main providers of BIM services (Bimtalk,2013). In figure 1 the percentage of market share is presented by each BIM producer companies:

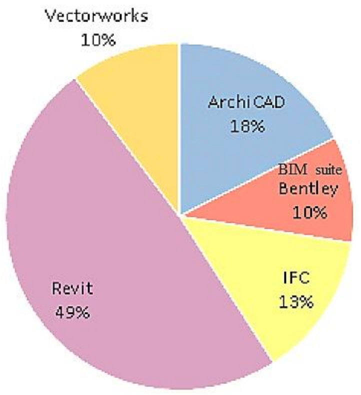

Figure 2. The percentage of market share is presented by each BIM producer companies

Many researchers had identified the advantages ofapplying prefabrication (OST, 2001&, YH,1997). Seven benefits of applyingprefabrication are used for conducting the survey: (i) frozen design at the early design for better adoption of prefabrication; (ii) better supervision on improving the quality of prefabricated products; (iii) reduce overall construction costs; (iv) shorten construction time; (v) environmental performance improved for waste minimization; (vi) integrity on the building design and construction; and (vii) aesthetic issues on the building.

3. The review of other countries' studies

A study about building information modeling is done in developed countries in the field of building industry in north America (Canada and America) and East Asia (South Korea, Hong Kong and japan). The following cases can be understood:

3.1. Standardization

This study shows that many of countries like America and UK have stablished and passed required standards in the field of BIM that makes it not only available as a method, but also makes it obligated in some cases (Mc Graw Hill Construction, 2014).

Some available standards in the field of building information modeling, could be described as fallow:

The standard of architecture, engineering and construction industry: this standard made available a general standard to use BIM and a separated standard for the users of Revit and BIM Suite Bentley specially for AEC UK based on BS 1192. This standard has been published in the early summer of 2012 (Hergunsel,2011& Chair,2012).

American National Standards: BIM National Standard has been stablished by American Intelligent Building Association that the firs version of it was published in 2007 and from 2012, the second version of it was published and the third version of it is being edited. This very great document looks useful and is used in COBIE project (Han,2008& NBIMS,2007).

Hong Kong Standard: BIM Hong Kong Standard has described the BIM goals and detail levels. (HKIBIM,2007)

American Army Retirement Building and Facilities Management Standard: the department of the affairs of American Army Retirement Building and Facilities Management has been provided a complete BIM guideline from the view of employer. This standard has been edited in 2010. (El Dado,2011& CFM,2010)

The executive program of the university of Pennsylvania: this program has been used as a foundation for BIM programming. Now, the second version of this standard which has been published in 2010, is used. (Engineering, P. S., 2010) the national guide for Australian digital modeling: this standard has been published by cooperative research center for innovation in construction in 2009. (Austoralia,2009& HKIBIM, 2007)

New Zealand and Australian Revit standard: this standard has focused specially on Revit. The third version of this standard has been available from 2012.

3.2. The published articles around building information

According to researches done with the end of 2015, The United States is remarkably pioneer compared to other countries in the world in the production of scientific documents in the field of building information modeling. This rate is 30% of all articles. The Scandinavian countries with the rate of 17.59 totally have the second rank in the production of science in this field in the world. (BuildingSMART, 2010, Carneiro, 2012). This issue is combines by a chart in 2012 by Carneiro et al and with further investigations by 2015 that has been updated and this ranking has been correct yet. It should be said that this much difference, shown in the following chart, can be due to differences in operating systems, more appreciation for new technology, the existence of universities and educational centers with special management tendencies and building information modeling. presents the distribution of the 65 publications by the country/region and the prefabrication production structures of these publications. United States, Hong Kong, United Kingdom, and Israel are the top four countries or regions, in terms of publications on BIM-PHP.

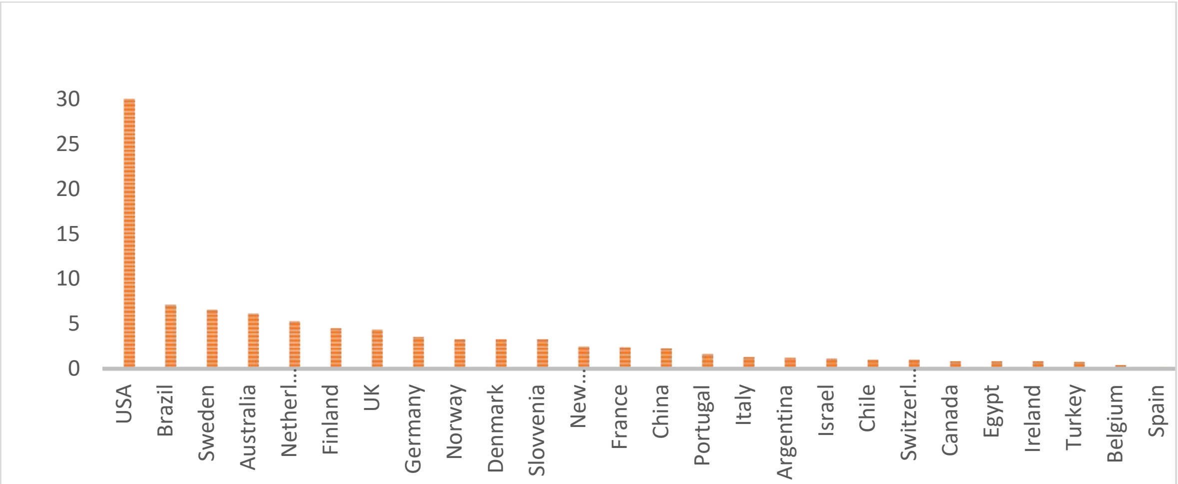

Figure 3**.** The chart of published articles in the field of building information modeling in different countries (Carneiro, 2012)

At last, the overview of the theories and other studies of researchers is presented in table *1:*

Table 1. The theories and other studies of researchers

	Enhancing coordination and control among stakeholders	Increasing effectiveness and reducing conflicts	Better project performance and quality	Faster project delivery	Waste reduction	Reduce construction costs	Business opportunities and income
(Beck, 2011)	*			*	*	*	
(Hergunsel, 2011)	*	*		*	*	*	*
(Radriguez, 2011)	*	*		*	*	*	*
(El Dado, 2011)	*	*	*	*		*	*
(Buiding Smart, 2010)				*	*	*	*
(Giel and Issa, 2010)		*	*	*			
Ashrai,2009)	*	*	*	*	*		*
Becerik- Gerber and Rice,2009)				*	*	*	
(Azhar, Hein and Sketo, 2009)	*		*	*			*
(Hardin,2009)	*	*	*	*			*
(underwood and Isidog, 2009)	*	*	*	*	*	*	*
(Han and Damaian, 2008)			*	*	*	*	
(Herley,2008)				*	*	*	

In the other view and according to the expressions and definitions of the building information modeling in table 2 and 3, the probable advantages and disadvantages and the opportunities and threats of implementation of building information modeling are presented in this analytical tables.

Table 2. The advantages and disadvantages of building information modeling

Weak points	Strength points
Traditional work processes and low acceptance of new technologies in construction projects (mainly in third world countries) Need to train employees and beneficiaries in contracting companies, consultants and employer agencies Definition of building information modeling in some of the companies that means 3 dimension design that was itself one of the obstacles to its serious application.	Increasing productivity and helping to get out of the recession in the construction industry Decreasing the reworks and increasing the rate of projects according to project delays Facilitating the employer, contractor and consultant communication and making quick decisions in times of change. Reduction of office work and routine correspondence Ability to connect material vendors and suppliers to formulate the required supply chain program

Table 3. The opportunities and threats of using the building information modeling

Threats	Opportunities
Lack of proper financial potential in the current situation The absence of binding rules for specific projects that serve the interests of companies in the direction of building information modeling. Lack of strict oversight of the implementation of construction laws, assuming the enactment of supporting laws a lack of familiarity among executives and decision makers Using building information modeling in some projects as a 3D display and comparing it with 3D MAX ... Lack of strong communication infrastructure for wide web interactions (mainly in third world countries)	Integrating information into construction projects to provide materials, financial estimates, and even at the macro level strategic planning to build the related industries required to deliver accurate estimates and reduce delays will strengthen active construction companies and reduce losses. Use of private sector in medium and large projects Reduce the environmental impact of construction projects with the help of energy, light analysis, and help achieve high environmental policies. The potential to emerge as a start-up for small companies that specialize in implementing this theme in projects.

3.3. An overview of research in Iran and research needs

The study and investigation of building information modeling that has been done in Iran is in this way that since late 2012 in Iran, building information modeling has been considered by researchers as a new field for research. A number of qualitative studies are needed to disseminate relevant knowledge and understanding of the effects that can be said on building information modeling in most of the areas except issues such as project delivery integration, maintenance, inter-software information exchange and process modification, Appropriate qualitative studies have been conducted in Iran, and now needs practical application with quantitative modeling and case studies to gain a deep understanding of the effects of applying this technology to the various aspects of the construction industry, a research vacuum being observed, and the only case that can attempt to implement building information modeling As a case study, is 3D modeling of the Carson 4 bridge used after the design and construction of the technology, which did not produce very tangible results and did not show the value that could be attributed to the technology in the project. Reasons for the construction industry's disapproval of the introduction of technology can be known due to the current recession, the existence of experimental contractors and traditional construction, the need to apply building information modeling technology to changes in rules, standards, working methods, project communications, definitions of work processes based on new philosophies (such as lean manufacturing) that without these changes it would not be possible to implement them fully, and the effect of building information modeling would be shown as a three-dimensional demonstration model of projects (Underwood, 2009& Arianhasal, 2016).

Arian Carmel and Majruhi Sardrood has evaluated and researched the impact of using this technology in reducing pre-construction problems by investigating the pre-construction problems and taking into account the unique features of building information modeling technology (Arianhasal, 2016).

3.4. Pre-construction

Prefabrication of building components as a degree of industrial manufacturing is a new method of construction that is widely used today in developed countries, reducing construction costs due to the mechanization of the manufacturing process, reducing the manpower involved, significantly reduced manufacturing time, increased quality and durability of structures due to factory-made components, reduced consumables and thus less environmental degradation are industry characteristics. Most importantly, the system is environmentally friendly and uses Resources are also significant during construction and productivity, and energy and space consumption, as well as pollution generation. It does not exceed environmental capacity and considers intergenerational justice (NBIMS,2007, Rodriguez, 2011 & Sacks,2012).

Prefabrication in building industry, design and Manufacturing of prefabricated and complex concrete and metal structures, prefabricated walls, prefabricated electrical and mechanical equipment are examples of applications of this technology. Qualitative and quantitative developments in housing construction and appropriate living space are correlated with economic, social, and cultural developments in different regions, and are not inseparable. In addition, taste of art and technology, have been some of effective elements in Qualitative and quantitative production of housing and according to papulation growth and Increasing need for housing and immigration to the cities, deep and fundamental developments are generated in this industry. In the meantime, a new construction method Entitled Pre-construction, quickly established itself in the building industry and its scope has become so widespread that in some countries it is now more than 70% of construction using this method.

3.5. Generation

Prefabrication in building industry has been considered named Prestressed Concrete in 1886 in United State for the first time and its defects were eliminated after half a century. Although Prefabrication in building industry began by Egyptian Pyramids, Roman and Greek temples and Sassanid and Achaemenid palaces, but its industrial development has been after the industrial revolution and the invention of concrete and steel and the emergence of new construction techniques. The first concrete and pre-construction sites were established in the United Kingdom, from which the construction of schools by the CLASP, SCOLLA and SEAC consortia can be noted. In general, the pre-construction development of the construction industry in Europe after World War II was the focus of reconstruction programs in the affected areas. The use of this industry in some countries has been such that it has completely replaced the traditional construction industry. Its years that this new method is used in European countries and development countries and has strengthened its position by technical tests and acceptable experiences. Prefabrication elements in addition to residential buildings, are used in the construction of industrial halls, bridges and other stuffs. Prefabricated construction industries and sophisticated systems create a tremendous speed in the implementation of construction programs.

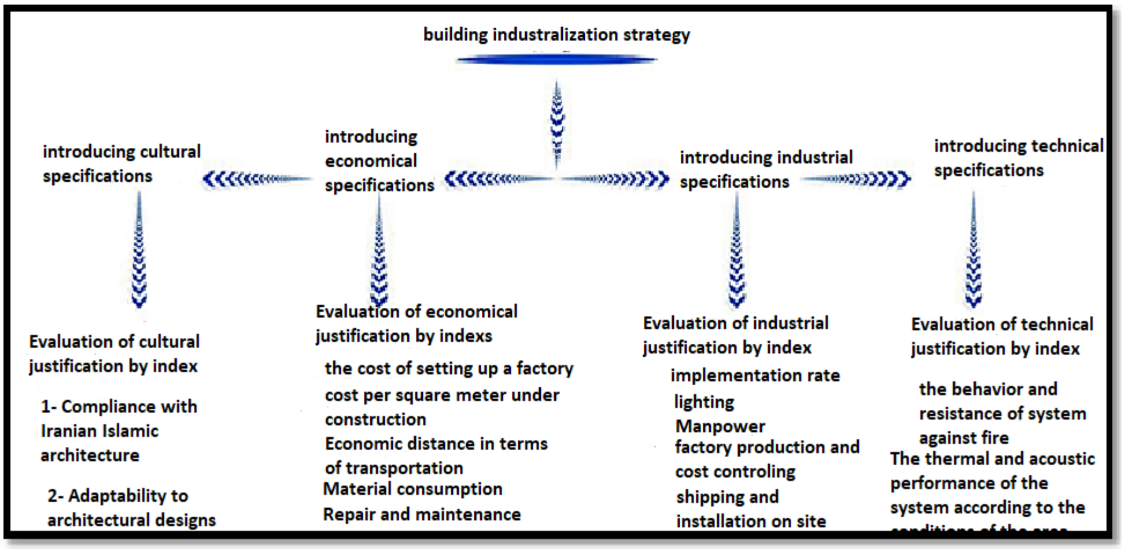

Figure 4. The total view of building industrial strategy

With regard to the history of pre-construction in the building industry, it should be noted that building production or domestic construction is carried out in two ways:traditional way.

3.6. Industrial method

The traditional construction includes common methods of construction in the country in reinforced concrete buildings that includes excavation and execution of foundations, columns, beams, ceilings, molding and concrete casting that every stage, depended on different causes need too much time and about buildings with steel frame, excavating and executing the foundation and setting up the skeleton and welding, itself takes a long time.

In addition to the above issues, how to implement concrete and steel structures in the workshop has its own problems. In concrete structures, the most important issue is the construction of concrete and its mixing design, and the manner in which concrete is poured and processed. In the case of steel frame, the welding of joints is particularly important which is done by semi-skilled workers. Industrial methods in Iran mainly consist of concrete structures and are discussed in three cases:

Avoiding Delays Due to Unfavorable Weather Conditions: Manufacturing of prefabricated parts is often confined, making it possible to perform work in any adverse weather conditions, which is one of the reasons for this type of construction in cold areas.

Increasing the speed of assembly on site: Although the production and manufacture of components using new technologies accelerated the manufacturing and processing of concrete, it can save more time on assembly on site.

Before using BIM and demanded software, prefabricated elements are coordinated and fragmented through CAD, that there is limitation in the complete imagination of the construction method of these 3 dimension structures, but after the appearance of BIM and the Software such as Tekla Structures that enables it to configure loading, partial mapping, assembly, and even in the case of a steel structure, also provides clipping program for the CNC machine. this procedure has changed in general and can be said to give high dynamics to the design and construction phases of these structures.

The prefabrication stages in building industry according BIM are as follows:

Total design of building by design team that is done like the common buildings and is sent for the prefabricated specialists to provide the prefabricating plan.

Then, the structural elements are divided to Fabricable pieces and portable, of course, with considering the traffic restrictions.

Actually, the structure that is prefabricated, is referred to design unit to make final decision and to provide the instruments and demanded materials.

Prefabricated pieces are assembled and produced on the assembly line based on instructions usually prepared according to the project execution schedule

After manufacturing the pieces, they Prefabricated pieces are assembled and produced on the assembly line based on instructions usually prepared according to the project execution schedule packaged and, counted and named and posted to the site according to schedule

Parts are installed on site

The conceptual framework also echoes the concept of industry 4.0 (Akanmu, 2015& Yuan,2016) which is considered as an emerging trend for achieving a timely interaction between the virtual platform and the physical environment through information technologies such as cyber-physical systems (CPS), the internet of things, cloud computing and cognitive computing.

4. Conclusion

The building information modeling is one of the most promising developments in the construction industry. Through this technology, one or several imaginary digital models are produced with high accurate and help to the design process and the combination the BIM with prefabrication provides this special opportunity to the contractors that prepare pre-fabrication methods including production and installation and equipment needed before the beginning the project. Whole the executive team including the main contractors, small contractors and builders in each production and installation section can work together in every part of production and installation through the imaginary simulation of the manufacturing process to practice the execution sequences (production and installation), locating production sites, depots, towers, elevators and project site management and assessing the impact of their decisions prior to implementation.

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Modular Construction vs. Traditional Construction: Advantages and Limitations: A Comparative Study

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Abstract

Modular construction is a novel technique that has several advantages over traditional construction methods; however, along with the benefits, there are limitations that make it challenging. Various aspects of modular construction need to be studied in-depth to improve the construction process, and the aim of this study was to accomplish that by investigating its advantages and limitations and comparing them with traditional construction. The advantages were identified through a thorough literature review, and were classified into five categories: project schedule, project cost, labor safety, project quality and productivity, and environmental. The limitations were also investigated through the existing literature and classified into five categories: project planning, transportation, public and expert acceptance, establishment cost and cost due to complexity, and coordination. The results revealed that the advantages of modular construction outnumber its limitations; however, further technological development and research would lessen or mitigate the challenges. The results of this study highlight the main benefits and challenges associated with modular construction and will help project stakeholders choose between this method and conventional construction methods for their projects.

Keywords: modular construction, traditional construction, modularization

1. Introduction

The Construction Industry Institute (CII) [2] defines modular construction as "*the use of offsite construction (including a segregated area onsite) and includes all work that represents substantial offsite construction and assembly of components and areas of the finished project.*" Implementation of modular construction has notably increased throughout the past several decades [1]. Projects improve in several areas, such as cost, schedule, safety, etc. when this method is properly utilized. The experts broadly accept that modularization will lead to significantly enhanced productivity in the construction industry in the next 20 years [3]; nonetheless, several challenges and barriers to proper implementation limit its use in some cases [4].

During the past few decades, researchers have studied different aspects of modular construction. Pasquire and Gibb [5] studied the advantages and challenges of off-site production of construction components and revealed that experience plays the most important role in deciding whether to use modular or traditional construction. Song et al. [6] developed a tool with which the decision makers could evaluate the feasibility of modularization in their projects. Choi [7] investigated the relationship between the factors that may impact the success of a modular construction project and the project productivity and indicated that there is a reasonable correlation between them. O'Connor et al. [8] revealed that when a construction project has a time constraint, modularization can be a useful method for completing the project in the allotted time. The most important challenges pertained to delays in the assembly of the components, overproduction, and long lead times.

Despite the fact that several researches have focused on different aspects of modular construction, few studies have compared the characteristics of traditional and modular construction to provide a guideline for deciding which method is best for a specific project. This study aims to identify the advantages and disadvantages of modular construction and compare them with those of traditional construction in a descriptive manner. The outputs of this research point will assist stakeholders in whether to use traditional or modular construction methods for a project.

2. Methodology

Relevant documents of different types were collected from the existing literature. The documents were obtained from four main databases: Google Scholar, ResearchGate, Scopus, and Science Direct. Keywords such as modularization, modular homes, modular vs traditional, prefab construction, off-site manufacturing, and others were used to explore various search engines. The content of the collected documents was analyzed with regard to title of the journal, nature of the study, year of research, need for modular construction, identification of factors contributing to the project success/failure, and data collection practices. The advantages associated with the implementation of the modular method of construction were identified and classified into categories of project schedule, project cost, labor safety, project quality and productivity, and environmental. The limitations of modularization in construction were identified and classified into categories of project planning, transportation, public and expert acceptance, establishment cost and cost due to complexity, and coordination.

3. Content analysis

The content of the documents used in this study was analyzed according to (1) title of the journal, (2) data collection practices, (3) research objectives, (4) year of research, and (5) need for modular construction. In the following, all of the content analysis stages are described.

3.1. Title of the journal

Over 80 journal articles, conference papers, dissertations, and research reports were examined. Approximately 50% of the documents were journal articles, followed by conference papers, guidebooks, dissertations, and project reports. Table 1 shows the list of journals and the number of collected articles from each.

Table 1. List of journals and the number of collected articles from each

Journal Title	Frequency	Percentage
Journal of Construction Engineering and Management	8	12
Journal of Cleaner Production	3	5
Journal of Management in Engineering	3	5
Project Management Journal	3	5
Journal of Engineering, Design and Technology.	3	5
Automation in Construction	2	3
Procedia Engineering	2	3
Journal of Injury Control and Safety Promotion	2	3
Journal of Architectural Engineering	2	3
Other Journals and papers	34	55
Total	62	100

Distribution of studied literature based on data collection method
(Combination means that the paper has used more than one methodology for writing. For example, Interview and questionnaire, literature review and case study, etc.)

3.2. Data collection practices

Figure 1 shows the distribution of the studied literature, based on data collection method used. As is shown in the figure, the data collection method most often used (48%) was exclusively from a literature review. Twenty-one percent (21%) of the data was from case studies, 9% was from surveys, and the remaining 22% combined the three methods to collect data.

3.3. Research objectives

Figure 2 illustrates the distribution of the studied documents according to their objective. Sixty-two percent (62%) of the studied literature focused on determining the advantages and promoted the wide use of modular construction. Eighteen percent (18%) of the documents concentrated on finding and discussing the limitations, and twenty percent (20%) of them examined both the advantages and limitations and suggested further research due to unavailability of data.

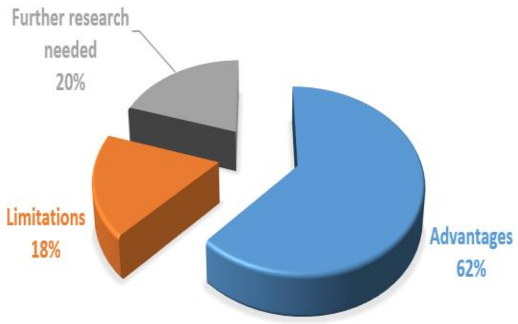

Figure 2. Distribution of documents according to their objective

3.4. Year of study

As shown in Figure 3, the number of journal articles published on the advantages of modular construction from 1995 to 2020 increased exponentially, which conveys that the need for modular housing has become more critical during the past two decades. Between 2015 and 2020, 36 journal articles were published on this topic, which was the highest number of studies among all five-year targeted intervals.

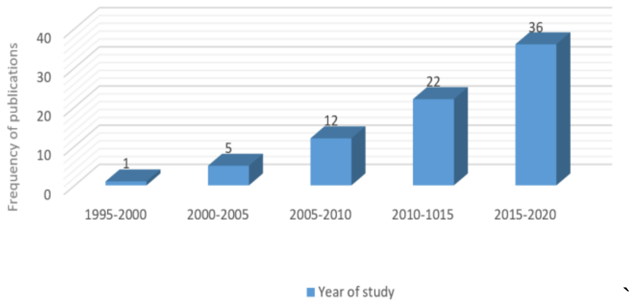

Figure 3. Distribution of publications on modular house based on year and frequency

3.5. Need for modular construction

After a careful review of the journal articles, it was found that two key factors influence the need for modular construction: (1) population growth, and (2) a high rate of deaths resulting from construction work.

3.5.1 Population growth and need for affordable housing

Data provided by the U.S. Census projects that the population in the United States is expected to grow from 300 million people today to over 350 million people by the end of 2025. Based on the average household (2.59 people per household), 19.3 million homes will be needed to accommodate the extra 50 million people. Many studies indicate that urbanization is influenced by housing factors [13]. Cities are not growing proportionately with the economy, and there is a gap between the upper and lower classes. This division can be addressed with proper housing for every class of people, which includes living in an environment that is healthy, affordable, and feasible [14]. Based on a survey in 2005, every third person in cities live in inconvenient and unsanitary conditions [15].

3.5.2 High rate of deaths in traditional construction

The construction industry has a higher rate of death than all of other sectors of work. In the U.S, nearly 20% of deaths result from the construction sector (OSHA). Klakegg [16] espoused that construction jobs at off-site plants are safer than on-site operations, as the majority of accidents occur on the construction premises. All of the information available in the Safety Hazards to Workers in Modular Home Construction video pertains to residential construction and does not differentiate between modular and mobile homes [17]. With the same deficiencies in data, [14] the Occupational Safety and Health Administration database contains reports of 125 accidents related to modular building construction, most of which occurred during installation processes and were caused by falls from roofs [16]. It is estimated that 80% fewer accidents occur from modular construction than from traditional construction [16]. Responses from a survey conducted by Becker [18] showed that 50% of the responders believed that modularization is safer than traditional construction.

4. Advantages and limitations of modular construction

Modular construction has several advantages and disadvantages that need to be considered while using this method [19]. Many of the advantages are related to improvements in costs, schedules, safety, quality, productivity, environmental performance, etc. [20], while the disadvantages are associated with project planning, transportation and site limitations, initiation costs, lack of knowledge, etc. [10]. These considerations are discussed in the following, based upon information derived from the literature.

4.1. Advantages

The advantages of modularization and the sources of the information are summarized in Table 2 and discussed in the following. In general, by carefully implementing modular construction methods, there are several advantages in broad areas such as quality, labor, cost, speed of construction, and environmental impacts.

Table 2. List of the advantages of modularization in construction and the sources of information

Advantage	Source(s)
Speedy	[10]; [19]; [20]; [21]; [22]
Cost effective	[2];[23]; [24]; [25]; [26]; [27]
Highly Safe	[28], [29], [30], [31], [32]
Highly Productive	[33]; [34]; [35]
Environmentally Friendly	[21]; [36]; [37]; [38]; [39]; [40]

Speedy: Two Important benefits of the modularization method for construction are that several activities can be performed simultaneously [21], and weather conditions have little effect on the schedule [19]. As a result, the time required to complete a modular construction project is usually 40% less than that of traditional construction methods [19], which can be very important for projects with a need for a quick turnaround [41], such as such as post-disaster reconstruction of infrastructures, hospitals, etc. [42]. Ramaji and Memari [20] indicated that the complexity of a project considerably affects the time-saving feature of modularization, due to the increased need for communication and on-site work [22].

Cost Effectiveness*:* CII [2] revealed that a 10%-25% decrease in the construction cost of projects is expected when modularization is implemented. Several factors contribute to the lower cost [15,16], such as reduced material transportation for on-site labor [17], the highly efficient installation of construction components produced off-site, and the lack of vulnerability to weather extremes [18]. Cartwright [19] emphasized that modular construction leads to lower costs because the design procedure is standardized and requires less time and engineering than the traditional design process.

***Highly Safe**:* Working on-site often involves activities that threaten the safety of the workers [28,43], and the increasing number of fatalities and non-fatal injuries have led many researchers to look for solutions [29]. Several studies have investigated the effects of modularization on the safety of the laborers and revealed that it results in a significant decrease in the number of safety problems [30]. The rate of accidents occurring in construction projects reduces by 80% when the modular construction method is used [31]. Even though modularization usually decreases the rate of injuries at job sites, safety frameworks need to be established for this method as well [31]. Thus, the Occupational Safety and Health Administration (OSHA), which monitors the on-site injuries in the U.S., provided requirements for the safety of the laborers who work on projects that implement modular construction [32].

***Highly Productive**:* The production of prefabricated components for modular construction is tightly controlled and mostly automated [33]. The laborers who produce the components are skillful if for no other reason than they repeatedly perform the same procedure [44, 45]. In addition, the components are not subjected to weather conditions that might affect the quality of the materials [34]. In summary, the modular products have the potential to be of higher quality, less expensive, and produced in higher quantities in a smaller time period than those produced at the construction site [35].

***Environmentally Friendly**:* The amount of waste generated by traditional construction methods has always been an environmental challenge for project managers and stakeholders [36]. Modular construction generates less waste than traditional construction [21], the products are easy to reuse and recycle, the waste is easy to dispose of [38], the components may be detached when their lifecycle ends [39], they don't produce on-site dust, greenhouse gases, or noise]40], etc. Thus, modular construction is a sufficient solution to the need for reducing the volume of waste [36,37].

4.2. Limitations

The limitations of modularization in construction and the sources of the information are summarized in Table 3 and discussed in the following.

Table 3. List of the limitations of modularization in construction and the sources

Limitation	Source(s)
Required Accurate Planning	[46]; [47];[48]
Transportation Challenges	[46]; [49]; [50]
Negative Public and Expert Perception	[51]; [52]
Establishment Cost and Cost Due to Complexity	[4]; [19]; [10]; [51]; [53]
Excessive Coordination Needed	[54]; [55]

Require Accurate Planning: O'Connor et al. [46] indicated that the project planning process of modular construction differs approximately 37% from the project planning of conventional construction. The differences might include the overall planning, cost estimation, scoping, design, etc. [46], which lead to considerable limitations. In addition, the planning process is especially challenging because of the complex components that have to be produced and assembled during the prefabrication process [47]. Thus, accurate planning with explicit scope and design details is required prior to the start of the project [48].

Transportation Challenges: An adequate number of vehicles is required to deliver the manufactured components to the jobsite for modular construction [49]. Oversized components need specific transportation considerations and cause delays, incur extra costs, and add complexity to the construction process [50]. The transportation limitations of modular construction are barriers to the timeliness and cost effectiveness of such projects [46].

Negative Public and Expert Perception: Overall, the concept of modular construction is viewed negatively by the public and even some of the construction experts [51]. This will have to change before it is widely used, and for this change to occur, the public will need to be made aware of its positive aspects [52].

Establishment Cost and Cost Due to Complexity*:* Even though the cost of construction is less for an off-site construction method, it requires the establishment of a fabrication plant [19]. Therefore, in areas where the labor and other requirements for traditional construction cost less than establishing a manufacturing plant for modular construction, on-site construction is more popular with the project stakeholders [51]. Modular construction requires suppliers, contractors, designers, and engineers who are experienced in and knowledgeable about prefabricated construction [4], and the lack of such experts is a considerable constraint to implementing this method [19]. Since many financial documents cannot be accessed, some researchers have expressed doubts about the positive impact of modularization on the cost of the construction projects [53]. For example, Kamali and Hewage [10] espoused that since modular construction is a relatively new and complex construction method, a wide range of studies need to be conducted to determine the costs. In addition, the modularization process needs to be monitored appropriately to correlate the timesaving factors with cost effectiveness.

Excessive Coordination Needed*:* In any construction project, establishing coordination and transitioning from one stage of construction to the next is key to completing the project on schedule and cost effectively [56,57,58,59,60,61]. Presumably, since the procedure in modular construction is different, the need for coordination will be a greater challenge [54, 55].

5. Discussion

Among the five major advantages of modular construction over traditional construction, the cost and schedule, which determine the productivity of a project [61], are interrelated. Saving time in construction activities equates to reducing the cost of the project [10]. Some aspects of these factors, however, such as the cost of materials, which is estimated to be lower than those used in traditional construction because they can be bought in bulk, independently impact modular construction [2,62,63]. Another example is the time that is required to design a modular project, which is significantly less than for traditional construction, because the designs are typically used for multiple similar projects [46, 64].

Safety is of high importance in any construction project, and data shows that modular construction is safer than traditional construction methods [65]. Much of the improved safety is due to the reduced environmental hazards in off-site manufacturing [2]. The safe and less hazardous environment also enhances productivity and the quality of the products [54].

The planning, cost estimation, scoping, and design in modular construction are different from those of traditional construction and have their own challenges and limitations that are likely to affect the whole planning process [47, 66]. In addition, the prefabricated components need special consideration when being delivered to the jobsite, which can affect the timeliness and cost effectiveness of a project [48]. In traditional construction, however, such challenges are not observed [67]. The probable extra costs incurred by using modular construction are the initial setup cost, lack of available skilled workers, and the complexity of the process [4,68]. The general disagreement about modularization [69] and the difficulties of coordinating the staff remain as impediments to this method being used more broadly. In summary, according to the studied literature on modular construction, although there have been improvements in several of the features of this technique, there are still opportunities for more [25,69].

6. Conclusion

Various aspects of modular construction technique were investigated in this study, and the positive and negative features were discussed as advantages and limitations. The major advantages discussed included project schedules, project costs, safety of the laborers, project quality and productivity, and environmental. The major limitations included project planning, transportation, public and expert acceptance, establishment cost and cost due to complexity, and coordination.

The results revealed that although modular construction has more advantages than limitations, further research is needed to mitigate or eliminate the challenges. The outputs of this study will be of benefit to project stakeholders who are trying to decide whether to use modular or traditional construction methods for their projects.

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Opportunities for Transportation Departments to Leverage Construction UAS Data

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Abstract

Unmanned Aerial Systems (UASs) are being used on infrastructure construction sites by contractors for many different applications and generate valuable data that could be potentially leveraged for Department of Transportation (DOT) applications. Representative UAS construction applications include construction progress monitoring, safety surveillance, quality assurance, documentation of work zone conditions following an incident, quantity measurement, and communication with stakeholders. The UAS data typically consists of high definition pictures and video from a standard commercial drone. Many of these constructor UAS applications directly relate to activities that are also important for DOTs such as monitoring construction activities, quality assurance, managing the safety of the work zone and construction project. This paper reviews the potential UAS applications that benefit both contractors and DOTs and presents results of a survey regarding common UAS applications.

Keywords: construction, Unmanned Aerial Systems (UAS), drone, Departments of Transportation (DOT)

1. Introduction

The construction industry utilizes UAS technology for numerous applications [1,2] and is at the forefront of expanding commercial UAS use in the private sector [3]. Data generated by these contractor led activities supports a number of DOT information requirements. The UAS applications discussed generally reflect a consumer grade UAS equipped with a high definition camera, and in some cases GPS and software processing to provide a georeferenced image. This reflects the kind of UAS commonly owned and operated by a construction firm. There are numerous new technologies being employed and developed for more sophisticated kinds of inspection, including LiDAR and FLIR (e.g., thermal, night vision and infrared) technology. These technologies provide even more detail of the structure and may be able to identify cracks, deformations, and delamination in structures [4]. While these technologies are starting to be used on infrastructure, the major focus of this paper is to identify how UAS images and videos captured during the construction process can be utilized by DOTs.

2. UAS applications for road and bridge construction

A literature review of UAS applications for road and bridge construction was undertaken to identify some of the most common applications based on commercial, off the shelf UAS equipment with imagery capabilities. The identified applications were used as the basis for a survey of road and bridge contractors and consultants. The construction applications identified are reviewed in the context of how a DOT could utilize the data to help achieve complementary objectives. For example, if a construction firm is utilizing UAS for progress photos of their job site, this imagery be useful for inventory analysis of DOT assets in the area such as signs, lighting, guardrails and drainage systems. The UAS applications for road and bridge construction are listed in Table 1. This section provides a summary of each application and identifies related potential opportunities for DOT opportunities.

Table 3. UAS Applications for Road and Bridge Construction Projects

Monitor construction progress and/or site inspection
Evaluate work zone to ensure safety of motorists and workers
Document work zone after incident or accident
Create imagery and 3D models for construction documentation and as-built information
Estimate stockpile and excavation quantity
Perform material tracking
Support construction site logistics planning
Support surveying operations
Support communications, marketing, public information and public relations

2.1. Monitor construction progress and/or site inspection

Construction Application. An early application of UAS in the construction industry was to provide documentation of the progress on a construction site. Barfuss et al.[5] reported the Utah DOT used imagery from a UAS on a parkway project to observe the construction progress, cut and fill regions (no measurements), and record the phases of construction. A survey by Irizarry [6] identified monitoring construction project progress was one of the most useful tasks for UAS. Generating weekly aerial maps of the construction site can reduce the time spent by construction personnel having to walk the site and provide a visual record of the project [7].

DOT Opportunity. These high definition images provide the constructor with information about construction progress, and can also be used by the DOT to monitor the progress of the construction project and serve as a record of work completed. The aerial imagery from UAS also provides a way to inspect construction activities in areas that are difficult to get to and/or are potentially unsafe [6]. For example, temporary erosion control and sediment control can be monitored via UAS to ensure effectiveness [8,9,10].

2.2. Evaluate work zone to ensure safety of motorists and workers

Construction Application. Evaluating the safety of a construction site through UAS imagery has been noted by numerous studies as an effective way to help improve worker safety on the worksite [7,6]. UAS images allow a safety manager to review large portions of the construction site quickly and safely and effectively evaluate the work zone to ensure workers are safe from the travelling public. The contractor can also use the images to ensure the work zone is accurately set-up, which ensures motorist safety and reduces liability. The resulting images can be used to communicate potential issues related to the work zone set-up.

DOT Opportunity. Worker safety is a concern for all stakeholders on a construction project. An accident on a construction site or in a work zone can cause many issues for all stakeholders and the project. In addition to the direct impacts of injuries and property damage, there are impacts due to lost time, project delays, reduced worker productivity, and administrative time for reporting and investigation. DOT benefits from new technologies that help support worker safety and from timely information on the work zone configuration. Drones provide imagery that can be used to identify adjustments that need to be made to correct a potentially dangerous work zone configuration and/or to ensure better traffic flow; as well as to document the improvements. This opportunity has been well established, and we documented a decade ago by [11] in an early feasibility study using drones to monitor work zones with drones.

2.3. Document work zone after incident or accident

Construction Application. Mapping crash scenes with UAS has been increasingly used by law enforcement at both the state and local level. Using UAS to document the crash scene (or site of the incident or accident) is faster than conventional methods, and allows the accident to be cleared quickly, which helps prevent secondary accidents [12]. While most of the focus has been on law enforcement requirements related to this function, contractors and DOTs also may benefit from the data obtained by a UAS at the crash scene [13,14]. Benefits include accurate documentation of the crash scene which is useful for insurance claims, criminal investigations, assessment of work zone configuration, review of traffic operations, and infrastructure condition such as the resulting damage to guardrail or bridge components [12]. Contractors may become involved in litigation related to the work zone incident or accident and UAS information may be helpful to provide an accurate representation of the construction site at the time.

DOT Opportunity: The data from a crash scene is useful for the construction contractor, and also may be useful for DOTs to improve work zone safety. The images and video may be used to evaluate why the incident occurred, and provide information to improve work zone design as well as train DOT employees in work zone design and set-up. Imagery of a crash scene or incident scene support future road safety improvements and can also support activities during litigation for all stakeholders, including DOTs. As noted by Rogers [15], video is often helpful in a legal setting to describe the incident. UAS imagery provides a much more robust context for incident or accident conditions, as compared to traditional accident reports.

2.4. Create imagery and 3D models for construction documentation and as-built information

Construction Application. An accurate 3D model representation of an infrastructure construction project once it is completed provides information for future repair, reconstruction and inspection. 3D models of the constructed facility can also be compared to the original design to assure construction accuracy [8]. These 3D models are based on data collected with UAS and photogrammetry software processing programs and may replace or be used as a backup to traditional drawings and specifications.

DOT Opportunity. There are numerous DOT benefits from 3D models that extend beyond the construction phase. The georeferenced images can serve as supplemental as-built information and provide a record of infrastructure condition. Cataloging images over a period of time provides DOTs with information that may be useful for warranty issues, for illustrating best practices, and for the provision of historic information that may be useful to improve future construction and maintenance practices for road and bridge systems.

2.*5. Estimate stockpile and excavation quantity*

Construction Application. The management of stockpiled material such as aggregate, and soil is important in the construction process to keep the project on schedule, and support material management, accounting and billing. Similarly, documentation of excavation and material movement during construction provides information regarding construction progress and is important for project documentation and payments. The volume of material and the excavation of material can be determined using UAS imagery and processing with photogrammetry software that generates a 3D model from 2D photos [16]. Accuracies are within approximately +/- 3% [16,17]. If more accurate measurements are needed, more sophisticated systems can be used (e.g., higher resolution cameras with more sophisticated use of base stations for calibration and/or LiDAR).

DOT Opportunity. Accurate information about current material quantities volumes and current status of excavation and earth moving are important for the construction contractor and also support DOT progress assessment, as well as payment and accounting. As noted by McGuire et al., [13] "Close inventory inspection of stockpiles ensures that the supplier provides the correct amount, avoids stock-outs of material, and proper moisture amounts for road construction."

2.6. Perform material tracking

Construction Application. The ability to quickly locate required materials on a construction site is important for inventory management and job site productivity. Inventory management may utilize material identification using photographs, barcodes, or Radio Frequency Identification (RFID) technology [18,19]. Commercial systems manage inventory with material tracking that may utilize UAS or vehicle based systems. Material management and tracking supports the contractor by providing timely and accurate information regarding materials that are currently in the inventory and ready for placement, as well as materials that are expected but have not yet arrived on the job site. Utilizing advanced technologies such as UAS for material tracking also reduces loss from theft and supports site security measures [20].

DOT Opportunity. Improved material management and inventory control benefits DOTs by supporting on-site efficiency, reducing costs and reducing delays, resulting in shorter construction times. The imagery provides a good record of inventory in case there are questions or disputes during and after construction. DOTs may also find it useful to use this kind of system to track materials for maintenance and operations at the district level (e.g., salt, sand and gravel), ensuring that the appropriate material is available when needed, and ensuring that the quantity delivered is timed and billed appropriately.

2.7. Support construction site logistics planning

Construction Application. UAS can support job site logistics and logistics planning on for construction [6]. During the pre-construction planning phase, UAS can provide detailed site information to facilitate a detailed logistics plan that is tailored to the job site, including the location of material laydown, equipment location, construction site access, construction office location and parking. During the construction process, aerial images can provide information to support evaluation of material flow and worker productivity, as well as identify potential construction issues [18]. All these logistic related activities support a more efficient and safer worksite, which benefits both the contractor and the DOT.

DOT Opportunity. The imagery provided in the preconstruction and mobilization phase of a construction project will also support DOT activities, such as examination and documentation of existing conditions, inspection and confirmation of the traffic control plan, and locations and effectiveness of environmental controls such as silt fences [13]. The imagery can also be used to identify potential assets (e.g. drainage structures, traffic signs, and guardrails) that may be affected by construction; these assets may need to be moved, modified, and/or protected during the construction project and the UAS imagery can help identify as well as provide a robust context prior to construction mobilization.

2.8. Support surveying activities

Construction Application. The capability of UAS to produce low cost survey maps is improving and has been aided by technology such as Global Navigation Satellite System (GNSS) Real-Time Kinematics (RTK), which enhances the precision of position data [21]. While surveying may still require high-accuracy data that can be provided by more traditional survey techniques, there are numerous surveying functions, such as progress monitoring, that may use lower accuracy photogrammetry methods that leverage UAS mounted cameras. Some advantages of lower accuracy photogrammetry UAS methods include lower cost and the ability to collect data in remote or hard to access locations [22]. The reduction of survey crews on-site during construction operations reduces the exposure of survey crews to construction hazards and improves construction site safety [22].

DOT Opportunity. Inadequate progress monitoring may contribute to poor performance in transportation construction [22]. This can be addressed by enhanced monitoring, including the collection of UAS data to document work in-progress and work completed; this documentation also supports payments and payment schedules. Work progress can also be important when communicating with the public regarding construction schedules, closures, and work zone changes, as discussed in the next section.

2.9. Support communications, marketing, public information and Public Relations

Construction Application. UAS photos and video can be shared with internal and external stakeholders (Dronedeploy, 2018) to support communications, marketing, and public relations. UAS aerial imagery provides the construction team with visual data that is easy to interpret. Construction contractors share UAS imagery with numerous stakeholders including current and potential clients, as well as subcontractors.

DOT Opportunity. DOTs can also use UAS photos and video to support communications, public information and public relations. UAS photos and video can be posted on social media and DOT websites, and shared with the media. UAS imagery shared with the public may be useful to provide an overview of the project and project progress [7]. Imagery of the construction site also supports information about road detours and work zones, which may increase motorist safety. Some DOT divisions and districts have already used UAS images and videos for public information and public relations.

3. Results of survey of construction professionals

An online survey of construction professionals was used to provide a better understanding of how UAS are being used on road and bridge construction projects. All responses were anonymous. The survey was distributed using a DOT construction listserv, which includes construction professionals who work for a DOT, as well as constructors and consultants in the private sector who do construction work under contract with a DOT. An objective of the survey was to identify how UAS are currently being used by contractors. Table 2 provides a ranked list of the applications currently performed by contractors from the survey. The most common application for construction projects is imagery for communications and marketing. Other popular application include estimating stockpile quantity (ranked 2nd) and imagery for as-built information and general construction documentation (ranked 3rd).

Table 2. Survey of UAS Applications

Rank	Application (number of respondents using this application)
1	Use imagery for communications and marketing (58)
2	Estimate stockpile quantity (39)
3	Create imagery and 3D models to provide as-built information and construction documentation (38)
4	Monitor construction progress and/or site inspection (for example, silt fences) (37)
5	Support surveying operations (37)
6	Estimate excavation quantity (33)
7	Support construction site logistics planning (23)
8	Evaluate safety of construction site for workers (15)
9	Perform material tracking (15)
10	Document work zone after an incident or accident (10)
11	Evaluate safety of work zone for motorists (8)
12	Use for security monitoring (4)

Based on the survey results, UAS are widely used in construction and are using UAS imagery for communications and marketing, as well as more specialized applications such as 3D models to estimate quantities and provide as-built information. As technology advances, the use of this UAS data for payments and to confirm milestones will become more prevalent.

Responses to survey questions illustrate that many contractors have provided clients with UAS data on past projects and would be willing to provide clients data in the future. Considering past projects, 60% have provided clients with UAS data when requested (44%) or if specified in the contract (16%); 19% have provided clients with all UAS data during the project. About a fifth (21%) indicated that they never provide UAS data to their client on past projects.

Concerning contractors and consultants willingness to provide UAS data in the future, the majority (57%) indicated that they would provide the data if it is required in the contract. A large percentage (40%) indicated they would provide the data if they are collecting the data anyway. Only 3% indicated they would not be willing to provide data. Keep in mind that some contractors may not use UAS, and depending on their area of expertise, it may be uncommon to utilize UAS. In the comments to this question, some respondents expressed concerns about liability issues. There were also concerns regarding the contractor’s burden and risk if UAS data is included as a contract deliverables.

Based on the survey results, UAS is widely used in construction, and there is interest in an expanded use in the future. The majority of constructors have their own equipment and are using UAS imagery for communications and marketing, as well as more specialized applications such as 3D models to estimate quantities and provide as-built information. As technology advances, the use of this UAS data for payments and to confirm milestones will become more prevalent.

Providing a contractual mechanism for DOTs to obtain UAS images and video captured by contractors during construction is one way to quickly integrate UAS data without requiring a DOT to own or operate UAS. Many construction firms already collect this data, and it can potentially be provided to a DOT with minimal additional effort. It is important that the data requirements be clearly defined, and that adequate consideration is given to minimizing the contractor burden and risk, since standards and procedures are still being developed.

Another important consideration is development of a data management framework to ensure that the UAS data collected can be accessed and leveraged to support all DOT activities, as needed. For full benefit, UAS data provided to DOTs by contractors will need to be in a consistent format and stored so it is readily accessible for the many potential applications and users. FHWA has recognized that a standard format for data is a key issue, and hopefully a national standard will be forthcoming; even with a standard, there will still be a need for DOT to identify their own database requirements. Development of a robust database that leverages GIS capabilities will ensure that all UAS data can be leveraged and used to its full potential.

4. Conclusion

UAS are being used on construction sites by contractors for many different applications, and constructors are generating valuable data that could be potentially leveraged for DOT applications. UAS construction applications include construction progress monitoring, safety surveillance, quality assurance, documentation of work zone conditions following an incident, quantity measurement, and communication with stakeholders. The UAS data could be identified as a deliverable item in DOT construction contracts, and may include high definition pictures and video from a standard commercial UAS, as well as data such as earthwork quantities moved, or stockpile quantities associated with materials contracts. Many constructor UAS applications directly relate to activities that are important for DOT, such as monitoring construction activities, quality assurance, and managing the safety of the work zone and construction project. In addition to the construction applications that directly overlap with a DOT's mission, data from construction sites could also be utilized for other DOT applications beyond the construction phase. These applications may include roadside asset inventory (including signs and culverts), as built documentation, classification of plant species in the right-of-way, and video and images that can be used for communication with the public. The findings include the results of a survey of constructors, which indicates general willingness of constructors to provide UAS video and data as a contract deliverable.

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Reticulated Roof Structures Optimisation Based of Triangular and Quadrilateral Planar Panels

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Abstract

The search for the form optimization of reticulated roof structures is a significant aspect in Architectural Engineering and Construction section. It consists of reflecting the intended aesthetic effect as well as an attempt to choose the most suitable technical solutions. Therefore the divisions of reticulated structures should be determined to pursuit of structural, material and technique of fabrication advancement. In contemporary construction practice, understanding how curved shapes describe the form becomes an significant design aspect. Structural divisions of free-formed canopies should be solved in architectural and structural design simultaneously at an early stage of designing. The choice of proper designing method becomes a complicated process, requiring the ability to selecting type of production and rationalize technical solutions mainly due to the computer aided design supported by algorithmic tools. The paper research analyzes curvilinear structures of canopies in search of optimal structures of geometrical divisions. Case study is based on reticulated roof structures with triangular and quadrilateral panelization. In recent twenty years, the most common and accessible solutions for free-form canopies are triangular divisions due to the ability to use flat glass panels. Panelized Quadrilateral surfaces, facilitate the fabrication process in many aspects, surpassing triangular panels. Their main disadvantage was the design of quadrilateral flat panel mesh. The finding of the study conclude assets and flows of both methods of shaping the geometry of reticulated roof structures based on material and technology of fabrication aspects. The study conclude that the crucial designing method is to determine the manufacturing technology in the early stage of architectural optimization.

Keywords: creative designing, generative designing, grid canopies, structural optimization, topology optimization

1. Introduction

In the 21st century, a change in the way of designing in Architectural, Engineering and Construction sector is noticeable. Sustainable Development adopted by the United Nations Assembly, influences on construction development mainly in natural resources usage without destroying natural ecosystems. It results in the implementation of optimisation methods and tools into designing, construction and exploitation phase of buildings life. It is visible in supervising of the entire production process, from BIM environment designing, through controlling the construction process, construction productivity, optimizing the material and shape with unprecedented precision [1]. The process resembles the designing approach of the medieval craftsman [2]. The dynamically progressing digitization is now "filtering" the design techniques and methods associated with structures optimisation. It is commonly used for Architectural Design Optimisation (ADO) [3]. Increased use of parametric design and simulation of building parameters enables optimization of, among other, material, costs, and time, for construction and subsequent maintenance, reducing the carbon footprint. In design practice, however, architects and structural designers still encounter significant difficulties in using algorithmic designing by: "insufficient knowledge of optimization based on multi-variant simulations, use of inefficient optimization methods based on genetic algorithms, lack of modern, easy-to-use optimization tools and lack of integration of optimization into architectural design." [4].

Computer based methods of digital modeling in designing free geometries structures improve not only the aesthetic quality but also the efficient use of materials [5]. It provides new possibilities in a creative search for "eco-efficient" architectural forms and technical solutions. Thanks to the availability of advanced, generative techniques as well as engineering methods, achievements in structural optimisation have remarkable outputs. Designers, thanks to computer aided design, can mimic forms found inspired by nature nature[6]. This trend in architecture, called biomimetic, can be used on different designing levels, from imitating the patterns found in nature to understanding natural ecosystems behaviour and implementing them into the building scheme. The design process is already at the concept stage dictated by the fabrication method. The development of free-form architectural designs has intensified the development of technologies which can shape the form differently. An essential issue in the problems undertaken by designers is: (1)the use of digital tools, with the use of biomimetics and mathematical algorithms, in search of optimal shapes and behavioural systems; (2) ways of fabrication of building elements, adjusted with appropriate selection of shape and preparation of elements for easy assembly; (3) search for the minimization of energy required to fabrication, the use of environmentally friendly materials, or the least amount of environmental degradation (including carbon footprint).

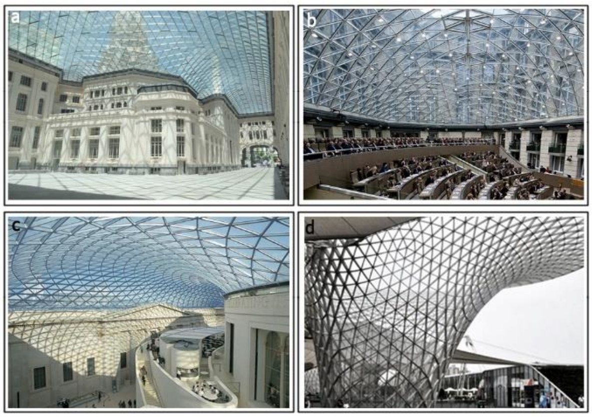
2. Background

Mathematical algorithms based on proportionality requirements analyse various variant solutions in order to find the optimal free-form geometry. It is thought-provoking particularly for prefabrication which nowadays is increasingly characterized by the idea of postfordism [7]. Striving for unification does not exclude the creative search for individual solutions. The use of the computational capacity of computers has made it possible to test many concepts based on many factors optimisation, especially designed with the use of laws of nature. Learning those rules has become the basis for formal experiments. These, in turn, form the basis for the designers [8]. Current research on structures with free shapes is the result of inspiration from natural forms found in nature. Biomimetic inspiration and the search for algorithms that describe its principles seem to be justified by fact that the processes governing living organisms are a matter of survival [9]. It is visible in the architectural realizations of famous architectural studios all over the world. This paper raises two main courses of the free-formed canopy panels shaping: using triangular panels (Fig. 1.) and quadrilateral panels (Fig. 2).

3. Literature review

Grid-shell geometry named also as retirculated surface structure is an attempt to perform simplified computational models of curvilinear structures [5]. They are the result of numerical methods of dynamic relaxation used in form-finding [10], alongside such optimisation methods as the force density method [11], particle spring system [12] or reference strategy [13]. The principle of form-finding can be illustrated as a process of shaping structures, with an assumed load, as physical models made by A. Gaudi or F. Otto in previous century. It is: "finding an (optimal) shape of a (form-active structure) that is in (or approximates) a state of static equilibrium" [14]. In designing free-form canopies, which are mostly doubly-curved structures, there must be a compromise between aesthetics and technology [15]. Planar glass panels filling the structural grid to achieve material savings become a technological requirement. The aesthetic requirement, on the other hand, is smoothness of the surface division (possibly without sharp edges) [16].

While analyzing the research literature, some factors of material minimization and affordability of fabrication process were found. Examples of comparison of freeform grid-shell structures with triangular and quadrilateral panels are presented in Table 1. The three most important factors influencing the selection of panels with quadrilateral or triangular geometry are distinguished: design method, the technology of execution, and architectural quality. The presented conclusions were made based on the analysis of research works from recent years[17,5,15,18].



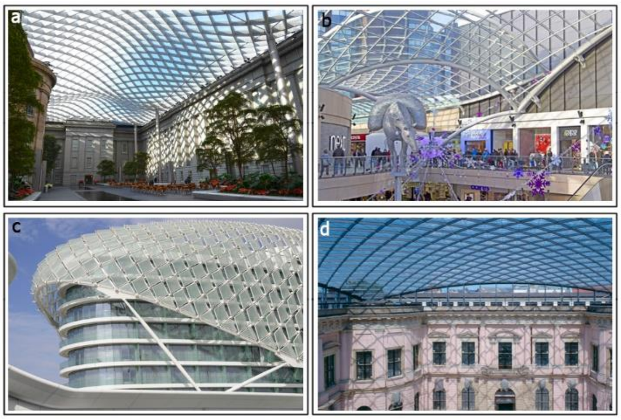


Fig. 1. (left)Free-form grid-shell canopy with mesh triangular panelization: (a)Matrid City Hall; (b) Meeting Hall Flemish Council in Belgium; (c) British Museum of Art; (d) Shanghai EXPO pavilion; Fig. 2.(right)Free-form grid-shell canopy with mesh rectangular panelization: (a) Kogod Courtyard w Smithnonian; (b) Trinity w Leed mall centre; (c) Yas Island Hotel in Abu Dhabi; (dGerman Historical Museum in Berlin

Table 1. A comparison of characteristics of free-form canopies in triangular and quadrilateral panels.

	Triangular Panels	Rectangular panels
Design method	+ easy subdivision of double-curved geometries into any flat triangular panels	- difficulty in developing flat-panel geometries on a quadrangle: when developing quadrilateral double-sided panels, further technological problems arise, such as thermal deformability; in the case of developing flat panels, designers often had to compensate for problems in achieving the correct curvature in the outer part of the cover (e.g., Courtyard Coord at Smithsonian)
the technology of execution	-difficulty in making joints in which six bars merge at different angles -more waste glass than in quadrilateral panels	+ ease of fabrication of joints where only 4 rods merge + minimizing the amount of waste of covering material of rectangular panels (comparing to triangular ones)
architectural quality	- a larger ratio of the surface area of the rod structural elements in comparison to the quadrilateral grids, which is equivalent to less translucency	- higher translucency and interior illumination thanks to a smaller ratio of structural elements is a covering material.

4. Research methodology

The selected models represented the construction of pavilion canopy. The area of each geometry is 900m^2. The paper compares the structures designed as free-forms curvilinear geometries using the Delaunay triangulation, regular triangle and quadrilateral divisions. The geometries with Delaunay triangulation divisions we optimised at first, because of random selections of nodes and bars lenght without designers interfere. The resultant geometry with the lowest total weight of the structure was the basis for subsequent more in-depth studies. A case study of reticulated structure with regular: triangular and quadrilateral divisions comparison was conducted, based on the parameters from initial Delaunay triangulation analysis: the total length of all bar, same length of single bars and number of joints.

In the geometry generating process of bar meshes, geometry and material optimisation softwares were used. Grasshopper /Rhinoceros was used in form-finding method, to create a catenary model and dynamic relaxation (Kangaroo2 and Karamba plug-ins was used to imitate physical forces and adjustment of the structure curvature and initial material optimization. Structural optimization was performed in Robot Structural Analysis. Thanks to adopting generative tools geometries are considered to distribute loads in the structures more efficiently than mathematically determined shapes such as parabola. The differences between the two curves are almost invisible to notice, but allow a significant optimization of material applying. Such research were noticeable in A. Gaudi's research(Fig. 3). The purpose of this numerical method is to find a geometry in which all forces are in equilibrium, allowing the minimum area (length) of the structure to be found.In the structures under study, the use of dynamic relaxation allows for significant minimization of materials e, which is visible in earlier studies of curvilinear structures [19].

Two-stage analyses of various grid canopy geometries were carried out: **Study 1**- analysis of the structural mesh based on Delaunay triangulation, (the analysed geometries were previously developed within the author's research); **Study 2**- comparative study of topological changes of the grid-shell on triangular and quadrilateral regular division, according to the guidelines parameters from Study 1.

5. Results and findings

5.1. Study I- reticulated structure optimisiation basing on mesh Delaunay tiangular divisions

Table 2. Results of Study I- analyzed Delaunay mesh grid-shell

Variant	The curvature height to the support span ratio	Adapted profile (type and dimensions in mm)	Maximum deformation [cm]	Total length of the rods [m]	Total weight [kg]
A	1/5	TRON 139x5,0	6,2	1376,14	22 865
B	1/4	TRON 139x4,0	6,6	1390,69	18 623
C	1/3	TRON 139x4,0	5,9	1420,48	19 022

A comparison of freeform structure systems showed that the average total mass decreased as the total height of the srtucture increases. The average total weight of the structures was 20 170 kg. The most optimal variant (with the lowest total weight) was *Variant B*. The total weight of this arrangement is 18,623 kg (with the roofing area of 963.41 m²).

Study I- summary, the following parameters were observed while analyzing the optimal variant B:

- **Finding 1:** The average total length of all members was 1395.77 m;
- **Finding 2:** the length of the members did not exceed 5.0 m;
- **Finding 3**: the sum of all nodes was 203.

5.2. Study II- reticulated structure optimization basing on regular quadrilateral and triangular divisions

Study II aimed to identify the most beneficial divisions of quadrilateral and regular triangular meshes, shaped according to the weight minimization and fabrocation process. Geometries were generated basing of conclusions of Study I.

Case study of the second phase consists of 18 covering structures, divided into three groups according to the total length of all bars, a single bar length of about 5 m and a total of all nodes of around 203. The resulting geometries (Fig.3-4.) show a significant difference in the density of the mesh. Also, the smoothness of the canopy varies between the geometries.

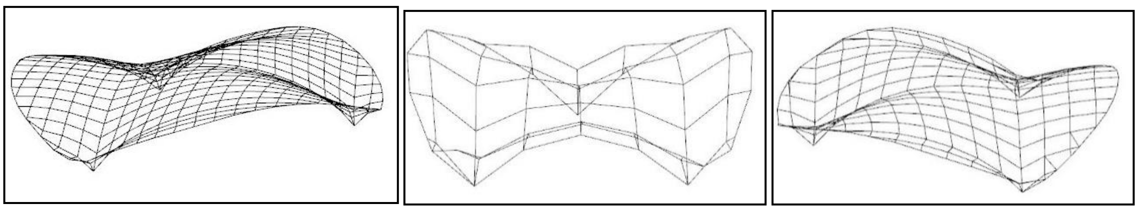


Fig. 3. PQ geometries generated according Findings: (a) fixed total length in the grid-shell~1390 m; (b) fixed length of each bar~5 m; (c) fixed number of joints

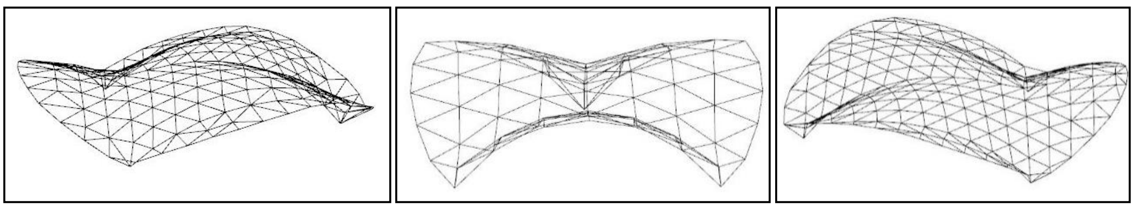


Fig. 4. Triangular panels geometries generated according Finding: (a) fixed total length in the grid-shell~1390 m; (b) fixed length of each bar~5 m; (c) fixed number of joints

Table 3. Results of Study II- analysis of regular rectangular and triangular meshes of the canopy

The curvature height to the support span ratio	Finding 1- fixed total length in the grid-shell~1390 m				Finding 2- fixed length of each bar~5 m				Finding 3-fixed number of joints			
	Planar quadrilateral grid		Triangular grid		Planar quadrilateral grid		Triangular grid		Planar quadrilateral grid		Triangular grid	
1/5	1.1.	24 684	1.4.	22 128	2.1.	26 987	2.4.	28 344	3.1.	26 952	3.4.	33 618
1/4	1.2.	18 310	1.5	22 159	2.2.	24 501	2.5.	20447	3.2.	21 983	3.5.	25 662
1/3	1.3.	16 696	1.6	22 609	2.3.	25 310	2.6.	20 398	3.3.	22 683	3.6.	23 697

6. Findings

The lowest total weight of the structure was achieved in quadrilateral panels *Variant 1.3* (with a total bar length of 1 390 m) with a total weight 16 696 kg. Among the variants with triangular divisions, Variant 2.6, with a total weight of 20,398 kg, was the most lightweight. The difference in best quadrilateral and triangular variants was almost 4 tons. However, triangular panelled reticulated structures are still more frequently chosen structures. It is due to technological difficulties from the design stage to the execution stage.

The technology of making PQ structures is more demanding in terms of technology and design than that triangular panels (for which finding a plane passing through all three points is remarkably easy). It is visible in the canopy structure of Kogod Courtyard, where a smooth surface of the roofing was obtained only from the inside of the courtyard, while on the outer side had a significant fragmentation of the surface. Therefore, the manufacturing technology and structural design aspects are the main points in interdisciplinary generative design. Architectural Design Optimization (ADO) in the initial designing phase implement the construction methods as equally important factors as aesthetic appearance. Choosing the fabrication methods for instance if the nodes are made by traditional welding (where the minimum number of welded elements is essential) or by 3D printing (where the most crucial question is to minimize the usage of the material and printing time). As highlighted in literature analyses, it was noticed that the construction of nodes connecting only 4 rods increases the amount of sunlight inside. By comparing the best results of structures with regular quadrilateral and triangular panels, a significant reduction in weight is visible in favour of the PQ. However, comparing the number of nodes in both structures (where the nodes give the most of shadows), there is a vast difference. The quadrilateral *Variant 1.3.* has 452 nodes, while the triangular *Variant 2.6*. only 75. Many aspects, such as the number and type of manufacturing of the nodes, become a fundamental aspect of designers' work. Comparing the result of the structure with the Delaunay triangulation divisions and the best variants in the regular quadrilateral and triangular divisions showed significant differences, which may ultimately affect the choice of a particular geometry due to technological factors, rather than merely optimizing the weight of the structure. Tabel 4. presents comparison of the main differences in structural data between the best geometries in each type of mesh divisions in canopies.

Table 4. comparison of choosen factors of types of reticulated mesh divisions

factor	Delaunay Triangulation	Regular rectangular	Regular triangular
Weight [kg]	18 623	16 696	20 398
Total length [m]	1390	1390	858,57
Length of individual rods[m]	1-5	2,3	5
Number of joints	203	452	75

7. Conclusion and discussion

Thanks to new computer aided optimization tools, designers undertake attempts in creating more advanced structures, such as free-formed reticulated canopies. The choice of materials and technologies becomes the key to broadening the boundaries of the knowledge and perception skills. The new possibilities of computational design, change multidisciplinary environment. In the case of designing a usage of relatively simple tools benefits in in-depth optimisation process. Obtaining efficient structural divisions of grids becomes an interdisciplinary task to be solved in architectural-constructional and manufacturing aspect. The selection of the manufacturing techniques influences on the process of designing. The ability to implant the type of the production and connected with it cost optimisation, become a crucial factor in choosing specific technical solutions in the construction phase. Searching for aesthetic effects and waste reduction can be attained due to the algorithmization of design tools. Due to multiple boundary conditions, which vary in each designing process there is never one best solution for all the designing and construction obstacles. The algorithmic design allows to correct assumptions: "this also includes the usefulness of the algorithm as a tool to verify design concepts and the talent of their creators." [20]. The author intended that the ideas presented in this work encourage further investigation in the field.

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A Broader View of Risk Management Process in Projects

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Abstract

Risks have to be managed with great care so that the final goal of delivering a successful project can be reached. The paper extends the risk management process with the value-based risk monitoring framework developed by the authors, where the primary purpose is to detect and monitor risks jeopardizing the expected project return, and if necessary, to start action plans in order to avoid losses. An important characteristic of the suggested integrated model is that it takes into consideration that risks are time-varying, that is, as time passes, the uncertainty of the occurrence of a risk changes. In this paper, the traditional risk management process is extended with the value-based approach, where risk factors are measured on a linear scale. The integrated project risk management process supports the organization-level decision making, and extends the fundamental roles of project portfolio management office identified by the literature.

Keywords: integrated methods, project risk management, risk management process

1. Introduction

Project risk management is about controlling unexpected issues that might affect the level of activities in the project, or the whole project itself. Project risk management became one of the most important aspects of project management so much so that significant international organizations issued standards on it (e.g., [1]). Risk management is one of the ten competency areas in the PMI's PMBoK (Project Management Institute's Guide to the Project Management Body of Knowledge). Project risk is defined by the PMI's risk management standard as, "an uncertain event or condition that, if it occurs, has a positive or negative effect on a project's objectives." [1]

Risks have an inherent uncertainty, their occurrence is not predestined, so they have to be managed with great care. The ultimate goal of project risk management is to achieve project success. There are several issues of project success [2] that are not subject to investigation in this study. To achieve this goal, the risk management process has to serve the optimization of risks. The optimization process is responsible for balancing the probabilities and both the positive and negative impacts of risks. According to the PMBoK, a well balanced portfolio of risk requires the following steps: Planning Risk Management, Identifying Risks, Qualitative Risk Analysis, Quantitative Risk Analysis, Planning Risk Responses, Implementing Risk Responses, and Monitoring Risks [3].

The current study focuses on integrating risk management into a common risk management process. There are three principles of the proposed risk management framework. On the one hand, the suggested model takes into account the minimum requirements of the owner. On the other hand, the model has to be able to operate and perform evaluation in the whole life cycle of the project, not only in the first, risk management phase. Furthermore, it is important that the evaluation process can be conducted easily in practice without solid financial knowledge.

Firstly, there is a brief survey on the traditional, category-based literature. Secondly, after this review of the traditional project risk management approaches, the process is presented with suggestions for the extension. In this section, there are recommendations how to integrate the traditional process with the value-based model. Finally, the fundamentals of the developed model are summarized.

2. Traditional project risk management concepts

The prevailing concept of risk management is about risk classification. The traditional risk management methods are widely presented in the literature [4], [5], moreover, there are numerous industrial applications [6]–[8]. The general purpose of comprehensive project risk management is to mitigate the risks with categorization [9], [10]. Project risk management has been an area targeted by researchers from the 1950's. In the last decades, subjective elements of risks have gained more and more attention [11], [12]. Obviously, the objective, quantitative side of project risk management still remained the most intensively researched area. Derived from the traditional risk classification concept, mathematical models, such as various probabilistic (e.g., [13]–[15]), and deterministic approaches (e.g., [16]) the analytic hierarchy process (e.g., [17]), fuzzy approximation and composition (e.g., [18]), artificial neural networks (e.g., [19]), Bayesian networks (e.g., [20],), and Markov modelling (e.g., [21]) are developed and applied to risk assessment.

For a while, integration efforts concerning project management and other professional areas appeared, reference [22] has successfully established a relevant relationship between risk management and project management, but the time for the synthesis with other distant fields has not yet come.

The paper extends the risk management process with the value-based risk monitoring framework developed by Tóth and Sebestyén [23], where the primary purpose is to detect and monitor risks jeopardizing expected project return, and if necessary, to start action plans in order to avoid losses. An important characteristic of the suggested integrated model is that it takes into consideration that risks are time-varying, that is, as time passes, the uncertainty of the occurrence of a risk changes [24]. The traditional risk management process is extended with the value-based approach, where risk factors are measured on a linear scale.

3. Integrated project risk management concept

From a financial aspect, the goal of a project is to achieve a higher expected internal rate of return than is possible from capital market investments with similar relevant risk. Lately, it has turned out that there are other several industry-specific objectives besides the financial ones, and these can be even more important [25].

To introduce a new approach to traditional category-based risk management from the area of the theory of finance, the harmful events must be identified. These harmful events are the financial bottlenecks, and have a negative impact on the project. On the one hand, the organization must be liquid, and has to maintain a positive cash flow (L_t) in each year (t). (1)

$$L_t = g(x_{1,t},\ldots,x_{n,t},\ldots,x_{N,t}) \geq 0 \qquad \forall t \in [0,T] \tag{1}$$

n = (1,...,N) refers to the nature of the parameter, and t = (1,...,T) refers to the given time period in years. On the other hand, the debt service coverage ratio ($DSCR_t$) cannot decrease below the value (C_t) that is specified by the loan contract in each year. (2)

$$DSCR_t = v(x_{1,t},\ldots x_{n,t},\ldots,x_{N,t}) \geq C_t \qquad \forall t \in [0,T] \tag{2}$$

The integrated model concentrates on one of the three typical harmful events. Firstly, the expected internal rate of return or the economic internal rate of return is less than or equal to the minimum requirements of the owners. Secondly, the yearly cash balance is negative. Thirdly, the yearly debt service coverage ratio is less than the specified value.

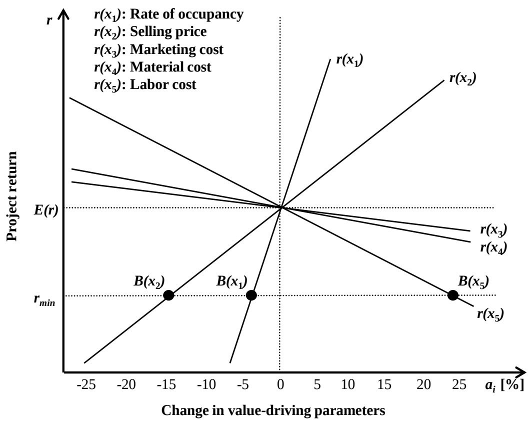

Fig. 1. Sensitivity analysis

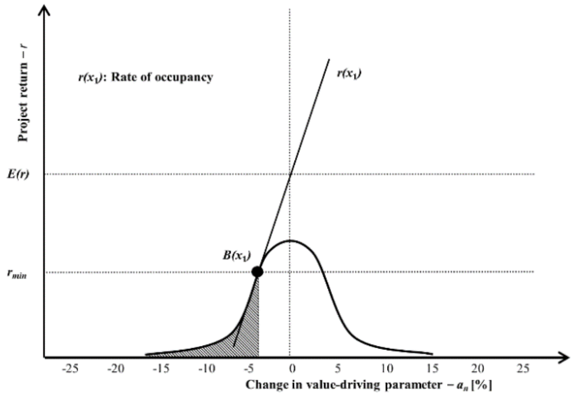

Fig. 2. Probability of the occurrence of a harmful event

In the integrated approach, risk management is based on the financial valuation of the project, and the risks are measured by the probability of the occurrence of critical deviance of the value-driving parameters from their expected values calculated in the planning phase of the project. This is the principle of the value-based financial risk management process [26]. Value-driving parameters become critical, when their deviations result in zero or negative *NPV* to the owners. The aim of risk monitoring is to follow some selected value-driving parameters and when they are in the intervention zone, launch the predefined action plans to restore the normal value-making process, and to reinitialize the business model. Risk analysis is a continuous process during the whole life cycle of the project. The value-driving parameters are in the focus of the integrated process. Value-driving parameter ($x_{n,t}$) can be any arbitrary variable that can have any effect on the financial condition of the owners of the project.

The economic break-even point ($B(x_n)$) is the critical value of each value-driving parameter that can be determined (3).

$$NPV = \sum_{t=0}^{T} \frac{s(x_{1,t}, \dots, x_{n,t}(1 + B(x_n)), \dots, x_{N,t})}{(1+r)^t} = 0 \tag{3}$$

where *r* refers to the cost of invested capital, $B(x_n)$ expresses the changes of parameter x_n that occurs evenly in every year, which makes the project's net present value equal zero. That is, a larger change in the value of x_n makes the project value-destroying.

The breakeven point $B(x_n)$ is a point of reference in the calculation of the probability that changes in parameter x_n. The question is how to find the region where the value-driving parameters are larger than $B(x_n)$. In this case, this component becomes value-destroying, and more attention should be paid by the management. In this region, the value driving parameters may be responsible for the poor performance. Based on Fig. 1 [27], the sensitivity analyses can be conducted to select the relevant value-driving parameters describing the project's total risk the best.

Based on Fig. 1, the occurrence of a harmful event can be determined. If the probability distribution function is identified properly, the probability of the value-driving parameter becoming value destroying is calculated. If the probability density function of occupancy ($f(x_1)$) is known, by integrating over minus infinity to $B(x_1)$, one can determine the probability (*P*) that the value of the value-driving variable is less than the break-even point (7). Thus, the variable deviates sufficiently in the negative direction to render the project value-destroying. Finally, retrieving the probability of becoming harmful to the project is the ultimate aim of this process. Let us assume that the random variable follows normal distribution in Fig.2. [28] The probability when changes in parameter x_n are over $B(x_n)$ is calculated by Equation (4). The project manager is interested in the probability that changes in parameter x_n are larger than $B(x_n)$.

$$P\big(-\infty < a_n \leq B(x_n)\big) = \int_{-\infty}^{B(x_n)} f(x_n) dx_n \quad (4)$$

4. Extending traditional project risk management process

Let us consider the traditional risk management process, review the basic steps, and complete the process based on the integrated concept after an evaluation.

In the PMI's standard work the integrated risk management of the projects are part of an organization's portfolio (or program) [3]. The owners and the managers of risks are at different levels and are in various clusters of projects. Certain risks are within the boundaries of the project, some others lie outside the project, but still inside the organization, and there are ones outside the organization. These risks must be identified and handled at the right level, and by the proper risk owner. The point in managing projects in an integrated way is to gain the highest value for a level of risk exposure, that is, the positive effects of risks should exceed the negative ones. Here it must be emphasized that the risk owner is not the owner of the project, and they have different interpretations. In our suggestion, the owner has as special a role in project risk management as in the theory of finance. Therefore, in the integrated concept, the extensions of the risk management process are based on the owner itself.

4.1. Plan Risk Management

In the Plan Risk Management phase, the risk management method must be selected along with the risk itself, and how important it is to the stakeholders and participants. All the subsidiary risk plans must conform to the global project risk management plan. The degree, the type, and the visibility of risk management are defined by the scope of the process and who are involved in it. The planning process is affected by the integrated risk model. New types of risk assessment points must be scheduled, which will be part of the risk management plan. As the PMI (2017) states, the risk appetite of stakeholders including the owner is recorded in the risk management plan [3]. The appetite for risk is quantifiable and measurable. The integrated model is in line with this condition.

4.2. Identify risks

In the phase of Identify Risks, all the individual and global risks are identified and documented. The organization reveals the sources of overall project risks. The identification process is a continuous activity during the whole life cycle of the project. All project stakeholders are encouraged to introduce new individual or global risk sources into the risk management process. The PMI (2017) highlights project manager, project team members, project risk specialist, customers, external experts from application area, end user, operations managers, stakeholders, risk management experts as relevant stakeholders [3]. There is no doubt that these participants have an important role in project risk management, yet the owner's significance is not outlined, as the integrated model is based on the owner's risk appetite via its minimum requirement. The risk register, which contains a list of risks with their size and complexity, differentiates the causes and effects of risks. To list the risk in the register ensuing from the owner's risk appetite is recommended.

4.3. Perform Qualitative Risk Analysis

The phase Perform Qualitative Risk Analysis is responsible for ranking project risks. The ranking process can be conducted in many ways, organizations even possess their own special methods, but all the methods are built on the assessment of probability of occurrence and the impact on the project. There is no difference between the principles of qualitative and quantitative methods in this sense. This process has to rank the risks by weighting the impacts with the probabilities using soft methods. One of the most important step of this process is risk categorization. Recently, widely used project risk management methods apply risk categories to identify the most important risk sources. Categorization can be conducted in several ways, finding common characteristics or root causes. Once a group of risks with the highest exposure is identified, greater attention can be paid to it. The Probability and impact matrix, and the Hierarchical charts are typical category-based tools for risk management. The Probability and impact matrix can be created for each objective. The matrix helps graphically to categorize the risks into groups in the dimensions of probability of occurrence and impact. If the categorization is conducted by three dimensions, the two dimensional matrix is insufficient. Hierarchical charts display risks in two dimensions by the two axes, but the size of a graphical figure (usually disks, bubbles) represents a third dimension (e.g., acceptance level).

4.4. Perform Quantitative Risk Analysis

The multi-dimensional concept of qualitative risk analysis underlies the phase Perform Quantitative Risk Analysis. On the one hand, this phase is optional, on the other hand, the analysis is numerical here. Quantitative risk analysis enables a reliable evaluation of risks. Frequently, the quantitative process is required by decision-maker stakeholders. The prerequisite of this assessment is the availability of relevant, quantifiable ratio scale data. A fundamental question in this phase is how to analyze the collected data. The analysis is usually based on simulation that determines the effects of risks, sensitivity analysis, or decision tree analysis. In a special sense, the integrated risk assessment method is in accordance with the phase of qualitative risk analysis. Therefore, the integrated risk management process must be conducted in this phase. The categorization of risks is a typical step for performing quantitative or qualitative risk analysis. Let us refer to two up-to-date cases of how researchers established a sophisticated risk management model with risk categories.

4.5. Final phases

In the phase Plan Risk Responses, to address project risks, activities for the plan and documents had to be defined. The responses include reviewing options, choosing strategies, and triggering actions. Properly selected responses are responsible for exploiting opportunities, and reducing threats stemming from risks. The project team including project manager selects the sufficiently important project risks, and gives the appropriate response. The appropriate response can be selected from a set of strategies. It is important to understand what the effects of the risk in question can be. If there are threatening effects, the project manager can escalate, avoid, transfer, mitigate, or accept it. If there are opportunities, very similar tools are to be employed: escalate, exploit, share, enhance, and accept. The last two steps are the phases of Implementing Risk Responses and Monitoring Risks.

5. Conclusion

To deliver successful projects, project risk management seems inevitable. The paper introduces the concept of an integrated project risk management process that takes an unusual aspect into consideration. The fundamentals of the model are introduced and presented. This study extends the risk management process, describes what the phases of the project risk management process are, and how to conclude the assessment with the value-based risk monitoring framework developed by the authors. In this paper, the traditional risk management process is extended with the value-based approach, where risk factors are measured on a linear scale. The suggested model handles the time-varying feature of risks as well, namely, the uncertainty of the occurrence of a risk changes as time passes.

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A Theoretical Assessment of the Impacts of Poor Risk Management in the Construction Industry - A Case of Ethiopia

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Abstract

The study examines previous literature on the impacts of poor risk management in construction industry, with specific aim of identifying the causes of poor implementation of risk management in construction projects. This is because the concept of risk management has attracted much attention in recent years and that researchers and research bodies, be it corporate or government that try to formulate remedies to poor risk management should begin with an understanding of the causes and impact of poor risk management. The totality of risk management in construction industries include the identification, measurement and prevention of all likelihoods of negative outcomes. The study is conducted with reference to existing theoretical literature, published and unpublished research. The study is mainly a literature review/survey on the cause and effects of poor risk management. One of the primary findings emanating from the study reveals that empirical studies have identified several important factors which causes poor risk management; such as project delays, project failure, reputational damages, and loss of profit, material scarcity, and inadequate project accountability amongst others. The study explores the causes and effects of poor risk management in construction projects and presents a robust background on the theories of poor risk management. This study will enable contractors, stakeholders and construction risk managers to achieve better result and quality projects.

Keywords: construction industry, construction projects, risk management

1. Introduction

Impacts of poor risk management in construction projects represents an important topic to study, some of the contracts or projects such as the construction of roads, hospitals, recreational facilities and schools are intended to improve the overall quality of life of the population residing in the jurisdiction of a particular municipality. However, with poor risk management to mitigate risks such as fraud, corruption and poor selection of competent service providers, most of the projects have either delayed or have completely failed [1]. In the period of progressive globalization, it's difficult to avoid risk, which has become an essential a part of daily life. Risk exist everyplace, in each aspect of our life. Effective risk management doesn't mean the removal of risk, which might apparently be the most cost-effective possibility [2].

1.1. Overview of construction industry

The Construction industry is multipart in nature since it calls for technology that is different, a fair color of the projects; a higher amount of organizational complexity, and various parties (client, permitting agency, Insurance, Bank, Supplier, consultant, contractor, and public). It's a significant role in the economic development of one society. Because it opens a chance for the massive employments to develop a marketplace for construction inputs providers as well as the services of its and the services delivered are feedback for various other sectors. As a result of the overwhelming investment of its, it is viewed as an economic uplifting of a nation. which is the reason why developing countries also invest in infrastructure development to improve their infrastructure status that's utilized to participate in the globalized world [3]. The construction industry plays a tremendous role in the economic system of developing countries. For instance, in several developing nations, significant construction pursuits account for approximately eighty percent of the entire capital assets, ten percent of the GDP of theirs, as well as over fifty percent of the money invested in fixed assets. Additionally, the Industry gives heavy employment opportunity and contribute considerable role to the economy of developing countries next to agriculture [4].

1.2. Risk management in construction projects

Construction projects contains numerous types of risks, including natural risks with climate systems (hurricane, typhoon, flood, etc.) along with geological methods (earthquake, volcanic eruption, geotechnical issues) along with human risks associated with a political, economic, financial, legal, well-being, managerial, complex, cultural and social dynamics [5]. Construction projects are extremely susceptible to risk due to higher spending, advanced interfaces, a range of stakeholders, integration of technologies, and materials, along with stringent timeframes. These problems are starting to be more and more complicated in the contemporary construction industry and related to other variables such as contractual, technical, and financial demands [6]. The construction is a risky industry, but plays a crucial part in turning the economic progress of developed and developing nations so management of risks in construction projects was recognized as an extremely crucial procedure to be able to accomplish the project goals in the terminology of the time, safety, quality, cost, and environmental sustainability. Identified risk management as a key tool in order to deal with construction risks and to overcome problems of task failure. Identified risk management as being a management tool which aims at finding energy sources of uncertainty and risk, determining the effect of theirs, and developing proper management responses. Moreover, risk management in the building project management context is a systematic and comprehensive method of determining, analyzing, and responding to risks to get the project goals. Risk management establishes the failure or success of construction projects [7].

Risk management is the summation of all systematic methods a company puts in place in order to reduce the likelihood of any threats and harms that may arise from uncertainties [8]. It involves the identification, measurement and response to project risks [9]. Various international and standardized organizations like IEC, PMI and PMBOK have agreed on risk identification, assessment, treatment and review of risks as the Three steps involved in risk management.

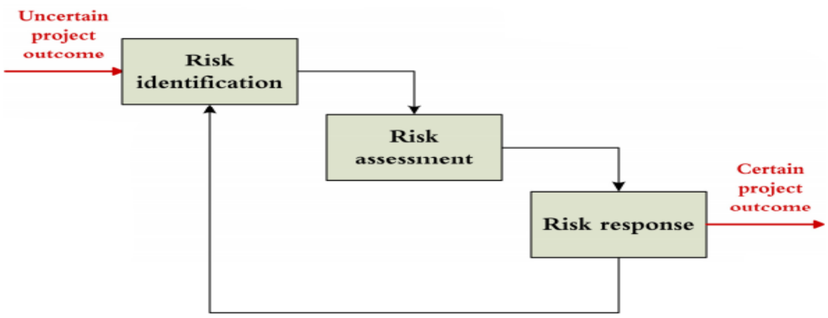

Fig. 1. Steps involved in risk management

2. Impacts of poor risk management in construction industry

Risk management is a major aspect that can either influence a construction project positively or negatively depending on how it is done. A good risk management protocols when followed can lead to high capital value, better competitive advantage, maximum market profit margins, and good shareholder equity. In the same way, a poor risk management which involves the use wrong tools for risk management and control, inadequate utility of required management processes, poor quality of management and assessment can lead to big calamity in any construction project set-up [10]. Not regarding risk chances in a project can result into financial loss, bitter relationship between company/client and even a complete project failure. Hence, at the point of actions, when major elements are missing or lacking cases of project delays, reduced project quality and loss of company reputation are inevitable [11]. The various impacts of poor risk management are described below:

2.1. Overgrowth of project cost

Bad risk management results in the skyrocketing of running costs of a project work when the internal and external incongruences of the project cannot be well managed. Also, when construction bodies are not mindful and do not forecast the risks which can evolve from the execution of a contract, unreasonable and unplanned expenses like emergency and maintenance costs tend to creep in. This by-costs reduces how major plans are to be properly funded hence bringing down the overall quality of the stakeholders and managers goals [11]. Secondly, looking at the contractors and labour force side of view, most cost increments which occur on-site are as a result of various changes in client's demands. Therefore, improper understanding of the risks that can be incurred from specific clients can further encourage acute deviations from the already laid-out expenditure plans. Newly motivated interest in trending materials or labour from customers and clients causes higher pay rates which if not smartly overseen, can raise overall project costs wildly [6]. Poor risk management leads to overspending and thereby might cause the construction body to run into debt if not properly controlled. Risk management swallows a lot of expenses but the cost of dealing with the consequences of poor risk management is far beyond the former. It pushes the project team to look for more money which has not been budgeted for elsewhere in order to prevent the project from failing. Budget overruns therefore occurs when associated risks and their consequences are not budgeted for from the initiation of construction works [10].

2.2. Project delays

To a layman, delays happen when agreed date for completion or delivery of a project is past and the project is still not finished. Unanticipated and unpredicted risks which arises as a result of poor risk control strategies can reduce the speed of a work-plan because longer period is now needed to track, analyse, and correct this newly developed set of project risks. Project hold-ups or delays can also arise when risk management plans take longer periods and then push out other plans of the construction project. Therefore, risk management plans have to be responsive, efficient and most importantly timely and fast in order to overcome cases of project delays [12].

2.3. Project failure

Fundamentally, the worst-case scenario of poor risk management is project failures. It leads to invaluable output or production, waste of time, resources and thereby making the aims and objectives not achieved. When industrial risks are not foreseen, especially for new and innovative ideas in technological and construction circles, the project fails out-rightly. Each and every wrong risk management step taken by the administrative levels and stakeholders has a negative impact on how the products are delivered. Risks can destroy the profits and benefits of a project in an instance or gradually kills the profit of a contract till the construction bodies runs into debts or big losses and the project thereby fails and is closed [13].

2.4. Loss of interest in the laid down management methods

Generally, as a result of the human nature of the labour, when projects fails as a result of poor management decisions, the engineers and the low-level workforce can lose interest or focus in the methods with which they are instructed to follow. This further causes poorer output quality and low productivity because the labours are no more working according to the standard of best practice [12]. This loss of interests in the method or tools is also referred to as poor user adoption. It arises generally when the process of risk management is very bureaucratic and unnecessarily procedural; making the workers to design shortcuts for standard processes to keep the project on motion. From the managerial point of view, It also happens when the process is highly advanced, robust and rigid forcing the project supervisors and managers to adjust these risk management plans to create avenue for on-site changes [10].

2.5. Reputational damage from customers

Poor risk management often result into a significant reduction in the confidence of customers or clients for a company. These dis-satisfied customers in themselves pose another financial risk towards the company since one bad response or review from them can deter the image of the company. Therefore, serious attention must be given towards poor risk management and control strategies employed by an industry. Generally, clients do not like to be attached to establishments with high potential of risks in execution of projects. The consequences of poor risk handling do not only make clients to see the company badly, it also makes even sponsors and donors to move their businesses towards other competing industries. They are likely to bring down the reputation of the former companies they have worked with thereby making it hard for these companies to re-build their trusts in the long run [14].

2.6. Loss of profit

Financial risk management also includes system of double-signature requirements for checks, invoices, payables, stringent counting procedures. Inadequacy of protecting against embezzlement, theft, and fraud during a project execution because of porous administrative system can lead to potential profit loss. The quality of financial analytics and business risk assessment can determine how a project team make its profit or loss. Companies which have not employed proper risk mapping, identified the regularity of risks or evaluate risks based on significance cannot clearly notice the border line between profit and loss. Other channel of profit loss stems from expense related risks, cost increase, cost of reclaims and rework, employee-related risks etc. [15].

2.7. Materials scarcity

Scarcity of materials are common in construction projects. Lack of organizational plans in the procurement, transportation and records of construction materials can result into scarcity of material or impromptu finish of the materials. The choice of location to get the materials, poor estimation of the material quantity, inconsistent demands in the managerial cabinets, unforeseen government restrictions are all management factors that can lead to scarcity of construction materials. In more complex projects, when less quality logistics are put in place by the risk managers, the labour force tends to waste most of the materials thereby leading to the expiry of some materials, underutilization of some materials and complete consumption of other materials before another agreed time of a new order [16].

2.8. Equipment damages

The risks involved in the use of engineering tools and technological machines employed for building and road construction can be minimized if proper plan is channeled towards the training of personals. Unfortunately, most construction agencies make use of unskilled labors to achieve their goals; hence, this lack of good human risk cover or management scheme can result into life damages to the workers as these machines pose serious and injurious threats to the lives of the untrained workers. The cost of repairing damaged equipment also creates another minus in the overall project cost and it is as a result of poor risk management plans [17].

2.9. Improper use of labour

Talent acquisition and management are perhaps the most critical parts of the human resources department of any construction agency. Generally, improper resource planning and recruitment program may lead to overstaffing or understaffing and a mistake in the recruitment processes could lead to hiring the wrong people for your company, improper placement of workers for uncomplimentary jobs and underutilization of labour potentials [18].

2.10. Inadequate project accountability

Another impact of poor risk management is inadequate project accountability. An unclear view of the interdependencies between the projects, the benefits, and the criteria against which success will be judged can result into bad project accountability. It is imperative that a leader can work well with your team. When tasks or goals are not met to standard, there should be ramifications. Rank tasks by priority and assign them to the most proficient individual in the clearest way possible [14].

2.11. Fear to explore new ideas

Many managers sometimes think ideas don't solve critical problems especially when the relationship between the project team is not smooth. Hence when ideas from the workers or another low scaled labour takes too long to get to the decision board or gets too long to be acted upon, others become fearful to suggest new ideas. Also, risk management firms with slow decision cycles kills innovative ideas and thereby discourage others from voicing out their ideas [19].

3. Lesson learnt

This review work has helped to itemize various impacts of poor risk management through integrative research. It is hoped that this work will help researchers to tackle the various uncertainties in the field of construction projects. Poor management strategies can lead to bigger consequences or impacts. Other impacts of poor risk management include creation of negative working environment and underutilization of opportunities.

4. Conclusion

This work is a theoretical approach to increase the understanding of risk impact on construction projects. This will create a more effective risk management practice and help the identification, assessment and control of risks. Unplanned expenses, project delays, project failure, loss of profits, cost overgrowth are the major risk impacts identified while improper use of labour, materials scarcity, inadequate project accountability can be classified as the minor construction risk impacts identified in this work. A good risk management protocols when followed can lead to high capital value, better competitive advantage, maximum market profit margins, and good shareholder equity.

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Attributes Indicating Communication Influence on Leadership Development: A Delphi Selection Process

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Abstract

Communication is an essential subject to the built environment and it generally presents special challenges. This is mainly true within the construction industry, were collaboration tends to be characterized by unfamiliar groups of people coming together for short periods before disbanding to their respective construction tasks, moreover the industry is dynamic and complex, which makes communication by industry leaders important. The study aimed at establishing the influence of different communication factors on leadership development in the construction industry. The study adopted the Delphi survey system of data collection to examine the study objective. Delphi experts (Construction specialists and researchers) were engendered from peer-reviewed conference proceedings and the South African construction industry professionals' database. The appraisal of different communication factors was done by identifying the influence of each communication factor on leadership development; these factors were measured between no influence and very high influence. Data collected were analyzed using mean item score and interquartile deviation. Of the different communication attributes evaluated, the ability for leaders to develop active listening skills had a high influence on developing communication attributes for leadership development in the construction industry. The article contributes to the frame of knowledge on leadership development and communication in the construction industry.

Keywords: communication, construction management, leadership

1. Introduction

Construction industry leaders serve as main channels to communicate values, strategic changes, and encourage followers within any organization. For example, [12] stated that communication is not only one of the key aspects of leadership performance, but that leadership can be seen productively as a communication process, and some say leadership is communication [3]. In this study, the focus is on the communication attributes that are interlined with leadership. There has been little research on the relationship between leadership and communication, despite studies confirming the importance of the topic, indicating that leaders who pay attention to their communication are more effective agents of change than those who do not [3]. Besides, superior communication styles are linked to their subordinates ' levels of satisfaction [12] and motivation [3]. The research article appraised the Delphi experts' views on the influence of different communication attributes on leadership development within the construction industry.

2. Communication and leadership

According to Kautilya an effective leader has the highest qualities of leadership, intellect, courage, and personal attributes. His research has given a lot of emphasis on communication by leaders. Communication implies effectively reaching and communicating clearly to the targeted audience. He further cited various scenarios where appropriate communication is required to get the things done. It is also important to note that a leader should always demonstrate the right kind of expressions and gestures while communicating. He stated 5 'must have' qualities in a leader, and they are - Visionary, Strategist, Able administrator, effective communicator, and Team Player [5]

Kings and rulers of earlier times can be compared with business leaders of today in most aspects of leadership. There are numerous books, essays, and dissertations on leadership than any other subject of management. The sheer volume of research and writing on the concept of leadership tells us that this is neither a subject that can be easily defined nor will there be a great deal of consensus. There is only one thing for which all these authorities agree, i.e., effective leaders are also effective communicators. However, the opposite is not universally accepted, that good communicators do not necessarily make good leaders [4]. Leaders can achieve success by combining a clear vision of the way forward, honest communication, effective teamwork, and demonstrating that they value the people who work for them.

In these testing times, survival can depend upon being able to keep close to the 'skin' of the business, managing costs tightly, and preparing for the upturn when it comes and for that to happen Leaders need strong communication skills so that they can deal with anything that comes their way [8]. In the construction world, excellent communication is vital for the daily operation of the industry, but can also affect sales and profitability. Without excellent business communication, the internal and external structure of a construction business can face numerous challenges that can ultimately lead to its demise [4].

Bennis describes the skills of a leader as four management competencies. Central to each of these competencies is effective communication. This includes: Management of Attention: this describes how leaders encapsulate a vision, which other people can endorse and buy into as their own. Management of Meaning: Ability to communicate clearly and successfully. Management of Trust: It binds the followers and leaders together. Management of Self: This is what gives leader credibility [9]. Most management training focuses on processes and procedures, which, on its own, is inadequate. Managers and those in positions of leadership need to know how to get the best out of the workforce, which requires a combination of awareness and excellent spoken communication skills.

Whether someone is talking to colleagues or customers, discussing clients, or asking for a promotion, there will be aspects of the interaction that would have had a more significant impact if they were better communicated. Moreover, Managers and other business leaders must also know how to listen, and in order to motivate and influence those around them, those in leadership roles must also have the capacity to "negotiate". However, with effective questioning and open body language it is possible to establish the goodwill of the other party who is then more likely to be motivated by what has been said if they feel that their point of view has been taken into consideration [6]. It is impossible to become a great leader without being a great communicator [2]

It is essential to give emphasis and understand Nonverbal communication, because words only constitute 7% of the communication and 93% covers gestures, facial expressions, and body language. The meaning of non-verbal communication is not to be found either in words or the accompanying actions, but rather in the relationship of each other, and also in the context of the situation in which they occur. Nonverbal communication becomes the yardstick against which words and intentions are measured [5]. If you want to become a better communicator, it's vital to become more sensitive not only to the body language and nonverbal cues of others, but also to your own [9]. Considering that communication is essential in human life, a thorough knowledge of the processes and practices of non-verbal communication can help managers to enhance the communication.

Effective communication skills are an essential aspect of any leader's portfolio of skills and experience [7]. Effective communication skills are tantamount to the success of an organization. Thud making Responsible leaders who communicate effectively. These responsible leaders work hard to prevent bottlenecks and assist keeping the communications channels open throughout the organization by (1) Establishing an appropriate working climate and adjusting their communication behavior to fit the situation. (2) Practicing techniques to improve communication in their organization. These leaders communicate strategically, translating important business objectives into terms through which employees readily understand their value. Communication skills are increasingly regarded as a critical skill set for leaders, particularly in situations where the leader is an instrumental driver of change [10]. It is, therefore, critical for construction leaders to keep enhancing their communication skills.

3. Methodology

The Methodology Section details the approach used to assess the effect of different communication factors on the growth of leadership in the South African construction industry. A Delphi survey was conducted amongst 13 experts (academics, built environment professionals and business owners) in the South African construction industry. A Delphi study is a group evaluation instrument compelling qualified experts who have an understanding of the subjects at hand [1]. Each expert was required to meet some of the following criteria; Knowledge: Knows construction management and project management; knowledgeable in leadership re-search; knowledgeable in the field of management theory. Academic Qualification: A degree related to any field and has had occupation and experience focusing on infrastructural development issues, psychology, construction management, project management, and social sciences. Experience: Previously or currently performing consulting and contracting services within the construction industry or any related infrastructure projects. The experts should demonstrate a high degree in the subject matter and also have an extensive theoretical understanding thereof. Research: Has researched leadership and management issues. Membership: Member of a professional organization or represent such an organization. Finally, Enthusiasm: Panel members must be eager to participate entirely in the Delphi study.

The recommendations of [11] were assumed for the current study, whereby they stated that respondents should be enough to consolidate the expert views successfully, but not so large as to analyze the results uncontrollably. With regards to the criteria, five of these criteria items were measured than the customarily advocated two. Experts were required to be in managerial positions and also have an understanding of leadership development. The initial Delphi survey was made up of 20 experts comprising academics and construction professionals who were randomly selected based on the criteria. The experts applied their knowledge on the leadership concepts raised through the developed questionnaire. From the 20 experts requested to participate in the Delphi survey, 13 responded and completed all the three rounds. These amount of experts was considered sufficient grounded on the literature recommendations from scholars who have previously employed the Delphi technique, whereby they cited that, it is viable to have between 6 and 16 experts, this makes 13 experts as seen in the current study reasonable [11]. Likewise, experts were asked to rate the impact factors influencing communication for leadership development in the construction industry as shown in table 1. Data attained from the survey instrument were analyzed from Microsoft Excel. The output from the analysis was a set of descriptive statistics whereby the mean items score and interquartile deviation (IQD) were determined through a scale that reflected no influence, low influence, medium influence, high influence and very high influence.

4. Findings

Results from the Delphi survey shows the (11) listed communication measurement variables, that were recognized by the experts as influencing communication for leadership development. When assessed, findings revealed that 10 of the 11 measurement variables achieved consensus with IQD cut off ($IQD \leq 1$) score (See table 1), and one variable did not achieve the consensus. The 11 variables reached the median score of 7 or more, which implied a high influence (HI: 7-8.99).

Table 1. Attributes influencing communication

Leaders…	*M*	*Mean*	*SD*	*IQD*
… demonstrate active listening skills	*8*	*8.29*	*0.61*	*0.00*
… communicate in a clear manner	*8*	*8.14*	*0.77*	*0.00*
… communicate in a precise manner	*8*	*8.14*	*0.70*	*0.00*
… demonstrate effective written communication skills	*8*	*8.21*	*0.58*	*0.00*
... seek to understand others' verbal and non-verbal communications	*8*	*7.79*	*0.83*	*0.00*
… share information appropriately among stakeholders	*8*	*8.07*	*0.66*	*0.00*
Ability to…				
… communicate the organization's mission and vision	*8*	*8.14*	*0.74*	*1.00*
… provide feedback to the subordinates	*8*	*8.36*	*0.70*	*0.00*
… ask team members constructive questions	*8*	*8.21*	*0.87*	*0.88*
… demonstrate confidence in public speaking	*8*	*7.75*	*0.68*	*0.00*
… be a story teller	*8*	*6.57*	*1.87*	*3.00*

Findings from the survey divulged that the following 11 communication dimension variables were contemplated by the experts to have varying influence on leadership development in the construction industry.

... demonstrate active listening skills (HI)
... communicate in a clear manner (HI)
... communicate in a precise manner (HI)
... demonstrate effective written communication skills (HI)
... seek to understand others' verbal and non-verbal communications (HI)
... share information appropriately among stakeholders (HI)
... communicate the organization's mission and vision (HI)
... provide feedback to the subordinates (HI)
... ask team members constructive questions (HI)
... demonstrate confidence in public speaking (HI)
... be a story teller (LI)

From the impact assessments of the factors; findings discovered that 10 of the factors had high influence towards leadership development.

5. Discussion of findings

Leadership is the most dynamic resource in the construction industry. Moreover, findings about communications indicate that is important to have the different traits as leaders in the construction industry, it further shows that communication training is paramount. Without adequate leadership communication, the industry will not be effective. This section bestows the discussions of the findings from the Delphi survey on the impact of communication variables on leadership development in the construction industry. Results reveal demonstrating active listening skills and the ability to communicate the organizations' mission and vision are fundamental for leadership development and this corresponds with the work by [11].

Further findings disclosed that it is essential for construction mangers and personnel to have the ability to provide feedback to those you are leading and this notion supports the effort by [12]

6. Conclusion and recommendation

The objective of this article was to evaluate several communication factors that influence leadership development in the construction industry. This was done using the Delphi survey technique. The study shows that communication has a high level of impact on leadership development. This study offers a strong base for communication and leadership development research in the South African construction industry.

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Barriers to ICT Adoption in Construction Revisited

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Abstract

The paper presents introduction to a study on the barriers to the implementation of information and communication technologies (ICT) in construction. In the study, we compared the ICT use in construction with some other industries - as reported in the literature and some industrial studies. We challenge the conventional wisdom that construction industry is not being rational in its choices to adopt (or not) various ICTs. We approached the issue from several methodological frameworks. In the paper we structure the reasons along the PESTEL framework. We examine each of the factors and suggest how they could be overcome. A survey has been designed and executed among the members of the Advisory Board of the EU Digiplace project. The results show that the industrial partners are less critical of the technology migration problems than researchers. The paper concludes that there is a need for a better way of deployment of and learning about new technologies that would benefit small and medium enterprises – the lag in productivity growth is largest there. This could be implemented in the form of industrial platforms in the context of the developments of the Industry 4.0.

Keywords: information and communication technology, technology adoption, construction platforms, construction industry

1. Introduction

Information and communication technologies (ICT) are one of the most rapidly developing fields of technology. They influence not only the closely related software and computing hardware industry but all sectors, including construction. One of the problems that the construction research community is facing is how closely it should follow these developments and which to augment for use in construction.

The construction industry too faces many challenges when making decisions on deployment and investments in ICT. Many (Brandon and Betts 1997, Turk 2000, Stouffs and Krishnamurti 2001, Amor at al. 2002, Sarshar, 2004, Flood, 2004, Yan, 2008, He, 2012, Chan, 2014, Mtya, 2019) have claimed that the penetration of modern ICT into the construction industry lags well behind the inventions of the research community and elaborated on the reasons for this.

While certainly valid and influential, what those reasons have in common is that they are looking for the causes outside of the construction information technology.

The hypothesis in this paper is that the construction sector is being rational about its adoption of ICT and that should we want to increase the use of ICT, a better delivery mechanism needs to be found. It could find an example in the delivery mechanisms for the general, popular information technologies, people, including construction professionals, use on a daily basis.

2. PESTEL analisys of the barriers

A PESTEL analysis (Professional Academy, 2020) is an approach originally utilized by marketers to understand the macro-environmental variables that have an effect on acceptance of a product, an organization, a system. The result the examination is then utilized to recognize dangers and shortcomings which is utilized in a SWOT analysis.

The acronym PESTEL stands for the following facets of examination:

- P – Political
- E – Economic
- S – Social
- T – Technological
- E – Environmental
- L – Legal

While the PESTEL was initially conceived to assist in marketing it, provides a framework to analyze barriers between customers (such as the construction industry) and performers (providers of information technology and other advanced technologies).

2.1. Political

These are about how and to what degree a government mediates within the economy. This may incorporate – government arrangement, political soundness or flimsiness in abroad markets, outside exchange arrangement, assess policy, labor law, natural law, exchange limitations and so on. It is evident from the list over that political components regularly have an effect on associations and how they do commerce. Associations got to be able to reply to the current and expected future enactment and alter their showcasing arrangement appropriately.

We have been finding that in construction, policies are lacking on a project, company, national and EU level that would mandate or encourage the use of advanced ICT and make their use profitable.

2.2. Economic

Economic factors are about how a company does its business and how profits and other economic goals are affected. The factors include GDP growth, interest and exchange rates, inflation, disposable income of consumers and businesses etc. A distinction can be made into macro- and micro-economic factors. Macro-economic ones are about the general economic climate in an economy. Micro-economic factors are about how customers need the products and services of the company.

We have been finding that in construction new ICTs are expensive, economic advantages not understood well enough; they are rather unfriendly, call for extensive and expensive training; low profit margins and tight deadlines discourage experimentation and novelties; near monopoly status of a few software companies.

2.3. Social

These factors represent the human and social characteristics, norms, customs and values of the people with which the business is involved with – including its own staff, partners and customers. These factors are believed (B2U, 2016) to be particularly important when targeting certain customers or constituencies. Additionally, these factors may include the attitudes of local workforce.

We have been finding that in construction there are some rigid and conservative practitioners, caution, unwillingness to learn, and widespread resistance to change that slow down the progress.

2.4. Technological

These factors are about technological innovations and how they affect the operations of the business and its industry. It refers to the level of innovation, technology incentives, automation, technological change research and development (R&D) activity, and the amount of technological awareness that a market possesses. These factors may have an impact on decisions to pursue or not pursue certain business opportunities, enter or not enter certain projects and domains. Awareness of what is going on technology-wise impacts medium to long term strategic decisions of businesses.

We have been finding that in construction technology is rather unfriendly, often lacking compatibility and interoperability. Standardization has not been fully achieved. But generally, it is seen less of a problem than other elements; OpenBIM in not fully realised, implemented and adopted.

2.5. Environmental

Environmental factors have been gaining attention rather recently with the increasing awareness of global warming and the need to address them – both in terms of mitigation as well as prevention. They are also important in the light of scarcity of raw materials, pollution, as well as carbon footprint targets set by governments. These factors include objective ecological and environmental aspects such as weather, climate as well as the attitudes of the people related to a business both as employees and customers. Therefore, many companies are increasingly involved in practices such as corporate social responsibility (CSR) and sustainability.

In construction we are finding that environmental policies (such a fighting climate change) are not a barrier but, on the contrary, a motivational element to include new technologies.

2.6. Legal

While there may be some overlap with the political factors, these factors include specific laws and regulations that impact that particular business. This is not at all limited to what is legal but is mostly about how regulations frame the business, its relations with customers and partners. Under this heading also standards, both the mandatory and the industry adopted ones, are included.

In construction we are finding that there are unsolved legal, copyright, and related IPR issues of working in a digital environment. Guidelines and regulation what the BIM centred process should look like are not generally available.

3. Survey

In the context of the Digiplace project a survey has been conducted among several companies across Europe. One of the questions was related to barriers of use of advanced digital tools such as BIM, 3D printing, thermal scanning, GIS, 3D modeling, etc.

When asked "do you use other more advanced digital tools" the number of replies maybe was 10, no 33 and yes 143 and in the questions of why don't you use more advanced digital tools, those that responded cited the answers as shown in the figure below:

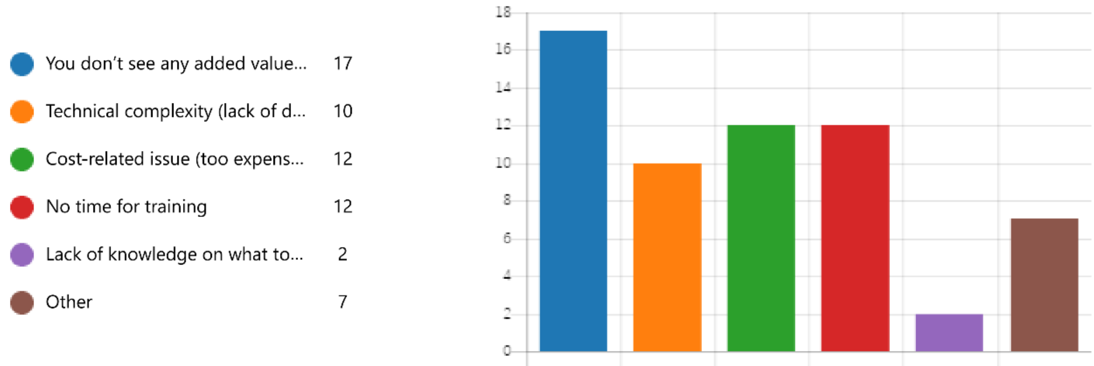

Figure 1. Why advanced ICT is not used more as per first Digiplace survey?

Top reason as per surveyed is the lack of added value. At the other end of the spectrum seems to be access to knowledge. The respondents seem to be knowledgeable on one hand but lacking time to learn on the other.

4. Conclusions and discussion

Construction is lagging in productivity growth of the other sectors of the industry (McKinsey, 2017). The lag is particularly large in small and medium enterprises while the bigger companies are following or exceeding the trends of their countries. This calls for technologies and tools that help the SMEs. Platforms are such an approach.

Past empirical and theoretical studies as well as initial survey of the Digiplace project have identified several obstacles and barriers to a more intense use of ICT in construction. First and foremost, it must be remembered that the ICT will be used when economic and competitive benefits can be demonstrated. The efforts of policymakers, public procurement and professional associations could help in that.

Some of the efforts are already present in the EC (2019) report which recommends a rise in public awareness for digitalization is needed. “Besides resulting novel opportunities, this process also leads to an increased pressure for businesses” (EC, 2019).

There is a broad support for “a new and extended digital platform” (EC, 2019). Such a platform would address the issues of lack of knowledge as it would provide a context for a more friendly technology delivery tool and could as well provide best practices, guidelines and regulations how to organize for a BIM centered workflow. It is important not to forget that such a platform should “enable international usage, while being able to take local regulations into account” (EC, 2019).

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Compatibility of Personality and Productivity: An Analysis of the Relationship with Construction Crews

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Abstract

The labor productivity of a crew depends on how efficiently workers are used in the construction process. Skills, capabilities, resources, and even personality affect the efficiency of the workers and may have an impact on the productivity of their crew. This paper illustrates how the personality profiles of the workers in a crew can be used to determine the relationship between compatibility of personality and productivity. Masons working in eight live construction projects completed the big five of personality to indicate their personality traits. Based on the personality traits, the compatibility of the crews was calculated. Productivity at the task-level was measured to determine the performance of the crews. Various statistical analyses are performed to establish the relationship between compatibility and crew productivity and the true value of the coefficient (and its likeliness). The results indicate that there is a high positive correlation between compatibility of personality and productivity at the task-level ($r_s = 0.758$). Results also indicate that in the worst case scenario, there is a moderate correlation between compatibility and productivity ($r_s > 0.3$; probability: 0.728). The implications of the relationship for managing crews in construction projects is discussed.

Keywords: compatibility, crew productivity, personality, productivity, statistical analysis

1. Introduction

The productivity of a crew is fundamental to the success of any construction project. Crew productivity can be affected by numerous factors such as site characteristics [1] use of resources [2], management practices [3], and crew motivation [4]. Additionally, personal characteristics and the interrelationship between the workers in a crew also affect productivity [5]. One of such personal characteristics is personality.

Personality is used to describe behavioral regularities and the underlying structures, dynamics, processes, and tendencies of an individual [6]. When working in crews, the personality of the workers is combined and this often affects productivity [7]. Productivity is expected to be higher in crews in which the workers have compatible personalities. However, this assumption has yet to be tested in the construction field and in real live construction projects. In masonry construction, the compatibility of personality among the workers in a crew plays a key role. Masonry is labor intensive and masons have to constantly coordinate when to raise the line to complete a course. This results in constant interactions between the workers in a crew. Therefore, the success of a crew to work together and achieve high production rates might be impacted by the adequate combination of personality of the workers in the crew.

Personality dimensions are used to understand relationships and interactions between individuals, as these are a function of the personal characteristics of individuals [8]. Personality dimensions have also been used for describing and predicting attitudes, behaviors, fit, and performance in many organizational settings [6, 9,10,11,12, 13]. A number of studies in construction have identified personal characteristics in crews that contribute to performance such as cohesion, motivation, affection, cooperation, and trust [3, 4, 5, 14, 15]. Other studies have gone further and investigated the effect of personal factors on performance such as personal confidence, job satisfaction, and self-organizing [16, 17, 18]. The effects of personality on teams and organizations have been studied for evaluating commitment, job satisfaction, attitude, and retention [3, 19, 20].

Personality is a psychological construct often used to describe the structures, dynamics, and tendencies that bring about behaviors and attitudes in individuals [21]. The personality of individuals is usually described in five dimensions (O=openness, C=conscientiousness, E=extroversion, A=agreeableness, and N=neuroticism) in a widely accepted theory among psychologists [22]. When individuals are grouped in teams, their personalities combine, and forming teams should follow a psychological approach. In other words, teams should be formed so that the different members in the team are compatible so that there is no conflict and workers can worker better together to increase their performance [11]. If it is expected that workers that have compatible personalities work better together and achieve higher performance, a manager on site would need to group workers with an adequate combination of personalities, as this can help the team be more productive.

However, the current construction literature has yet to determine and quantify the relationship between personal compatibility and crew productivity in actual real live projects. Factors that have been investigated that influence crew productivity are typically technical factors such as skills, capabilities, and qualifications. These factors typically have a low variation, as it can be assumed that the workers have the minimum skills, capabilities, and qualifications to be working on a construction site [23]. Since productivity has a high variability, it can be assumed that there are factors that also have a high variability and that can be used to explain such variability in productivity. This study explores whether personality and the compatibility of personality can explain some of that variation. To help determine the relationship, this study explores in isolation whether personality and the combination of personality between the masons in a crew has a relationship with productivity.

2. Model components

2.1. Compatibility of personality

In this study, compatibility was defined as a tendency of a crew to share similar personality characteristics. To measure similarity, the average of the dimensions of personality was calculated based on the method of operationalizing personalities for different team compositions [24]. Because masonry construction processes are additive tasks, that is, require summing of resources from different workers to achieve performance, the mean level of the personality factors was the most appropriate level. The mean guarantees that the contribution of each worker adds to the crew and helps achieve performance.

The principle of similarity theory was used to calculate compatibility. Compatibility will assess how similar in terms of personality the workers in a crew are. For this, it is assumed that workers with similar personalities are more compatible that workers with dissimilar personalities [25]. For calculating compatibility, explicit comparisons were used to measure similarity in each of the five dimensions of personality between the masons in a crew [26]. The distance measures using the Euclidean distance were used to determine similarity. A smaller distance reflected a higher similarity (higher compatibility) and a greater distance a higher dissimilarity (lower compatibility). For a further discussion about this procedure, the reader is referred to [23].

2.2. Productivity

Performance of the masonry crews was measured using productivity. Productivity is generally measured as the ratio between the output of a process over its inputs. The single-factor productivity at the task level was used as the measure in this study [27] because it is commonly used in labor-intensive operations such as masonry construction [5] and it is focused on the work being performed at the task and crew levels. The work output was the quantity of composite cavity wall construction (measured in m^2) completed per crew on a weekly basis. The input were the work hours measured as productive time, that is, the summation of work hours minus unavoidable delays such as weather and meal breaks. Productivity was measured during 16 consecutive workweeks using the base line methodology framework to select the seven most productive weeks [28].

3. Relationship between productivity and compatibility of personality

This section is based on the eight masonry construction projects and results presented in [23], where 28 masons grouped in 20 crews working in the North West of England participated in the study. Data collection was done simultaneously across the projects to minimise the variability in weather conditions and the baseline methodology framework was used to average the most productive weeks and minimise other project conditions. All the projects had two-mason crews and the size did not change because workload was stable throughout the data collection process. Each crew was laying masonry units and installing rebar for reinforcement and was managed by a site manager and assistant site manager in the field. All the masons were experienced bricklayers that had worked in masonry projects for at least 5 years. Table 1 shows the five dimensions of personality and a sample of the assessment questions.

Table 1. Big Five personality factors

Dimension	Factor
Extraversion (E)	Talkative
	Reserved
	Full of energy
	Generates enthusiasm
Agreeableness (A)	Finds fault with others
	Helpful, unselfish with others
	Likes to cooperate with others
	Quarrelsomeness
Conscientiousness (C)	Does a thorough job
	Somewhat careless
	A reliable worker
	Disorganized
Neuroticism (N)	Nervous
	Depressed, blue
	Emotionally stable, not easily upset
	Remains calm in tense situations
Openness (O)	Ingenious, a deep thinker
	Shows an active imagination
	Prefers work that is routine
	Inventive

Twenty-eight subcontracted masons working for a general contractor participated in the study. The masons were grouped in 20 crews. All the masons were male with a minimum age of 18 years and the mean age was 36.12 years. The experience in masonry construction ranged from five to 47 years with a mean of 23.3 years. The BFI adapted from [29] was completed by each mason early during the data collection process. With the questionnaire responses provided by the masons for their individual personality profiles and using the Euclidean distance, the compatibility for each of the 20 crews was calculated as shown in Table 2. Note that the range of the compatibility coefficient was between 0.36 to 0.78 (with a mean of 0.53 and a standard deviation of 0.12). The results also pointed out different facts. Crews with a significantly elevated score on neuroticism for a mason had low compatibility. Two masons had the highest level of neuroticism (m4 and m23) and these two masons had little variation in their personality profiles. Additionally, the two masons that displayed the lowest level of extraversion also had very low levels of compatibility within the crew sample (see Table 2). Productivity data are also presented in Table 2 for the seven most productive weeks, using the baseline productivity method [28]. Every week the productivity of the 20 crews was measured in the eight projects totalling about 273 hours per crew. Productivity per crew ranged between 0.887 m² to 1.494 m² per hour.

Table 2. Big Five personality factors (Adapted from [23]).

Crew	Masons	Compatibility	Productivity	Crew	Masons	Compatibility	Productivity
1	m1 m2	0.55	1.36	11	m21 m22	0.46	1.33
2	m3 m4	0.39	0.96	12	m23 m24	0.46	1.03
3	m5 m6	0.55	1.23	13	m25 m26	0.39	1.18
4	m7 m8	0.65	1.23	14	m27 m28	0.55	1.23
5	m9 m10	0.41	1.11	15	m22 m25	0.46	0.99
6	m11 m12	0.43	0.88	16	m21 m26	0.50	1.06
7	m13 m14	0.59	1.19	17	m23 m28	0.57	1.16
8	m15 m16	0.54	1.17	18	m9 m17	0.76	1.50
9	m17 m18	0.63	1.48	19	m24 m27	0.36	0.95
10	m19 m20	0.59	1.40	20	m12 m16	0.78	1.30

3.1. Data analysis

The main objective of this study was to determine whether greater compatibility of personality between the masons in a crew results in higher productivity. To test this, a hypothesis was establihsed:

H_o: Greater compatibility in the crew does not increase productivity

H_1: Greater compatibility in the crew leads to higher productivity

The first step in the analysis was to determine the reliability of the questionnaire responses.The internal reliability was examined and the results displayed high reliability across the factors (Cronbach alpha ranged from 0.64 to 0.85). The second step was to perform a correlation analysis to assess the relationship bewteen compatibility of personality and crew productivity. Spearman's correlation analysis was used since the Spearman's rho coefficient (r_s) determines the direction and strenght of the relationship between two variables. The Spearman's coefficient correlation between the big five factors are shown in Table 3. Note that neuroticism was negatively correlated with the other personality dimensions. Similar findings have been reported in previous studies in non-construction domains [31]. The strongest negative correlation was between neuroticism and conscientiousness ($r_s = -0.686$). The most significant positive correlations were observed between agreeableness and conscientiousness ($r_s = 0.575$) at the $p < 0.05$ significance level.

The null hypothesis was tested unsing a one-tailed test to determine whether greater compatibility of personality leads to higher productivity in the crews. The Spearman correlation analysis was performed and it showed a positive correlation between compatibility and productivity ($r_s = 0.758$). A Spearman correlation coefficient ranging between 0.51 to 0.70 represents a good relationship and a coefficient ranging between 0.70 to 0.89 represents a high correlation [30]. Therefore, as $p < 0.01$ the null hypothesis was rejected, that is, the data supports the possibility of a positive correlation between compatibility and productivity.

Table 3. Correlation between the Big Five personality factors

Factor	E	A	C	N	O
Extraversion (E)	1.000	-	-	-	-
Agreeableness (A)	0.204	1.000	-	-	-
Conscientousness (C)	0.505**	0.575**	1.000	-	-
Neuroticism (N)	-0.438**	-0.373**	-0.686**	1.000	-
Openness (O)	0.255	0.340*	0.507**	-0.360*	1.000

** Correlation is significant at the 0.01 level (one-tailed)
* Correlation is significant at the 0.05 level (one-tailed)

A bit of Bayesian statistics was performed to give a better idea of what the data obtained is telling. The advantage of this approach is that in constrast to the common used approach (whose outcome is a p-value), the Bayes approach gives the possibility of computing how much more likely is a hypothesis compared to another given the collected data. Let's denote by H_ρ the statement "the correlation between compatibility and productivity is exactly ρ". Given any set of data of size N, let r be the correlation coefficient obtained in an experiment with this data set. The random variable $u_r = \operatorname{arctanh} r$ is approximately normally distributed (from the data we have $u_r = 0.6267$). Using Bayes theorem, the probability that the correlation is larger than 0.3 (that is, the correlation is at least moderate) is (see equation 1) :

$$\int_{0.3}^{1} p\left(H_\rho \middle| u_r = 0.6267(r = 0.724)\right) d\rho = 0.674672 \tag{1}$$

Hence, according to the data, it is led to believe that having a correlation of 0.3 (a moderate correlation) is twice as likely as having a correlation lower than 0.3 (a weak correlation). The reader is referred to [23] for the calculation details.

4. Concluding remarks

In construction research there has not been a study that evaluates the relationship between compatibility of personality and productivity. To fill this void, this paper presented an exploratory study using masonry crews working in eight construction projects in the UK. The study was conducted with 28 masons grouped in 20 crews working on residential projects. To determine whether higher compatibility of personality between the masons in a crew leads to higher productivity, a hypothesis was developed and tested. Compatibility of personality was quantified using a metric based on the Euclidean distance. Personality profiles were used to calculate the compatibility between the masons using an adapted questionnaire based on the big five of personality. Productivity at the task-level was measured in the eight projects during 16 consecutive weeks. Correlation analysis was performed to investigate the relationship between compatibility and productivity.

The first part of the analysis showed that the questionnaire for assessing personality had consistency and acceptable reliability across the factors. Further analysis showed that conscientiousness and agreeableness were the personality traits that had the strongest relationship with productivity. People high in conscientiousness plan or systematically work towards goal completion so in teams that spend a fairly amount of time completing interdependent tasks, conscientiousness has a positive effect on productivity. In the case of agreeableness, the effect of this personality trait is through interpersonal facilitation within the team. In this study, the crews in which both masons scored highly on conscientiousness (greater than 5.5) and highly on agreeableness (greater than 5.3) were the crews with the highest productivity. Significant correlations were observed between agreeableness and conscientiousness, openness and conscientiousness, and extraversion and conscientiousness. Another finding was that neuroticism correlated negatively with all the other personality traits and low compatibility between masons commonly occurred when neuroticism was significantly elevated in one mason in the crew. From this, it can be established that crew members high in neuroticism can have an adverse effect on the productivity of the team by disrupting cooperation.

The correlation analysis showed that compatibility of personality has a moderate positive relationship with productivity at the task level. The correlation coefficient was found to be 0.724. This finding shows that personality influence productivity and need to be accounted for by foremen and managers when forming crews of workers. In this case, crews should be formed with workers that have similar personalities. Although the eight projects were located in the same region in the UK, weather conditions could differ in other geographical locations and this may have an effect on productivity that could be accounted for. In addition to weather, other human-related factors that affect productivity other than personality (e.g. skills, capabilities, cohesion, and experience) could be accounted for to develop a more comprehensive labor productivity function.

This result is significant, as it shows that personality characteristics influence productivity and need to be accounted by foremen and managers when forming and managing masonry crews. Through a series of statistical analyses, the evaluation of the coefficient and is true representation of the true coefficient (of the population) and its expected value were performed. Bayesian statistics was performed to evaluate how much more likely a hypothesis is compared to another. It has been shown through Bayesian statistics, based on the data, that having a correlation of 0.3 (moderate correlation) will be 67% more probable than having a correlation lower than 0.3 (weak correlation). This analysis shows that compatibility of personality and productivity are in a worst case scenario at least moderately correlated. These findings will support construction managers, contractors, and subcontractors in the process of forming teams of workers and structuring jobs with highly productive crews. Crews should be composed of workers that are highly agreeable and conscientious because personality offers unique potential for understanding and improving team work and for better predicting productivity. A natural extension of this work is to test the relationship with crews of larger (and different sizes) in masonry sites and other labour-intensive construction projects. By doing so, a wider scope of data can be analysed to further test whether the relationship still holds with other team size and construction tasks.

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Construction Control Room for Project Monitoring and Control

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Abstract

The world is a dynamic and ever-changing environment leading decision makers to believe that from plan to execution, unforeseen conditions will undoubtedly occur. The military is known to face unforeseen obstacles while conducting the operations forcing leaders to plan deviations. The construction sector is not far from the military in terms of planning and executing under uncertainty. One common problem the sector faces is delay in completing tasks and, consequently, projects. To mitigate the effects of uncertainty during operations, the military uses control rooms in order to deal with the worst when it occurs. Military control rooms provide a comfortable and collaborative environment for teams to proactively anticipate, highlight and mitigate potential plan deviations and to resolve emerging problems and constraints fast and efficiently. This paper introduces the concept of military operation rooms to construction by proposing a technology-based Construction Control Room (CCR) where several commercially available technologies are integrated into one comprehensive and inclusive framework for monitoring and controlling ongoing construction activities. It is a collaborative space where all relevant design and construction entities are present. Site data and requests are received, monitored, and processed directly in the control room for proactive and corrective measures. Moreover, this paper presents the elements of a simulation-based tool which outputs the required number of personnel in the CCR. Real project data is obtained from a live project that one of the authors worked on in Western Europe. Data is used to build a discrete-event simulation model that mimics the workflow in the real system in order to analyze the flow of information within the room, suggest the optimum number of members that should be present in each entity, and monitor the resource utilization of each entity. The results of the model show the potential of using such control rooms for enhancing construction project delivery.

Keywords: construction control room, discrete-event simulation, technology, lean construction

1. Introduction

The world as we know it is a dynamic and ever-changing environment. Decision makers believe that between the plan and execution, unforeseen conditions will undoubtedly occur [1]. In the word of military operations, every step within the plan is susceptible to change. Helmuth von Moltke (1871), Head of the Prussian & German Staff, explains, “No plan of operations extends with certainty beyond the first encounter with the enemy’s main strength. Only the layman sees in the course of a campaign a consistent execution of preconceived and highly detailed original concept pursued consistently to the end”. The construction industry is akin to the military in terms of planning and execution uncertainty. One of the most common issues construction faces is project and task delays [2]. Planners also face uncertainties on a regular basis throughout the project’s lifecycle. Researchers have found that more than 56% of construction projects suffer from uncertainties [3]. Additionally, uncertainties affect not only project objectives and means, but also impact production systems in terms of workflow and resource availability [4].

To mitigate the effects of uncertainty during operations, the military uses control rooms in order to stay on alert to proactively detect any unforeseen enemy ambushes and to deal with the worst when it occurs. Military control rooms provide a comfortable and collaborative environment for teams to resolve emerging problems and constraints in a fast and efficient way. Several economic and trade sectors have adopted control rooms to monitor and control their tasks such as in nuclear power plants [5].

In construction, several technologies are being developed to enhance the planning and control aspects of projects [6]. Li et al. 2015 used game engines to develop a tool that visualizes the location of workers wearing location tracking devices during pre-cast concrete installation to proactively detect any unsafe behavior [7]. Moreover, several frameworks and tools have been developed for visual planning and monitoring in construction. The closest concept to the military control room in construction has been introduced for the purpose of visualizing the progress during meetings. A computer application has been used to display current project data and compare different scenarios during team meetings [8]. Furthermore, Virtual Reality (VR) technology is also being used to create a collaborative VR environment. An immersive VR-Based collaborative environment enhances the experience and efficiency of constructability related meetings [9]. Another framework has been proposed to allow engineers to visually inspect and analyze project data and the interdependencies between building elements [10]. McHugh et al. 2019 integrated the famous lean construction system, The Last Planner System (LPS) for Production Control with Building Information Modeling (BIM). The research presented a case study in which the researchers implemented this integration using a tool named VisiLean. VisiLean allows planners to develop look-ahead and weekly plans in a digitized system which is directly visualized in the BIM model rather than the traditional sticky note method. In the presented case study, the proposed system was implemented in a meeting room having digitized walls to screen the system [11]. Although researchers have developed many tools to enhance project collaboration and project control, little effort has been made to develop a concept similar to that of the military control room. Perhaps, the system presented by McHugh et al. 2019 is the closest in concept to the military control room. However, the presented system is mostly used during meetings and planning sessions rather than on-going 24/7 monitoring and control.

This paper aims to add to the previously developed concepts in construction management to enhance project monitoring and control by presenting the Construction Control Room (CCR). It presents the concept of a technology-based control room to proactively and continuously monitor on-going projects and detect any deviations from the plan. Several technologies are used to connect the flow of information from the site to the CCR, and integrate them into one comprehensive and inclusive framework for project monitoring and control. A simulation model is developed to simulate and analyze the workflow within the control room showing the collaboration of different entities present in a construction project. Moreover, various technologies and tools that can be used within the control room are discussed, such as: (1) Obtaining live feed from the actual project construction site through Unmanned Aerial Vehicles (UAVs) and static cameras in order to stay updated with the progress, faced constraints, delays etc., (2) using Building Information Modeling (BIM) to track the progress of the project and to obtain updated models of the actual project, and (3) incorporating the Metrics Prediction Tool developed earlier by the authors [12,13] into the proposed control room. The tool is fed inputs directly from the site and gives metrics that are crucial for project monitoring and progress prediction. Moreover, the tool allows for better activity progress monitoring at the weekly work plan level by detecting clashes, delays, area congestions, in addition to predicting important metrics such as the PPC and a newly developed Percent Improved Complete (PIC).

2. Literature review

In this section, we will go over topics related to the idea of this paper. First, the implementations of control rooms in various industries will be discussed. To the best of our knowledge, no simulation model has been built to mimic and study the significance of using control rooms in construction. Hence, simulation will be explained and discussed to introduce it as part of the methodology of this paper. Finally, we will go over the major philosophies, tools, and techniques of Lean construction which is the theme of the proposed CCR.

2.1. Control rooms

Due to the complex and unpredictable nature of military operations, commanders and generals need a system to keep an eye on critical ongoing operations; this is the military control room or operation control center. This concept is recognizable from military-themed movies. These rooms have two main elements; a collaborative workspace and technological support. The control room allows commanders, generals, and all relevant personnel to be working together in a shared physical room. These rooms are equipped with all necessary technologies to support the flow of information and live feedback from the location the operation is being conducted in, to the control room. The control room allows its users to focus on missions, communicate effectively with other members of the command, operational teams, and support groups, and work collaboratively in an organized and comfortable environment.

Due to the aforementioned advantages of control rooms, several different industries have adopted such systems to enhance their processes. Electric power plants use control rooms to monitor electric supply grids and to communicate with field and generation operators [14]. Nuclear power plants also use control rooms to monitor and control operations, processes, and any deviations in the process state. Their control rooms use alarm systems, diagnostic systems, and cameras to allow for better monitoring [15]. All airports also have control rooms that use radar technology to monitor and plan airplanes' arrivals, departures, and takeoffs [16]. To monitor roads and highways, transportation control centers are equipped with large screens that acquire live video feed from city roads. These control centers are used to monitor traffic intersections and any accidents that might occur on the roads [17].

In construction, Fischer et al. [8] developed a tool called CIFE iRoom that integrates several project information and documents such as CPM and 4D schedules. The information is presented and visualized on three large screens so that all entities in the room can have visual access to the presented information [18]. In Lean Construction, a similar computer-aided system named VisiLean is developed which focused on enhancing planning sessions within the Last Planner System. VisiLean is used to perform phase, look-ahead, and weekly planning in a technological framework. The main goal behind developing this system is to integrate the production planning of lean construction with BIM. Planners are able to place virtual sticky notes during planning sessions onto building elements within the BIM model [19]. A research study has shown that using VisiLean in collaborative rooms similar the CCR presented in this paper, can reduce defects and labor cost, and improve program efficiency [11]. To the best of our knowledge, no simulation model has been built to mimic and study the significance of control rooms in construction.

2.2. Simulation

Simulation as defined by Shannon [20] is the process of building and experimenting with a computerized model of a system to understand its behavior or to evaluate different operation strategies. The use of simulation was first introduced to construction by Teicholz in 1963 [21]. In construction, simulation can enhance our understanding of the processes, and allows us to perform different types of experiments to lower costs and optimize schedules [21]. Several simulation software have been developed including Cyclone, EZSTROBE, and STROBOSCOPE [22].

There are several types of simulation. System Dynamics (SD) is suitable for strategic decision-making or policy analysis [23]. Discrete-Event Simulation (DES) is a process-centric simulation where a chain of activities linked together through certain conditions and resources are represented. DES models are dynamic, as time is a significant factor where only discrete points of time are considered, such as the time of occurrence of an event [24]. Another type of simulation is Agent-Based Modelling and Simulation (ABMS), which is defined by agents and the environment in which they exist. The behavior of the agents and their interactions among themselves and with their environment are described by certain rules that are defined in the model. ABMS's ability to model complex systems has enabled it to become one of the most popular simulation techniques.

The process of building a simulation model begins with setting the goals and objectives of the model. Developed ideas can then be translated into simulation terminologies where important parameters, resources, and relations are defined. Since real systems are extremely complex, simulation models sometimes assume or neglect some factors for simplicity purposes. After a model is built, verification and validation must be performed. Verification is checking if the model is built right, while validation is checking if the right model is built. In the former, the model's scope, inputs, and performance are checked in compliance with the initial concepts and expectations. In the latter, the model's execution and output are checked to be in harmony with the real world's behavior [24]. In construction, simulation techniques are being used in numerous settings for decision making on construction projects [21].

2.3. Lean construction

The goals of lean thinking redefine performance based on three aspects: a uniquely custom product, instant delivery, and zero inventory [25]. "Creating Value for the Customer with no waste" [26] succinctly defines Lean production; with waste being defined as anything that does not add Value to, and in the eyes of, the customer. It is suggested Lean thinking can provide the basis for improving the efficiency of the construction sector and significantly increase its value-offering. Lean construction is a relatively new approach to managing construction [25]. It emerged in the mid-1990s [27] focusing on two aspects. The first is time, money, and equipment waste reduction, while the second is managing flows [28].

Several lean tools and techniques have been introduced to the industry including the Kanban system, which is a Japanese word meaning card or sign board. In the Toyota Production System (or Lean Production), cards are used to control materials flow through the factory by only requesting components delivery from a supplier when they are needed [27]. Another tool is the Obeya system or "big room". It is similar to a control room where a group of experts are gathered to review the progress of the program and discuss key decisions [29]. Toyota identified 14 main principles to establish a lean process within a production system. One of these principles is "Use Visual Control so No Problems Are Hidden". Construction is starting to adopt this principal through dashboards which clearly visualize important project metrics and data. Researchers are developing guidelines to follow while developing construction dashboards. For example, the dashboard should fit to one screen, and vibrant colors should be used to grab the users' attention to important values or messages [30].

3. Methodology

This study adopts Design Science Research (DSR) as the main research methodology. DSR produces scientific knowledge as opposed to explanatory research that aims to understand and predict phenomena in a certain field [31]. It also connects research and practice leading to stronger relevance of academic construction management [32]. This paper aims to link research (technological advancements in construction) with practice (a practical framework for project monitoring and control) by designing a control room that integrates different technologies into one framework. The construction control room is inspired by military operations rooms where different entities work together collaboratively in an open space. Site data and requests are received, monitored, and processed directly in the control room for proactive and corrective measures. The control room integrates several construction technologies and uses real project data to build a discrete-event simulation model that mimics the workflow in the real system.

4. Architecture of the construction control room

As mentioned earlier, the construction control room coordinates, supervises, and controls all ongoing live construction activities. Hence, it combines all relevant design and construction entities. The project commander (Construction Manager or Superintendent) is the highest authority in the control room whose job is to facilitate the flow of information within the room. The room includes entities such as construction managers, architects, and engineers from all disciplines as shown in Figures 1 and 2.

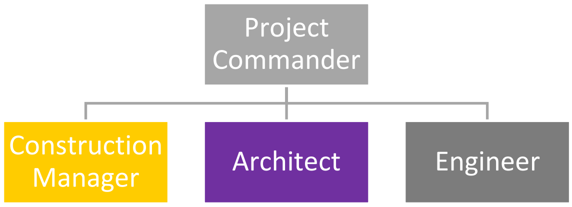

Figure 1. Personnel Hierarchy

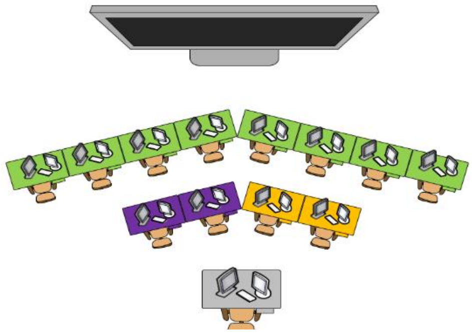

Figure 2. Control Room Layout

Lean construction posits integrating several project entities into one collaborative room, also known as Obeya Room where progress is monitored, and decisions are made collaboratively. In the control room, large screens can be used to monitor several streams of incoming live data in order to facilitate data analysis and data-based rapid decision making. Several technologies can be used to obtain project data and monitor its progress. Some of the suggested technologies are discussed next.

4.1. Unmanned Aerial Vehicles (UAVs)

UAVs are aerial vehicles that can fly autonomously or via human remote control without the need for onboard human assistance. The terms UAV and drones refer to the same aerial vehicle in this context. Recently, UAV applications have increased in several industries due to their ease of use and relative affordability, and construction is no exception [33]. UAVs are used to capture images and videos for construction sites to build an as-built 3D model. The models are then compared to the BIM models to assess construction progress [34]. Moreover, drones equipped with laser scanners are able to estimate the volumes of soil excavations quickly and more accurately than traditional human surveying methods [35]. In logistics management, drones are used to track materials on-site using GPS and ultra-wide band radio frequencies. Drones are also used to check for structural failures and defects in concrete bridges [36]. Coifman et al. 2004 used drones for transportation surveillance on highways and road intersections and numerous researchers have investigated the applicability of drones for safety inspections on construction sites [37].

4.2. Trello

Trello is a cloud-based and Kanban-style project management tool that aids users in managing and organizing their tasks. Trello uses a wide virtual board on which users can see all activities and information. Users only require internet access to view the content on the project's board, and those who wish to add content to the board are required to have an account on Trello [38].

4.3. Location Based Management System (LBMS)

Location-based schedules are linear schedules that show the progress of tasks within the working locations [39]. LBMS is mostly known for visually managing buffers between tasks, achieving continuity in workflow, monitoring task progress, forecasting task progress, and warning about cascading delays [40]. LBMS aids the process of project control, as the sequence of control in LBMS is monitoring progress, forecasting, and identifying and solving problems [41]. Hence, using LBMS in the CCR to monitor task progress is recommended due to its highly efficient visual techniques.

5. Testing CCR on a real-world case study

To build a DES model, data was obtained from two sources. Regarding the delay times per entity, Mohamed et al. 1999 [42] found that the construction manager needs 3.52 hours to resolve and issue, while architects and engineers need 3.72 hours (Figure 3).

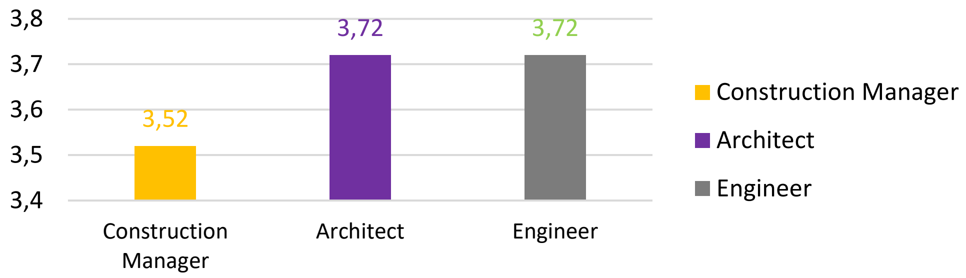

Figure 3. - Delay Times per Entity

Reasons for non-completion of certain construction activities were obtained from a leading Global Project Management And Engineering Company, while delay times per entity were obtained from a research paper by [42]. The reasons for non-completion of planned tasks were recorded for 94 weeks. Afterwards, each reason was attributed to a project entity in charge of addressing the issue (Table 1), and the percentages per entity were as follows: the construction manager was responsible to resolve 67% of the requests for information (RFIs), the architect was responsible for 17%, and the engineer was responsible for 16% (Figure 4).

Table 4. Reasons for Non-Completion of Construction Activities and Their Responsible Entities

	CM	Architect	Engineer
Scope of Work		✔	
Client-Driven Changes/Delays		✔	✔
Arch/Eng/Design RFI		✔	✔
Schedule/Coordination	✔		
Prerequisite Work – Self	✔		
Qualified Staff Availability	✔		
Materials/Suppliers Availability	✔		
Site Conditions			✔
Incorrect Time Estimates	✔		
Safety Non-Conformance	✔		
Cost/Commercial Prerequisite	✔		
Total Number of Reasons	2604	636	633
Percentage	67%	17%	16%

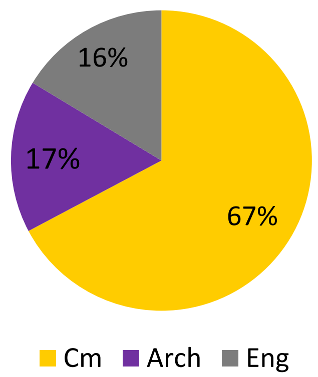

Figure 4. - Percentages of Responsibility per Entity

6. Information flow analysis by Discrete-Event-Simulation

Discrete-Event Simulation (DES) is used in this paper to represent the workflow within the CCR and to model the process of data transfer between the entities present in the room. The data collected and monitored from the site through the aforementioned technologies is transferred to the control room and consequently to each concerned entity in the room. The time taken for constraints to be removed and RFIs to be dealt with can be one of the indicators for the efficiency of the model.

In the model shown below (Figure 5), site data is collected by drones, LBMS, BIM, and Trello, and are automatically sent to the Commander who is the highest authority in this CCR. He then distributes the data to the responsible entities according to the obtained percentages (67% to the CM, 17% to the Arch, 16% to the Eng). Once the Construction Manager (CM) receives the RFI, he resolves it and sends it back to the commander for approval. If the commander approves it, it is considered resolved. If he disapproves it, it is sent back to the CM for re-resolving. As for the architects and engineers: once they receive an RFI, they resolve it and send it to each other and to the CM (not the commander). The addressed RFIs are then either approved or rejected by the CM, leading to a wasteful cycle of iteration requiring further attention.

Figure 6 offers a simpler representation. The commander first sends the RFIs to construction manager, architects, and engineers. The CM resolves the RFI and sends it back to the commander for approval. Architects and engineers resolve the RFI and send it (1) to each other and (2) to the CM for approval.

In the first run, a configuration of one commander, one construction manager, one architect, and one engineer was modeled. From the simulation run, delay times per entity and resource utilization (RU) values were obtained. The results of the first iteration are unsatisfactory. The delay time of the CM is too long (378 hours) and the resource utilization is too high. High RU values are physically and mentally draining for entities and lead to fatigue and exhaustion. Several iterations of different configurations (increasing the number of CMs, architects, and engineers) were modeled to reach a balance between delay times and resource utilizations. RU must not be too high, and delay times must be close to those suggested by Mohamad et al. in companies that use web-based management systems (WBMS).

According to the simulation runs, the best configuration for this particular project data is one commander, four CMs, two architects, and two engineers (Figure 7). This configuration gives acceptable delay times that are close to the ones suggested by Mohamed et al. 1999 [42] and average RU values.

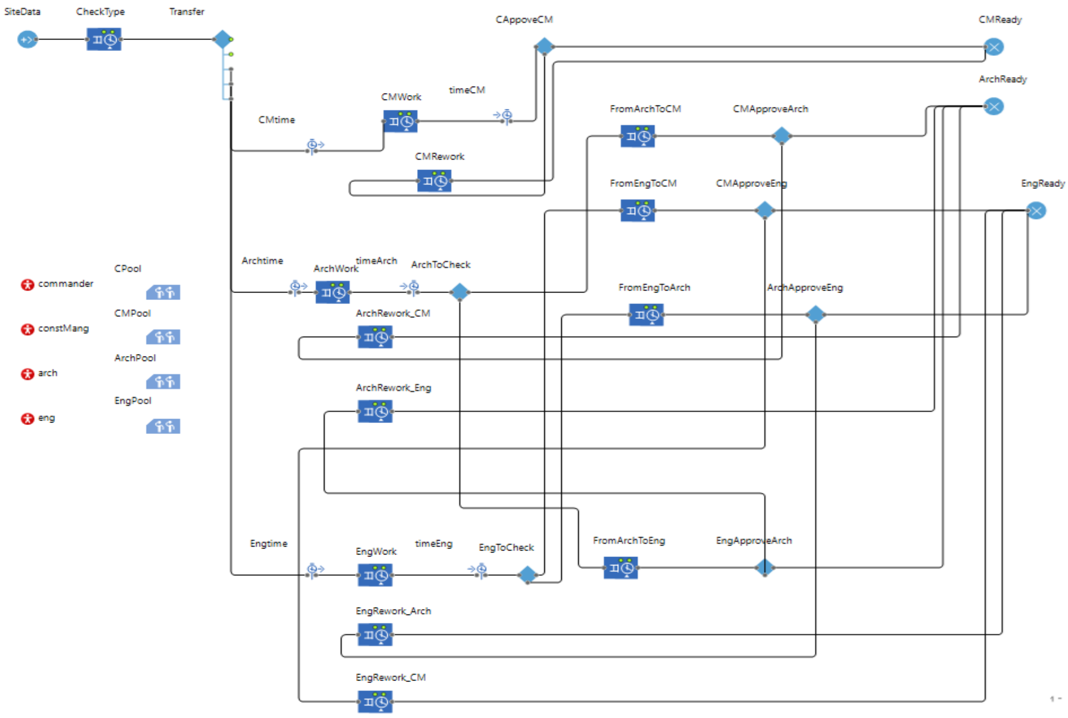

Figure 5. DES Model

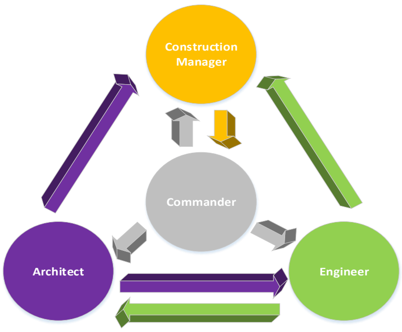

Figure 6. Entity Relationships

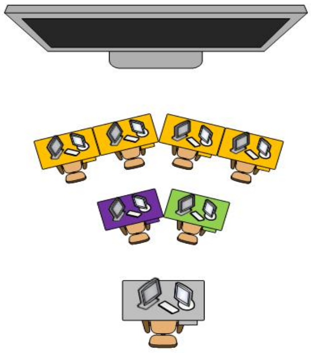

Figure 7. New CCR Configuration

Table 5. Different Simulation Runs with Different Configurations

Trial #	Commander	# of CM	# of Arch	# of Eng	CM Duration (hr)	Arch Duration (hr)	Eng Duration (hr)	C Util.	CM Util.	Arch Util.	Eng Util.
1	1	1	1	1	378.89	4.88	5.08	69%	100%	44%	43%
2	1	2	1	1	11.54	6.01	5.61	47%	90%	57%	60%
3	1	3	1	1	4.23	5.54	5.89	47%	62%	59%	61%
4	1	6	1	1	3.52	5.81	5.32	47%	33%	54%	52%
5	1	6	4	4	3.51	3.53	3.45	47%	32%	14%	14%
6	1	5	3	3	3.56	3.61	3.52	47%	38%	19%	18%
7	**1**	**4**	**2**	**2**	**3.65**	**3.66**	**3.67**	**47%**	**50%**	**26%**	**29%**
8	1	4	1	1	3.66	5.17	5.45	48%	48%	57%	54%
OPTIMAL [51]:					3.52	3.72	3.72				

7. Conclusion

The goal of this paper is to introduce the concept of military operation rooms to construction by proposing a technology-based CCR where several technologies are integrated into one comprehensive and inclusive framework. Such technologies include drones, LBMS, BIM, and Trello. A CCR allows for global collaboration among various project entities, accurate progress monitoring, and proactive issue resolution. While similar concepts such as the war room have been developed and used in the construction industry, no research or application has been found similar to the one presented in this paper. The work suggests that each project should have a CCR that not only is used for meetings but also overlooks all related activities of the project 24/7. Thus, as long as there is a task being executed on site, the CCR will be monitoring and controlling the execution of this task.

DES is used calculate the number of personnel in the CCR and to model the process of data-transfer and RFI resolution among all project entities. It represents the flow of information from the point the information or request reaches the CCR, to the point of resolving the request and sending it to the site. To build the model in an accurate manner, data from a project one of the authors worked on was used. Afterwards, the authors were able to calculate the total number of requests issued per week and the percentage of requests that were sent to either the construction managers, the architects, or the engineers for them to resolve. The simulation model was then used as tool to assist in calculating the optimum number of entities from each department that should be allocated in the CCR. For the project in hand, it was found that there should be one commander, four construction managers, two architects, and two engineers. The model can be used for different projects to calculate the resource allocation of the required CCR.

Future work will further develop the concept of the CCR. The authors plan to investigate the feasibility and the costs and potential savings of using the CCR. Moreover, further study is required to identify the most suitable individual in the project team to command this CCR or decide if an individual from outside the project's team should host it for an objective, independent, unbiased viewpoint to counter the optimism witnessed in many projects that go over schedule and budget. Finally, future studies will also focus on investigating the most suitable delivery method to use the CCR.

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Development of a Risk Management Process for the Construction Sector

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Abstract

Projects are surrounded by a range of risks that can hinder their success, especially at the moment that characterized by the acceleration of economic growth, advanced technology, and intense competition. Construction projects have a special nature and one of their most important features is the project duration that may lead to changes in the conditions, which makes them contain multiple risks due to the long duration of the implementation period and the multiple stages that leads to increases in the probability of occurrence of the risks, which reflects negatively on the economics of construction. Therefore, risk management has emerged as a solution to control risks in a systematic and scientific way to avoid their negative effects.

This research aims to extend the processes of risk management from the perspective of construction to provide a framework for construction risk management processes. In this regard, the research highlighted the standard risk management processes based on PMBOK. Furthermore, we investigated the processes of construction risk management in the literature which lead to introduce two more processes besides the standard one, which are risk analysis verification and risk plan experimentation. This facilitated to develop the risk management outcomes in order to bring benefit to the organization. Additionally, we introduced some suggestions for construction risk management such as training and establishing a project risk information system in order to improve construction risk management. These suggestions shed more light on increasing the effectiveness of risk management through new ways.

Keywords: construction project, risk analysis, risk management, risk management process

1. Introduction

Due to the lack of proper risk management, projects usually end up with financial losses and waste of resources which, in turn, affects the credibility of the organization that has a negative impact on it is image and relations with stakeholders [1]. Therefore, it is essential for projects to implement risk management to succeed and achieve their planned results and objectives. Risk management helps to recognize the potential risks that the project may be facing and identify steps and procedures that mitigate the effects of these risks on the project and its consequences. Additionally, it develops the decision-making, planning and prioritization methods through a comprehensive and systematic understanding of project activities, the negative and opportunities available. Furthermore, it brings important benefits such as reduced cost, and increased stakeholder engagement. It was found that most construction risk management decisions have done based on previous experience, intuition. and judgment of the manager. As a result of the lack of formality of the system and the lack of integrative mechanisms of risk management among the parties involved in the project [2] [3]. The fundamental objective of integrated risk management for the construction project is to identify, manage and control risks more intelligently, and appropriately.

Considering that the implementation of these projects must be in accordance with the approved budget, on time and within the required specifications [4].

2. Construction risk management processes

Construction risk management is a proactive process and a systematic approach to control and minimize risks and even prevent their effects. These steps are carried out throughout the entire project life cycle. Certain risks are within the boundaries of the project, some others lie outside the project, but still inside the organization, and there are ones outside the organization. These risks must be identified and handled at the right level, and by the proper risk owner. Here it must be emphasized that the risk owner is not the owner of the project and they have a different interpretation of risk. The Risk Owner is usually the one who can best identify and monitor the risk and that can best drive the specified countermeasures.

2.1. Plan risk management

It is a very important and essential process that determines the way in which the other processes will be followed and therefore the basis of their success. In this process, the risk management method must be selected along with the risk itself and predict how important it is to the stakeholders and participants. The stakeholders of the project may have a strong perspective on project risk. While some stakeholders may be risk-tolerant, others may wish to staff and structure the work to minimize extreme outcomes [5]. During this phase, the degree, the type, and the visibility of risk management are defined by the scope of the process and who are involved in it. Also, roles, responsibilities, the required resources for performing risk management processes should be appointed, and new types of risk assessment points must be scheduled, which will be part of the risk management plan. Moreover, all the subsidiary risk plans must conform to the global project risk management plan.

The plan should provide guidance to the project management team in the use of risk management, both in the baseline schedule development and for the schedule updates. The plan development will serve to persuade the project management team to realize that managing risk is a formal procedure, with a regimented process to be used as the approach to a standardized plan [6]. As the PMI states, the risk appetite of stakeholders including the owner is recorded in the risk management plan. The appetite for risk is quantifiable and measurable. In some construction firms the risk management is not being taken into account seriously in the practice of the project management. There are many reasons for this such as the project managers often neglected or underestimated the project risks, and there are not special departments or special full-time staff to perform risk management duties.

2.2. Risk identification

Risk identification process involves identifying all the risks that the project may be exposed, their sources and their potential consequences regularly because the risks arise and develop throughout the life of the project as well as their characteristics. Therefore, risk identification is a continuous activity during the whole life cycle of the project. It's impossible to identify and manage all the risk in the construction projects. It can be a waste of time and counterproductive, so it's crucial to focus on the vital risks only [7]. All project stakeholders are encouraged to introduce a new individual or global risk sources into the risk management process. The PMI highlights project manager, project team members, project risk specialist, customers, external experts from application area, end user, operations managers, stakeholders, risk management experts as relevant stakeholders [8]. Identifying other stakeholders during this phase is recommended such as:

- Organizations or functions that provide decision making, funding, services related to the risk (including outsourced providers), policy (including regulators).
- Organizations/groups that will be impacted, directly or indirectly by the consequences should the risk occur but who do not fit into the categories. These are secondary stakeholders.

A more holistic approach to project management by incorporation of the departmental head at the primary stages of the project. Departmental heads need to be involved in order to promote higher levels of communication between departments and therefore reducing risks that are likely to occur [9]. There are numerous ways in which construction project risks can be categorized, for example in accordance with their occurrences in different construction stages, or in accordance with the nature of the risks [10]. Risks can be classified in several ways for different purpose as shown in table 1.

Table 6. Risk Identification Categories

Risks Classification	Author
Investors risk, Contractor risk, Material supplier risk, Project managers risk, Government risk, Other project stakeholders risk	(W. Lin, L. Yaqi, and W. Enmao) [11]
Preliminary design, Tender, Detailed design, Construction works, Financing the investment	(N. Banaitiene and A. Banaitis) [12]
Resources, Productivity, Design, Managerial, Payment, Client, Technical, Subcontractors	(I. Dikmen, M.T. Birgonul, S. Han, 2007) [13]
Project management, Engineering, Execution, Suppliers	(A. Nieto-Morote, F. Ruz-Vila, 2011) [14]
Construction safety related, Construction management, Engineering design, Natural hazards, Socio and economic	(Y.C. Kuo, S.T. Lu, 2013) [15]
Quality related, Environment related, Safety related, Cost related, Time related	(P.X.W. Zou, G. Zhang, J. Wang, 2007) [16]
Internal (Owner, Contractors, Subcontractors, Designers, Suppliers), External (Social and Cult, Economic, Political, Natural, Others)	(S.M. El-Sayegh, 2008) [17]

2.3. Qualitative risk analysis

Qualitative risk analysis is responsible for the ranking of project risks. It is carried out throughout the project life cycle to ensure it's effectiveness by making the necessary changes. The ranking process can be conducted in many ways, organizations even possess their own special methods, but all the methods are built on the assessment of probability of occurrence and the impact on the project and combining them as primary factors as well as secondary factors such as the time allocated to the response to risks and the degree of project tolerance for these risks through limitations. The qualitative analysis is sufficient for rank-ordering risks. It allows sorting the risks from most to least important [5]. One of the most important steps of this process is risk categorization. Categorization can be conducted in several ways, finding common characteristics or root causes.

The Probability, impact matrix and the hierarchical charts are typical category-based tools for risk management. The matrix helps graphically to categorize the risks into groups in the dimensions of the probability of occurrence and impact. If the categorization is conducted by three dimensions, the two-dimensional matrix is insufficient. Hierarchical charts display risks in two dimensions by the two axes, but the size of a graphical figure (usually disks, bubbles) represents a third dimension (e.g., acceptance level). This may lead to developing more effective risk responses by focusing attention and effort on the areas of highest risk exposure, or by designing standard risk responses to address groups of similar risks. Once a group of risks with the highest exposure is identified, greater attention can be paid to this category [8].

The guiding principle for the grouping of risks is based on risk breakdown structure (RBS) or work breakdown structure (WBS), and the aim of this process is to assign the groups to proper risk management plans and actions. The RBS generally focuses on the causes of risks handled by additional management attention, while the WBS is built on functional disciplines maintained by more leadership attention and organizational involvement [18]. The hierarchical structure very effective in construction practice, because risk factors are numerous, especially in large projects, and the ability of humans to evaluate several factors at the same time is very limited [10]. The priorities can be compared against targets or other criteria to measure risk management performance, to identify risks for which further analysis are needed, and to direct the development of action plans and the allocation of resources [19].

2.4. Quantitative risk analysis

The multi-dimensional concept of qualitative risk analysis underlies the phase perform quantitative risk analysis. On the one hand, this phase is optional, on the other hand, the analysis is numerical here. Quantitative risk analysis enables a reliable evaluation of risks. It is carried out on the risks identified in the qualitative analysis by conducting an impact analysis and numerical estimation for decision-making in case of doubt. The prerequisite of this assessment is the availability of relevant, quantifiable ratio scale data. The analysis is usually based on simulation that determines the effects of risks, sensitivity analysis, decision tree, or more rigorous statistical methods that provide further insight into project risk. The categorization of risks is a typical step for performing quantitative or qualitative risk analysis. The best way to deal with risks in a project is done frequently to ensure that the risks are addressed.

Frequently, the quantitative process is required by decision-maker stakeholders. Through undertaking the necessary activities for quantitative risk analysis, a newly updated risk register is achieved by introducing changes to the risk register obtained after qualitative analysis. The output of this phase is a list of risks that have been quantified in order of priority sorted by a combination of the probability analysis of the project, the probability of achieving the cost and time objectives, and the consequences [6]. Risk analysis is an essential step to help identify appropriate ways of dealing with risks. Organizations appreciate the benefits of risk management in construction projects, formal risk analysis and management techniques are rarely used due to lack of knowledge, inexperience, and doubts on appropriateness of these techniques for construction projects [12].

2.5. Risk analysis verification

It reviews the risk analysis output in order to define whether the listed risks are relevant to the organization’s goals and could cause real threats. It's aimed to filter out all the risk not relevant to the organization’s goals. This phase must be conducted by different employees in the organization who are not associated with the team who worked on the previous phase. The filtering technique provides useful resources for the real risk pretending to business objectives and saves the organization resources from working on risks not related to their goals [20].

2.6. Plan risk responses

The risk planning process aims to identify the appropriate methods and activities for the plan to address the risks identified in the risk register according to their priorities and relevance, in order to minimize their impacts. The responses include reviewing options, choosing strategies, and triggering actions. Properly selected responses are responsible for exploiting opportunities and reducing threats stemming from risks. The appropriate response can be selected from a set of strategies. If there are threatening effects, the project manager can escalate, avoid, transfer, mitigate, or accept it. If there are opportunities, very similar tools are to be employed: escalate, exploit, share, enhance, and accept. The organization should determine how they should be combined into its overall strategy, according to the extent to which it is prepared to accept or tolerate risk. Policy decisions such as this must be made at senior levels in the organization, not left to individual managers [19]. Ensuring that the cost of confrontation is proportional to the severity of the risk. The cost of confrontation should not be greater than the losses that occur if the risk occurs, in addition to the appropriate time of confrontation to avoid further losses.

After determining the appropriate strategy to address each risk, a number of changes are made to the risk register such as: specific risks, their clarity, the aspects of the project affected, their causes and the manner in which they may affect the project objectives, agreed risk response strategies, how to implement the chosen strategy, funding and time required to implement the selected strategies, contingency plans, standby plans where the specific response method is not appropriate, and contingency precautions. A part of documenting the decisions should include preparing a risk mitigation plan for those unresolved risks and acting on that plan. The risk mitigation plan might include just monitoring unresolved risks to ensure that they don’t become a driver of productivity or delay [6]. According to risk management standard the stakeholders reach an agreement on which risk treatment is accepted. A detail treatment plan should be defined on how to be executed. Also, during this stage, reporting and communication are established to the stakeholders. The purpose is to share the knowledge obtained during the execution process [21]. In any project, the development and implementation of detailed action plans for reducing risks is the key to successful project risk management in practice [19].

2.7. Risk plan experimentation

It examines whether the risk planning performed in the previous step is accurate and comprehensive. It also checks if all risks are applicable to the organization and are correctly classified according to their impact and probability. It's aimed to prevent wasting resources throughout the implementation phase by assuring the validity of the risk [20].

2.8. Implement risk responses

It is implementing the most suitable and strict controls and procedures for the identified risks.The planned and agreed responses are executed here to decrease individual project threats, and to increase individual project opportunities. During the execution phase, risk control might require modifying the current execution plan, ending the risk or even starting a contingency plan if the current plan is found to be ineffective and requires starting from the beginning of the risk process if a new risk has been identified [22]. One of the major mistakes in this stage is that the risk management process is incomplete. The risk management process includes a throughout identification and analysis, risk plans (with lessons learned register, risk register, and risk report), but no effort and action are taken to finish it.

2.9. Monitoring risks

It is a tracking process for the implementation of the risk response plan. It is aimed to monitoring of residual risks and the identification of new risks and sources that could present after an action and should be communicate to the stakeholders to assess the effectiveness of risk management on all aspects of the project using the performance information obtained during the project implementation, which also enables to see if there is a follow-up that risk management procedures are in place, introducing the necessary changes to the project management plan and adjusting emergency reserves appropriately with the changes that occur. A proper tracking process results in decisions based on current information about project risks. Traditionally the data analysis consists of technical performance analysis and reserve analysis. The tools and techniques of monitoring are audits and meetings besides the data analysis. This phase is critical for formation of the lessons learned database [23].

3. Suggested solutions to improve construction risk management

Construction firms should establish a series of risk resistance mechanisms, include risk management planning process, risk management organizational mechanism, and risk management functional division. Moreover, the risk management department shall be established and assign a full-time experts and team who responsible for risk identification, control and management, and contribute to coordinate and solve the risk management problems existed among the relevant departments and the involved parties [4]. Construction projects include a widespread distribution of participants, complex specialty and huge information. Therefore, project participants need to know each other's information quickly and effectively, and project decision-makers need timely project information to take the right decision. The project risk information system shall be established, in order to reduce the cost of collection, exchange, and transmission of project information. Training is the keystone to any risk management plan. A risk management approach will most likely not be adopted or followed without a formal training effort. Training should not only take place at the beginning of the processes but should also include regular informational session to display any lessons learned, policy changes or identified leading practices. Also, refresher sessions are required to maintain employee’s consciousness of risk management policies and procedures and assure that organizations are committed to risk management. Implementing a standard process is very crucial to ensure consistency and avoid duplication of reporting. The project team including the project manager selects the sufficiently important project risks and gives the appropriate response. The responsibility for responding to risks when they occur for only one person in order to ensure focus and not to be distracted and neglect. Some project managers are trying to manage all risks themselves. Therefore, Identify and hire risk owners with the experience and ability to develop and execute risk response plans effectively and efficiently.

4. Conclusion

The organizations are required to deal with risks carefully by adopting scientific methods to face them and ensure the success of their projects, and this can only be achieved by following the risk management approach in the project. Effective risk management, especially in the construction industry, helps to execute projects correctly, which reflects on project success positively, and brings benefits to all parties of the project. Keeping in mind that managing risks effectively does not mean avoiding it, rather recognizing it correctly and knowing all the opportunities and risks associated with it. In this paper, an extension of standard risk management had been introduced from the construction perspective, which includes two more processes that are risk analysis verification and risk plan experimentation, in order to implement the risk management smoothly and achieve the project objectives. Furthermore, some suggestions had been highlighted to improve construction risk management and execute risk management system effectively and efficiently.

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Education's Impact on the Decline of Craft Workers in the United States Construction Industry

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Abstract

As the number of craft workers in the United States has declined significantly in the past 20 years, various news articles and studies cite multiple reasons that have led to the decline. Perhaps the most significant impact is the evolution of technology. As technology has evolved, younger generations have not been exposed to the same opportunities as their parents and grandparents; therefore, they have not developed hands-on skills, causing a lack of interest in craft labor from an early age. If today's generation is not acquiring interests in these skills during their own time, has America's educational systems responded to this change by strengthening their vocational programs to maintain interest from the younger generation? For this study, data provided by the National Center for Education Statistics (NCES) was analyzed to determine the availability and interest in construction trade programs throughout the United States, to conclude if educational opportunities have impacted the recent decline in the construction trades.

Keywords: career, and technical education (CTE), higher education, occupational, vocational

1. Introduction

The craft/skilled trade worker labor category is extremely broad; it includes higher skilled occupations in construction (building trades, craft workers, and their formal apprentices), natural resource extraction workers, occupations related to the installation, maintenance and part replacement of equipment machines and tools, and also production occupations (Code of Federal Regulations, 2017).

Unfortunately, the construction industry has experienced a nationwide shortage of skilled labor. Construction is the second largest employer in the country and according to a recent study performed by the Construction Industry Institute, 75% of contractors are experiencing labor shortages that are resulting in cost overruns and/or schedule delays (Christine Fiori, 2003). Upon analysis of why there is a decline in the number of workers, there are many possible explanations; however, the most significant factor is simply that the younger generation is not replacing the older generation at the rate at which they are leaving the industry.

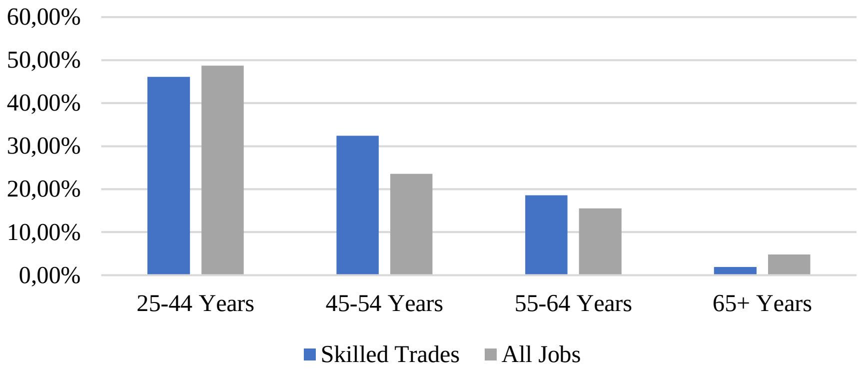

Figure 1. Age Breakdown: Skilled Trades vs. All Jobs (Wright, 2013)

According to EMSI (Economic Modeling Specialists International), in 2012, 53% of skilled-trade workers in the United States were 45 years and older and 18.6% were between the ages of 55 and 64. In comparison, 44% of workers were 45 years and older and 15.5% were between the ages of 55 and 64. A more significant statistic is that skilled-trades have only 1.9% of workers 65 and older, whereas the total labor force has 4.8% (Wright, 2013). Unfortunately, these numbers allude that older skilled-trade-workers are often not able to avoid an early retirement due to physical ailments, as their jobs are more physically demanding than a typical white-collar job. As a result of earlier retirements from the current workforce, there is more pressure for the younger workforce to replace them at a faster rate.

Another possible explanation for the decline in skilled labor trade could be the lack of interest and negative perception of the industry from the younger generations. When surveyed about possible career choices, high school students ranked a career as a construction worker 247 out of 250 occupation options (Bigelow, Ostadalimakhalbaf, & Escamilla, 2016). Unfortunately, many view the construction industry as undesirable because of the high job intensity, dangerous and dirty working environments, and ambiguous career paths. This is unfortunate, as the construction industry is evolving and working to overcome this perception by implementing strict safety programs and offering new programs to improve craft worker's physical health such as regulation health examinations, health guidance, smoking cessation measures, and nutritional education (Shan, Ph.D., P.E., M.ASCE, Imran, Lewis, Ph.D., P.E., M.ASCE, & Zhai, Ph.D., 2017).

The negative perception of the construction industry is a result of the United States' education system. Unfortunately, the past two generations have been encouraged by American high schools to attend a four-year college, promising more employment opportunities and a greater salary potential. However, as more people are seeking college degrees, many are finding that a degree doesn't necessarily provide employment in high paying positions. In order to meet the growing demand of the construction industry, education systems across the United States must emphasize the high and growing demand for construction trade workers, the significance of the industry to our economy, and encourage America's youth to return to the construction industry (The Construction Labor Shortage: Where Did All the Skilled Labor Go?, 2017).

To change the perception of the industry, the United States should look nations like Germany, where craft work is regarded not as merely a trade, but a career, with schools offering apprenticeship programs for high school students. Richard Sennett, a New York University sociologist states, "Corporations in Germany realized that there was an interest to be served economically and patriotically in building up a skilled labor force at home; we never had that ethos" (Uchitelle, 2012).

2. Background

The Smith-Hughes Act of 1917 was the first authorization for the Federal funding of vocational education. Subsequent legislation for vocational education (now termed career and technical education) included the Vocational Act of 1973. The Carl D. Perkins Career and Technical Education Improvement Act was initially authorized in 1984 and re-authorized in 1990, 1998 and 2006 (Smith-Hughes Act, 2003). On May 17, 2017, the House Education and the Workforce Committee unanimously approved its Perkins reauthorization bill, H.R. 2353, the Strengthening Career and Technical Education for the 21st Century Act (Hyslop, 2017).

The Perkins Act provides almost $1.3 billion annually to career and technical education programs in all 50 states until 2016. Federal funds provide the principal source for innovation and program improvement. State and local funding supports the career and technical education infrastructure and pays teachers' salaries and other operating expenses (Smith-Hughes Act, 2003; Issue Brief Carl D. Perkins Act, 2017). Overall, the program's purpose is to increase the quality of technical education programs throughout the United States, providing both academic and technical skills in order to create successful workers in a knowledge-based and skill-based economy (Hyslop, 2017).

3. Purpose of the study

The purpose of this study is to explore what construction trade focused/vocational/occupation trade programs are being provided for the current generation. More specifically, at what age level are construction-related vocational programs being offered and discussed as a potential career pathway with students, what types of programs are being offered, and are students interested and enrolling in these programs? While vocational educational opportunities and support in schools may not be the only factor that contributes to the overall decline in skilled trade labor, it is a significant factor, as it allows all students the opportunity to be exposed to and try a variety of skilled trades. Furthermore, school counselors' encouragement and support for these programs provides students that are not interested in a four-year university or seeking a white-collar profession with a career pathway that will allow them to become an expert in whatever skilled trade that may best suit their interests.

4. Rational for the study

There is a substantial need for Technical Programs in schools, specifically within the construction trade industries. Based on current market needs, without school intervention, the craft worker and trades will not have enough labor support. Unfortunately, as a result, contractors will experience project labor shortages and cost escalation, lengthening of schedules and recordable incidents

Furthermore, it is the responsibility of educational programs to utilize funding for these programs and be dynamic in making sure that the future workforce is not being funneled down a four-year college preparatory career, but is instead supporting youth to explore various learning opportunities, include Career Technical Educational Programs. Statistics prove that high school students involved in CTE programs are more engaged, perform better, and graduate at higher rates. The average high school graduation rate for students in CTE programs in 90.18% compared to an average national freshman graduation rate of 74.9% (H.R.2353 - Strengthening Career and Technical Education for the 21st Century Act).

Mr. Paul Tse, Project Manager at Shapiro & Duncan cites how a local career and technical education program at Thomas Edison High School of Technology not only provided him with a sense of direction. Moving to America from Hong Kong at the age of 10, Mr. Tse lacked direction in his life and career, and upon the advice of a guidance counselor, enrolled in a HVAC program his senior year of high school. Upon graduation, he had two (2) job offers for an apprenticeship from local companies (H.R.2353 - Strengthening Career and Technical Education for the 21st Century Act).

Skylar Huggett, the 2017 recipient of the Georgia Occupational Award of Leadership (GOAL) scholarship was on the career path to be a nurse, at a four-year college. She soon realized that was not the right fit for her and she transferred to a community college to pursue an associates degree. Inspired by a documentary of a woman welder, she enrolled in welding classes at the earliest opportunity and realized after the first day of classes that this was a "career – something she was passionate about and truly enjoyed." As a "four-year college" drop-out, she cites that pursuing a vocational career was something that she didn't initially consider. However, she quickly realized that it was the right fit for her, and has encouraged friends that finished college with degrees and who are unemployed or who are unsure if it is the right fit to pursue vocational classes. She states, "Had I started with technical school I wouldn't have the student debt that I do and would already have been years into my career. Vocational schools and trades need to be promoted and supported more." As a welder, she is very much aware of the decline in the workforce: "The people currently in the workforce are getting closer to retirement and there are less younger individuals entering the trades. This is a huge problem, as the experienced men and women in these are needed to pass on their way of the trade or the tricks and secrets to successfully get a job efficiently done. I am personally seeing a generational gap in my welding field and it's a problem." (Huggett, 2017)

5. Research design

The National Center for Education Statistics' (NCES) reporting system for national information on career and technical education (CTE) (Career and Technical Education) provides data based on a compilation of information from a variety of existing federal data collections. The wide variety of data sources provides an accurate overview of current statistics, as well as historical trends, and prediction models (National Center for Education Statistics, n.d.).

By utilizing CTE statistics, I am hoping to determine not only the availability of construction trade programs in high schools/vocational schools and vocational colleges, but also students' interest and participation in vocational/occupational construction trade programs in the past decade. By analyzing the statistics and exploring relationships between related figures, I will be able to determine the presence of any significant correlation between the availability and interest in vocational education programs to determine if this has contributed towards the decline in craft workers.

6. Data and analysis

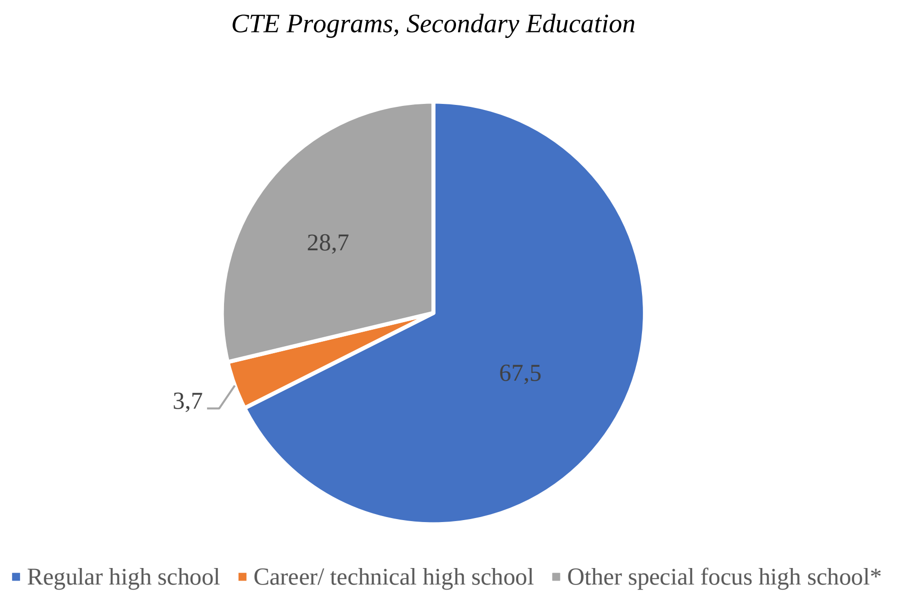

Figure 2. Percentage of public high schools that are regular, career/technical, and other special focus, and various characteristics of each school type: 2008, (National Center for Education Statistics, n.d.).

According to the U.S. Department of Education, National Center for Education Statistics, Schools, and Staffing Survey (SASS) Public School Questionnaire, for the school year 2007-2008, approximately sixty-eight (68) percent of public high schools were "regular" high schools, meaning that vocational programs may be offered as elective classes for students, but the overall curriculum was not "vocationally" driven, but was based on a standard teaching curriculum. Approximately twenty-eight (28) percent are considered "other special focus high schools" such as science or mathematics schools, performing arts schools, talented or gifted schools, and foreign language immersion schools), special education schools, alternative schools, and other types of schools that do not fall into these categories. Nevertheless, only four (4) percent are considered "career/technical" high schools (National Center for Education Statistics, n.d.).

Recognizing the growing demand for vocational trade, the Perkins Vocational and Technical Act has funded several new Career/Technical high schools in North Carolina, specifically. In Wilmington, the first Career and Technical Education high school will be opening in the Fall of 2017 (DelaCourt, 2016). This school was modeled after the Vernon Malone College and Career Academy in Wake County, North Carolina, which opened in August 2014. Due to the success of the Vernon Malone College, the North Wake College and Career Academy was opened in September 2016. While this is limited to the piedmont/coast of North Carolina's educational system, school systems around the United States are recognizing not only the need for these programs, but their success and contribution to not only providing students with education and career paths, but matching students with career paths that are in high demand by industry (Wake County names new CTE high school and hires its principal, 2016).

Table 1:Percentage of public high schools offering various occupational preparation opportunities

	Regular High School	Career/Technical High School	Other Special Focus High School
Career/Technical Education Courses	93.6%	100%	55.1%
Work-based Learning or Internships Outside of School	70.6%	79%	51.5%
Specialized Career Academy	26.7%	61%	13.2%

(National Center for Education Statistics, n.d.)

While many school systems are recognizing the need for career/technical high schools, the vocational education system is not lost in the "traditional" or "regular" high school curriculum. As seen in table 1, in ninety-four (94%) of regular high schools across the United States offer career/technical courses. It is important not to overlook the importance of offering vocational courses to students. Often, many students may consider a vocational course just as an elective, but by merely giving students an opportunity to be exposed to trades, schools are allowing students to be exposed to different career paths. These "traditional" vocational classes are extremely valuable and allow students exposure and appreciation of trades without having to formally commit to that career pathway. Therefore, it is important to realize that while Career/Technical high schools may provide educational opportunities to students who are interested in committing themselves to vocational/trade career paths, regular high schools offering career/technical courses are equally as important, as they provide the "traditional" or four-year college pathway students with exposure to the trades, without formal commitment (National Center for Education Statistics, n.d.).

The data also demonstrates that there is not a significant difference between the percentage of internships available outside of school in "traditional" high schools compared to career/technical high schools. This is extremely important, as apprenticeships offer students the ability to not only learn more about a trade but the opportunity to build their confidence in their future and to see how this trade could provide them with opportunities to shape their career. Nancy Hoffman, the author of *Schooling in the Workplace,* states that the United States' vocational education program is falling behind its European Counterparts. The unemployment rate in the Netherlands and Switzerland is (5%) compared to the United States' twenty-two (22%). Ms. Hoffman cites that the "forgotten half" of students (between the age of 16 to 22) who will not attend a four-year college will be at risk of trying not to land in jail, be unemployed and living on the street, or eternally job-hopping. By allowing students to participate in apprenticeship programs you allow students to enter the workforce and instill responsibilities that allow them to gain confidence in their trade and provide experience that will prepare them to enter the industry immediately following graduation (Goldstein, 2012).

Apprenticeship programs are vital components of all vocational programs. However, part of the challenge in providing apprenticeship opportunities is overcoming the perspective of many Americans that most sixteen (16) year-olds are not ready for the responsibility of learning a trade. In her book *Schooling the Workplace,* Ms. Hoffman mentions that Volkswagen is starting an European-style apprenticeship program in Tennessee, but it is only available to high school graduates. Ms. Hoffman also suggests that the United States should look towards Switzerland for the implementation of apprenticeship programs. The Swiss government invests in the in initial analysis of workplace training for apprenticeship hosts, and supports research between employers and government. Unlike Switzerland, there are only a small amount of institutions or non-profits in the United States that provide these services (Goldstein, 2012).

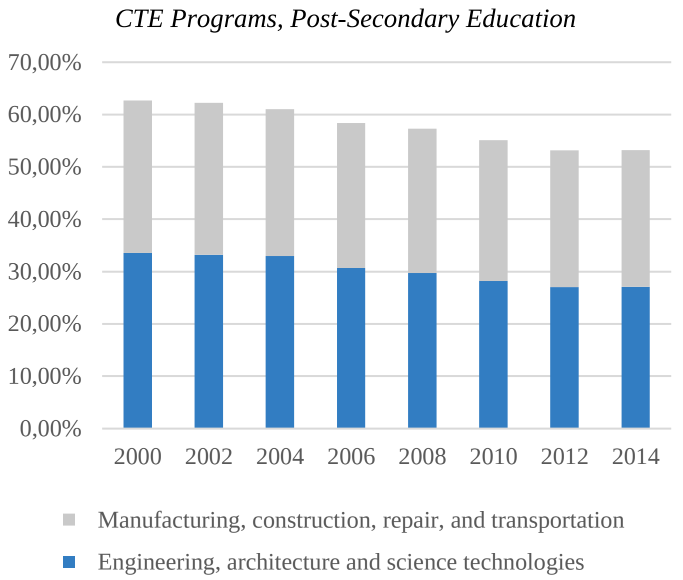

Figure 3. Percentage of post-secondary institutions that offer sub-baccalaureate occupational education programs (National Center for Education Statistics, n.d.)

While many students may enter vocational career programs in high school, often they are first exposed to vocational careers in post-secondary education programs, as they offer more diversity than the sub-baccalaureate programs. Therefore, students are often are able to determine a trade that is the best fit for their interests and career aspirations. Throughout the past decade, there has been a decline in the number of sub-baccalaureate programs offered in vocational schools, as seen in Figure 2. Typically, Career Technical Education (CTE) programs are offered based on student enrollment in previous years. It is evident that the 2008 Housing Market Crash had somewhat of an impact as the enrollment in engineering, architecture and science technologies fell three (3) percent from 2008 to 2012. During that same time period, the enrollment in Manufacturing, construction, repair, and transportation fell approximately one (1) percent, from twenty-seven (27) percent to twenty-six (26) percent (National Center for Education Statistics, n.d.).

While the decline between the years may not seem significant, a one (1) percent decrease in the overall enrollment of twenty-six percent is significant when it reflects to a statistic that is applied based on participation in these programs across the United States. Nevertheless, industry's growing demand for this trade has created a large push for support from sub-baccalaureates vocational programs throughout the United States, providing scholarships and supporting educational programs with apprenticeship programs. Mr. Jonathan Begue, the Construction Management Program Director at Cape Fear Community College in Wilmington, North Carolina, cited that as the local housing market has picked up following the 2008 crash, there has been a large outcry by local construction firms and the local Homebuilding Association as to why there are so little interest in the construction management/construction trade programs. Mr. Begue cites that while there was a decline following 2008, enrollment in these programs has been somewhat steady in the recent years (Begue, 2017).

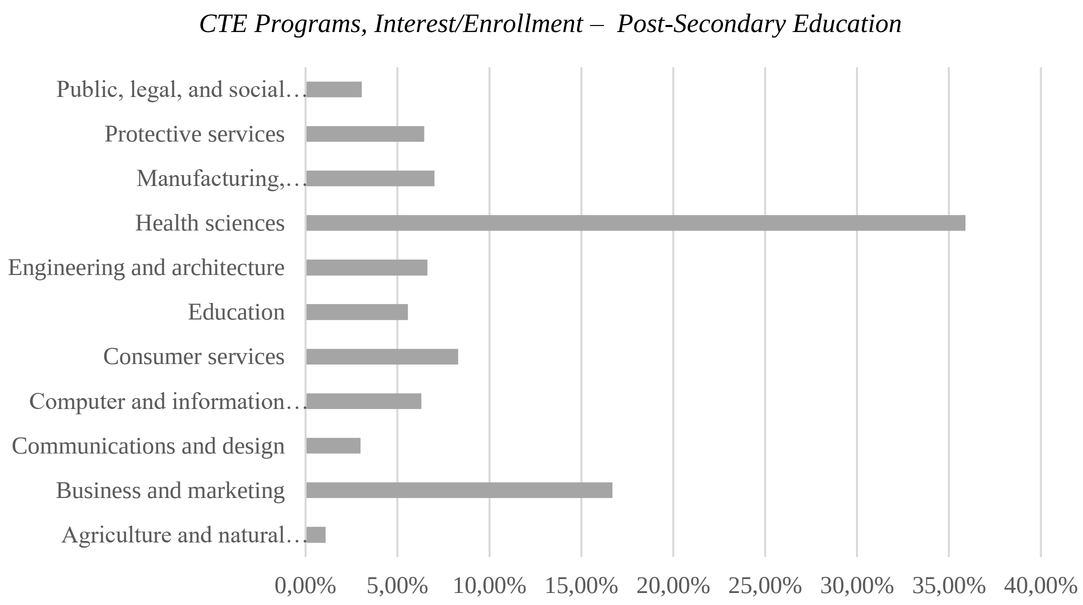

Figure 4. Percentage distribution of credential-seeking, sub-baccalaureate occupational education students within each field of study, in all institution types (National Center for Education Statistics, n.d.)

Perhaps the most obvious question in this research is if students are enrolling in construction trade programs, what other programs are appealing to vocational students? And if students are not entering construction trade programs, why are they choosing these other programs? Mr. Begue began working in the construction industry as a teenager, and speaks from first-hand knowledge of the industry; unfortunately, it comes down to one thing: wages (Begue, 2017).

According to the Bureau of Labor, the median hourly salary of a construction trade worker is $22.88 and the annual mean wage is $47,580. In comparison, the median hourly salary for a Registered Nurse is $32.91 and the annual mean wage is $72,180 (National Occupational Employment and Wage Estimates United States - May 2016, 2017). While each state has prevailing wage rates for each specialized trade, there is still a significant variance in wages between jobs. Another issue for many skilled trade workers is benefits. Compensation packages often do not include benefits such as insurance and health care. Far from a white-collar office setting there is the threat of unsafe working conditions and injuries on a construction job site; in addition, the construction market is relative to a good financial market. The real estate crash of 2008 was a difficult time for many skilled trade professionals, who were forced to leave the industry in order to find work.

Mr. Begue acknowledges that the construction market is difficult. While many companies are now implementing stricter safety policies and procedures, and the real estate market has leveled out, students looking for career options must consider the negatives and the positives. While there has been a decline in the construction trade industry, it is difficult to convince students looking for new career opportunities to take a risk in a volatile industry without receiving competitive pay, to supplement workers who must provide their own benefits. It's an industry that has its booming times, but also has difficult times as well. Mr. Begue stresses to students that while there are negatives with every job, construction trades are unique in that you can provide your own services, your own abilities towards a final project. The satisfaction out of knowing that you are physically contributing your talents and skills towards a final goal makes provides satisfaction that is not captured in data, but captured by those who are driven to see their hard work, their creativity, and their skills produce items that are part of a larger concept. This is something that is not service – it's a trade, a skill that you have not only received education and training to practice, but something that you are so passionate about, that it's what you have chosen as your career (Begue, 2017).

7. Conclusion

Based on the data, it can be determined that the education system in the United States has responded to the decline in construction trade workers by offering more vocational career programs in high schools. As more vocational trade high schools open throughout the country, it is obvious that schools are not only interested creating more opportunities for students, but they are challenging the "traditional" four-year college concept.

Around the United States, schools are helping to change the way that society views vocational careers, with the growing emergence of schools dedicated towards finding a vocational career. By instilling pride in students early on for learning a trade, vocational-focused schools are shaping the concept that a person does not have to have to attend a four-year school to have a "career." A vocational career is another alternative, and one that takes a student who has as much dedication, determination, drive – but maybe not towards a obtaining a business degree, but becoming a highly-demanded welder, brick mason, or a terrazzo floor specialist.

By providing more opportunities for students to be exposed to construction trade careers earlier in their education, there is an increased likelihood that students will follow their interests and pursue careers. Apprenticeship programs and mentors are also extremely valuable and can provide shy students with experience and knowledge to push them not only to learn but to reach their highest potential in their trades.

While the vocational education program has grown significantly, it has only begun its transformation. Based on interviews and data analysis of the availability and interest of vocational programs in schools, one can be sure that America's educational system is embracing this change and supporting industry's need by providing not only more schools, but higher quality schools to help students interested in vocational programs have an opportunity to determine if that is the right fit for them. By overcoming the concept that four year degrees equal "careers," the American school system is changing the public's outlook of the trade careers. Removing this stigma will provide more opportunities for students, and more employees for the industries.

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Effective Project Management Principles and Strategies in Transportation Infrastructure Projects

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Abstract

Departments of Transportation (DOT) are experiencing unprecedented pressure to deliver projects on time and on budget. An obvious response to this pressure is to improve the project delivery process by adopting effective project management principles and strategies. The research team for this study investigated the DOT's implementation level of effective project management practices and strategies for transportation infrastructure projects by first performing a literature review to discover the project management strategies and practices historically used in transportation projects. Then, they designed a survey to identify the general project management practices implemented in the delivery process. They pilot tested the survey, distributed it to state transportation agencies via an online platform, and collected 96 completed surveys. The results revealed that team qualification was ranked the highest of the implementation level of strategies, and that environmental planning and quality management were ranked second and third. The outcomes of this study will help decision-makers and project managers in their assessments and selections of the most useful best practices for delivering an infrastructure transportation project on time, on budget, and with a high level of quality.

Keywords: tansportation infrastructure project, project management strategy, project management principle, design phase, construction phase

1. Introduction

In the last decade, there has been a sharp increase in the number of infrastructure transportation projects in the US, and on any given day, a DOT has hundreds of projects of different sizes underway, with the common purpose of ensuring that millions of travelers experience transportation networks that run smoothly. Transportation agencies and project managers are experiencing unprecedented pressure to deliver projects on time and on budget [1]; however, the projects frequently fail to meet owners' expectations in terms of cost and schedule performance [2, 3, 4]. In 2010, Thomsen et al. [5] conducted a study that showed that between 40% and 50% of all construction projects fall behind their baseline schedule. When a construction project is delayed, the construction either has to be accelerated, or its completion date has to be extended, which causes cost overruns. An obvious response to this pressure is to improve the project delivery process by adopting the available successful project management practices [6, 7]. This study attempts to delve deeper into the strategies that are effective for successful project delivery and project management by answering the following questions.

Q1. What are the most adopted project management principles in infrastructure transportation projects?

Q2. What are the most implemented project management strategies in infrastructure transportation projects?

Project managers will be able to use the findings of this study to assess the managerial practices and strategies of infrastructure transportation projects and select the ones that are most beneficial to preventing schedule delays and cost overruns.

2. Literature review

2.1. Success criteria for a construction project

Project success is the foundation for monitoring and managing a construction project [8]. Tuman [9] defines construction project success as "*having everything turned out as hoped … anticipating all project requirements and having sufficient resources to meet needs in a timely manner*." De Wit [10] describes construction project success as when primary stakeholders, the project team, and end user are completely satisfied with the project outcome. In 1987, Pinto and Slevin [11] stated that a project could be called successful when it has been completed on time and on budget, has met all of the project objectives, and has satisfied the client. Sohail and Baldwin [12] presented five success criteria for projects: schedule, budget, cooperation and partnership, quality, and socioeconomic content. Most researchers believe that measuring the budget, schedule, and quality performance, which have been called the "iron triangle" in project management, is very important to the success of a construction project [6, 13, 14, 15, 16,17]

Project management plays a critical role in successfully delivering a construction project [18]. In 2008, the PMBOK@GUIDE [19] defined project management as the utilization of knowledge, tools and techniques, and skills for project activities to meet construction project requirements. In 1996, Tan pointed out that most construction projects need to adopt both the art and science of project management and that implementation of an adequate level of tools and technology is necessary or managing a project that can be considered efficient and effective. Owners are usually satisfied with high quality and reasonable quantity provided at the least cost in the least amount of time [20], and achievement of the project success criteria is vital [21, 22] to providing this satisfaction.

In 2004, Morrison and Brown [23] presented the following factors that are needed to improve the effectiveness of project management: (1) clarity of project objectives, (2) alignment of project objectives, (3) effective consultation with the client, (4) effective consultation with the end-user, (5) effective project leadership, (6) sufficient qualified human resources, (7) availability of resources, (8) adoption of a novel and systematic project management approach, and (9) an effective project organization and authority structure.

In 2009, Siemiatycki [24] described five best practices and strategies for efficiently managing and improving the cost and schedule performances of a transportation infrastructure project: (1) improvement in the methods of monitoring a project's performance and reporting and sharing the related knowledge and information, (2) improvement in the areas of responsibility and accountability for changes and/or overruns, (3) improvement of workforce qualifications, (4) application of state-of-the art forecasting techniques, and (5) focusing early on plans to be completed.

Although some studies have identified current useful managerial strategies and practices, two knowledge gaps are apparent in the existing literature: (1) a comprehensive study about the implementation level of effective project management strategies adopted for highway, roadway, and bridge projects by DOTs; and (2) a comprehensive study about managerial practices that can improve the efficiency and effectiveness of project management in successfully delivering highway, roadway, and bridge projects. This study attempts to fill those gaps and will benefit state DOT agencies as they identify and adopt successful project management practices and strategies for their transportation infrastructure projects.

3. Research framework

The research framework developed to fulfill the objectives of this study is depicted in Figure 1. It shows that a comprehensive literature review was performed that focused on the managerial issues that DOTs encounter, and effective mitigating strategies and practices that could help them deliver projects on time and on budget. A structured survey was developed, based upon the literature review, and was distributed to the personnel of 52 state DOT agencies. After two follow-up emails, 96 completed surveys were collected, the data was analyzed, and results were obtained.

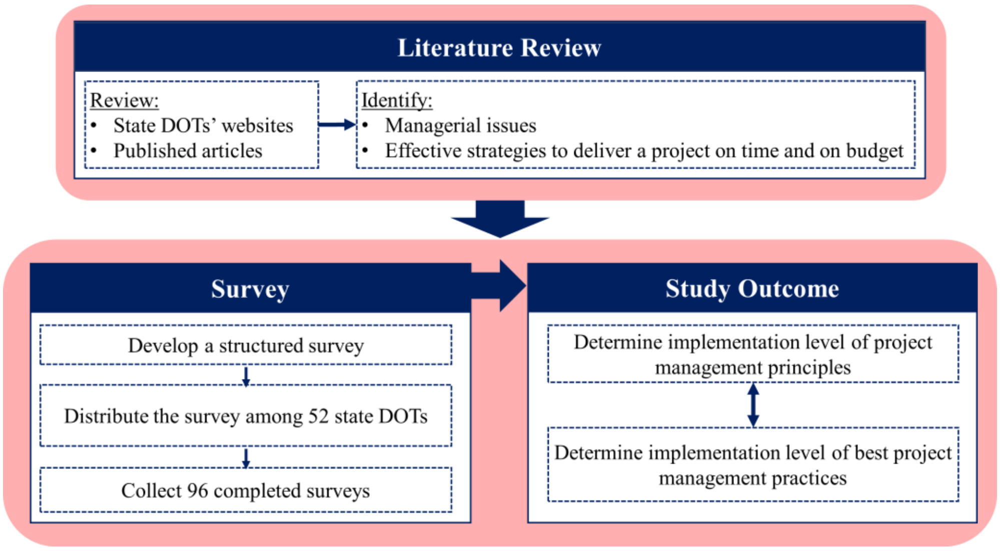

Figure 1. Research Framework

4. Data collection

The research team identified potential questions associated with the project's objectives by conducting a comprehensive literature review. Next, they categorized the potential questions into two main categories, managerial issues and project management best practices, and designed the survey, which ultimately covered six categories of questions: general information, project delivery, cost management, time management, project management, and best practices. Four experts and professionals were asked to pilot-test it, and after receiving their feedback and suggestions, the research team made the final modifications and finalized the online version.

The research team identified potential respondents from different state DOT agencies and emailed them to ask them to participate in the survey and to share their points of view. After multiple follow-up emails, 96 completed surveys were collected. The demographic information of the respondents presented in Table 1 shows that approximately 90% of the respondents had more than 10 years of experience with a state DOT agency, and roughly 15% had been project managers. The regions and the associated frequency of the survey responses are presented in Figure 2, which shows that one or two surveys were completed by respondents located in 14 different state DOT agencies (Washington, Idaho, South Dakota, Nebraska, Minnesota, Oklahoma, Texas, Louisiana, Kentucky, Tennessee, Maine, Vermont, Maryland, and Connecticut). Three or four respondents were located in state DOT agencies in Oregon, Iowa, North Carolina, Alabama, and New Mexico, and more than five responses were from state DOT agencies in Florida, Arizona, Utah, Colorado, Virginia, and Ohio. The respondents were asked to reveal the type of project on which they based their answers to the survey questions, and the results showed that 46% had selected a highway project, 32% had selected a bridge project, and 22% had selected a roadway project.

Table 1. Demographic Information of Survey Respondents

Position	Experience	Percentage
Construction Engineer	More than 10 Years	48%
Construction Manager	More than 10 Years	7%
Chief Construction Officer	More than 10 Years	7%
Administration Director	More than 10 Years	6%
Construction Supervisor	More than 10 Years	1%
Contract Manager	More than 10 Years	1%
Deputy Director	More than 10 Years	1%
Field Engineer	Less than 5 Years	4%
	Between 5 and 10 Years	1%
Project Manager	More than 10 Years	13%
	Between 5 and 10 Years	3%
Staff Engineer	More than 10 Years	4%
	Between 5 and 10 Years	1%
Superintendent	More than 10 Years	1%

5. Analysis & discussion

5.1. Effective project management principles

According to studies conducted by [25, 26], project scoping is one of the primary steps in successfully executing the construction of highway projects. Multiple researchers and authors have stated that the level of implementation of the scope definition can considerably affect a project's cost and schedule performance by mitigating the number and cost of change orders [25,27, 28, 29]. This is because the project's needs and risks can be identified and assessed when a construction project is fully defined, facilitating more accurate cost estimates and resulting in fewer change orders at lower cost [30, 31].

The survey participants were given a list of 13 project management principles that had been identified through the existing literature as useful for infrastructure transportation projects and were asked to provide information about their DOT's implementation level of each of them. The results, as shown in Table 2, indicated that 70% of them thought that their DOT agencies make an effort to ensure that project scopes are fully defined.

Table 2. also shows that 70% of the respondents reported that their DOT agencies establish effective communication among DOT staff and have an escalation process to resolve project conflicts and issues. Communication in a construction project refers to the exchange and transfer of data, information, and knowledge among the project's parties and team members [32, 33]; therefore, establishing effective communication enables the timely transfer of knowledge and skills [34, 35]. On the contrary, ineffective communication among the project's staff leads to a lack of timely information and skills, and can result in an increase in the number of design changes and modifications that might ultimately increase the number of schedule delays and cost overruns [36]. In summary, the development of effective communication in a transportation project has the potential to improve the cost and schedule performance.

Table 2. Implementation of Effective Project Management Principles

Principles	Percentage
Ensure that the project is fully scoped	70%
Establish and maintain effective communication among DOT staff; develop an escalation process to resolve conflicts and issues	70%
Actively oversee consultants and contractors to ensure work is complete and timely and meets quality standards and regularly requirements	70%
Participate in partnership meetings	54%
Know and understand pertinent regulations	50%
Begin work only after funding authorization has been obtained	50%
Ensure that the project team has the required qualifications, certifications, and experience	46%
Develop a project management plan and follow it	42%
Manage the project to meet approved project plans and specifications in order to successfully pass inspections and complete the final acceptance process	27%
Develop a succession plan that designates replacement staff for key positions	15%
Establish and implement effective quality-management procedures	15%
Accurately complete all paperwork, retain it for required time frames, and submit it on schedule to ensure full reimbursement for all eligible costs	8%
Finish the project within the required time	4%

5.2. Effective project management strategies

The respondents were asked to provide information regarding the implementation of project management strategies by their DOT agencies. Multiple questions about the implementation level of various management strategies were included in the survey as a five-point Likert scale, from very low to very high implementation. The questions asked were about team qualifications, quality management, scope verification, communication plan, risk management, environmental planning, safety management, document management, and repair prevention. The results are presented in Figure 2.

As shown in Figure 2., roughly 60% of the respondents stated that their DOT agencies highly implement the strategy of team qualification in their projects, and about 20% stated that their agencies moderately implement it. Since a construction project's success is strongly dependent on the project team tasked with delivering it, the best-planned projects may fail to meet their objectives if the project team does not perform to the best of its ability (37). The effective development and integration of the project team is essential to the success of a construction project because it is responsible for the delivery of the defined scope of the project throughout its lifecycle. Unqualified team members result in decreased productivity, an increase in the number of reworks, and schedule and cost overruns [38, 39].

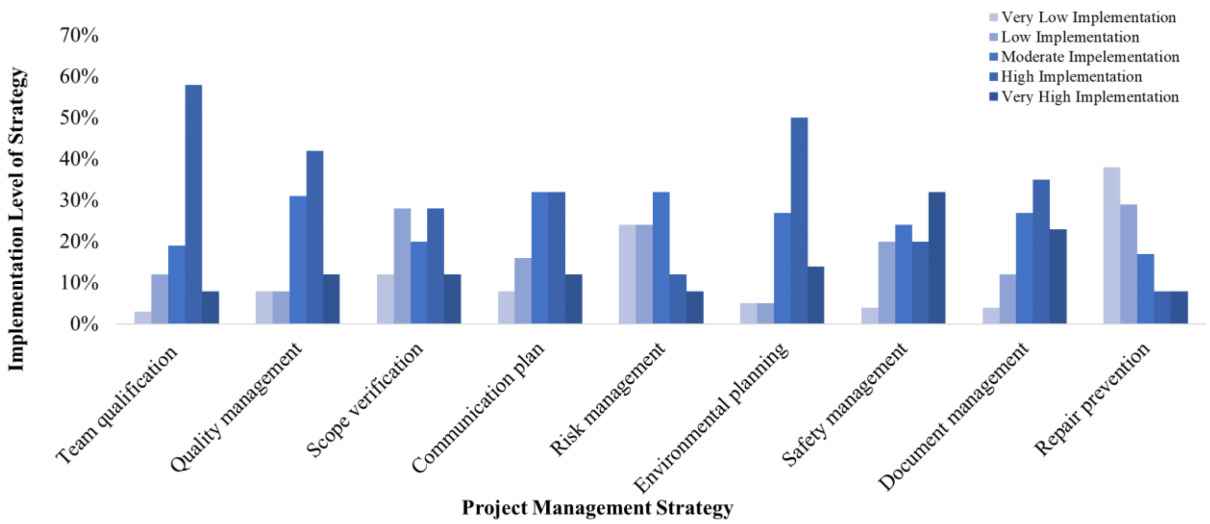

Figure 2. Implementation Level of Effective Project Management Strategies

The respondents were also asked to provide information about the implementation level of quality management strategies. Quality management strategy refers to the incorporation of all of the activities conducted to improve the efficiency, contract compliance, and cost effectiveness of the design, engineering, procurement, quality assurance (QA) and/or quality control (QC), construction, and startup elements of construction projects. Implementation of this strategy prevents failure to comply with the material, equipment, and construction specifications, and as a result prevents early failure of the infrastructure projects [40,41]. As shown in Figure 3, more than 40% of transportation agencies highly adopted quality management strategies in their projects, and more than 30% of them moderately implemented them.

Figure 2 indicates that one of the strategies that the respondents were asked about was scope verification, which refers to the process of formalizing the project parties' acceptance of the project scope. It requires reviewing the work products and results to ensure that all were completed correctly and satisfactorily (42). Scope verification strategy commonly occurs at the end of each project phase and as part of the project closeout process. Dicks et al. [43] believed that state DOT's implementation of the project scope verification strategy leads to significant improvement of the project's performance. As presented in Figure 2, approximately 30% of respondents described the level of implementation of the verification strategy as highly adopted by their agencies, while 20% described it as moderately adopted.

The survey asked the participants to provide information about the implementation level of a communication plan for their projects by their DOT agencies. The strategy of communication plan was defined as the process of driving alignment between the communications function and the organization's core objectives. This strategy should always include consideration of employees as the key audience. As many different parties are commonly involved in a construction project, it may be difficult to organize and align them toward the same vision and goal [44]. Figure 2 illustrates that roughly 35% of the respondents believed that their agencies adopted a high level of communication plan strategy in their projects, and about 35% indicated that their DOT agencies moderately implemented the strategy.

The survey participants were asked to provide information about risk management also. A risk management strategy provides a structured and coherent approach to identifying, assessing, and managing risk. It builds in a process for regularly updating and reviewing the assessment based on new developments or actions, the lack of which can result in undesirable consequences that seriously affect the project's performance [45,46]. As illustrated in Figure 2, about 30% of the respondents indicated that their agencies moderately adopt risk management best practices, and 50% indicated that their agencies' implementation of risk management strategy in their projects is inadequate.

6. Conclusion

This study had two main outcomes associated with highway, bridge, and roadway state DOT projects. It determined the implementation level of effective project management strategies in transportation infrastructure projects, and it determined the implementation level of effective project management principles. The results demonstrated that team qualifications, quality management, environmental planning, safety, and document management are the project management strategies most widely implemented in state DOT projects. Team qualifications received the highest implementation level among the adopted strategies, and environmental planning and quality management were ranked second and third. The results also revealed that three project management principles of "ensure that the project is fully scoped," "Establish and maintain effective communication among DOT staff; develop an escalation process to resolve conflicts and issues," "Actively oversee consultants and contractors to ensure work is complete and timely and meets quality standards and regularly requirements" were recorded as the first rank accounting of 70% among the DOTs' management principles.

The results of this study will assist decision-makers and project managers in making key decisions pertaining to the selection of effective managerial strategies and principles that will deliver an infrastructure transportation project on time and on budget, and with high level of quality.

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Effective Use of United States Foreign Aid to Fund Infrastructure Projects

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Abstract

Foreign aid is one of the tools the U.S. Government uses to promote stability and economic growth around the world. U.S. Foreign assistance to the region is currently guided by the U.S. Strategy for Central America which was announced in 2015. According to the U.S. Agency for International Development (USAID), average U.S. foreign aid to the Northern Triangle countries exceeded $400 million per year over the ten year period between 2008 and 2018. During this period approximately 10% of U.S foreign aid was used to fund infrastructure projects. Despite recent investment, the World Economic Forum ranks the infrastructure of the three countries in the Northern Triangle in the bottom half of all countries surveyed. With continued investment and unremarkable results over the past decade, it is useful to examine the efficiency of the investments and ensure available funding is effectively invested. USAID is the primary conduit for the distribution of US foreign aid. The United States Government works through several federal agencies outside the borders of the United States and much of this work is focused on security and military development in foreign countries. The U.S. Army Corps of Engineers (USACE) is one such agency and is currently managing overseas operations around the world. The main overseas mission of USACE offices appears to be in line with the development of military construction projects for foreign governments. In this paper, researchers examine the basic tenets of the proposed arrangements for the US to engage in funding infrastructure projects in foreign countries to alleviate un-employment related issues. The said funding also enhances the construction talent in countries receiving such funding. This is a qualitative research exploring the success of the proposed funding in the Norther Triangle region of Central America. Results from interviewing key personnel and literature review reveal that this opportunity can be improved to the benefit of all parties.

Keywords: foreign aid, infrastructure, Northern Triangle, USACE, USAID

1. Introduction

The United States Government is currently struggling to address an influx of refugees seeking asylum at its southern border. Immigration has a long history as a volatile political issue in the United States and around the world. A significant portion of the people seeking asylum around the world choose to leave their native country as a result of war or some form of natural disaster. Many of the refugees coming to the United States southern border are arriving from the Central American countries of Guatemala, Honduras and El Salvador which collectively make up a region known as the Northern Triangle. This region has struggled recently with political economic and social unrest which has contributed to a mass migration. The United States Government currently spends Billions of dollars on foreign aid around the world [1]. This research will provide an in depth review of the portion of that aid that is directed towards infrastructure projects in the Northern Triangle region. Despite recent investment, the World Economic Forum ranks the infrastructure of the three countries in the Northern Triangle in the bottom half of all countries surveyed

[2]. With continued investment and unremarkable results over the past decade, it is useful to examine the efficiency of the investments and ensure available funding is effectively invested. USAID is the primary conduit for the distribution of US foreign aid. This agency works through the Department of State to identify and distribute funding through Mission Offices established in developing countries. The United States Government works through several federal agencies outside the borders of the United States and much of this work is focused on security and military development in foreign countries [1]. The U.S. Army Corps of Engineers (USACE) is one such agency and is currently managing overseas operations around the world. The main overseas mission of USACE offices appears to be in line with the development of military construction projects for foreign governments. However, USACE also has a mission that includes the development of water resources, flood risk management, navigation and infrastructure and environmental stewardship. This mission is in line with the stated goal of infrastructure development in this region. With existing expertise in the identification, award and execution of infrastructure projects, USACE may be in a unique position to execute studies that ensure existing funding is efficiently utilized. Such oversight could provide a significant impact on the value added by infrastructure investment providing a greater benefit to the host nation and the U. S. taxpayer. This research will explore the current efforts of United States Agency for International Development (USAID) in the role that agency plays in the distribution of US foreign aid for the development of infrastructure projects in Northern Triangle Countries. In addition this research will explore the role that other US Federal agencies such as USACE can play in the identification, award and execution of infrastructure projects in Central America.

2. Literature review

The distribution of U.S. foreign aid is currently governed by the 1961 Foreign Assistance Act which established the United States Agency for International Development as a sister agency to the United States Department of State and attempted to streamline the government's efforts to provide assistance around the world[1]. Prior to 1961 the first large scale use of foreign aid by the United States Government was when President Hoover created the Commission for the relief of Belgium (CRB) at the onset of World War I in 1914. The goal of this effort was to combat food shortages in German occupied Belgium and Northern France. Following World War I, the United States Food Administration provided millions of impacted civilians with food.

Following World War II the United States Government used international development as a tool for foreign policy with the Marshall Plan. This effort diverted $13 billion in aid to allow Europe to rebuild its infrastructure and strengthen its economy. At the beginning of the Cold War, in 1949, President Truman proposed an international development assistance program. The goal was to reduce poverty, increase production and combat communism in developing countries. The Foreign Assistance Act (FAA) of 1961 created USAID with a mission to promote democratic values abroad and advance a free, peaceful and prosperous world. USAID was tasked with leading the United States Government's international development and disaster assistance through partnerships and investment. President Kennedy also launched the Peace Corps the same year. The overall intent of these actions was to spread the goodwill and positive image of the US government around the world. The FAA underwent several changes throughout the 1970s as the nation focused on prioritizing food and healthcare when assisting foreign nations. The 1980s largely continued the focus on food and healthcare with some large high profile events such as the Live Aid concert where celebrities were engaged to help raise awareness it issues of hunger in developing nations.

The 1990s saw a major shift in US foreign policy with the end of the Cold War. USAID's top priority shifted to sustainable development and a focus on helping nations become self-sufficient. The events of September 11, 2001 created an extra urgency around foreign aid as a means of creating stability. Development of foreign countries was now seen as central to US national security. This period saw the creation of The President's Emergency Plan for AIDS Relief and the Millennium Challenge Corporation in 2003 and 2004 respectively. Today we define aid as the unilateral transfer of U.S. resources by the U.S. Government to or for the benefit of foreign entities. These resources include more than goods and funding. Aid can often take the form of technical assistance, educational programming, healthcare and other services. Foreign governments are not the only recipients of this aid. Local businesses, charitable groups, international organizations and other nongovernmental organizations are all potential targets for U.S. foreign aid. Over the years, there have been a variety of strategic and humanitarian goals of U.S. foreign aid. However, there has been an overarching theme of using aid to address crises, promote security and encourage self-sufficiency through development.

3. Research methodology

The research used the qualitative approach focusing on structured interviews. This process allowed individual experience and situational knowledge to be collected and analysed. A pilot interview was conducted using one former USAID and State Department employee and one current construction manager with experience executing federally funded construction projects. The questions were revised based on feedback form pilot interview and administered through written interview questions. The personnel considered for the interview were involved in the selection, award and execution of infrastructure projects associated with USAID mission offices across Latin America and the Caribbean. Project sizes that were under the supervision of the interviewees ranged from small local projects valued under $100,000 to large scale multi-year national projects valued over $50,000,000.

4. Results

The interview questions were grouped and ordered into three main sections. The first group of questions focused on the role of the interviewee within the organization and the role of the Mission Office in the execution of infrastructure projects funded through US foreign aid. The second area of focus was the role the office or individual played in the contract and construction management of infrastructure projects. This area also focused on gaining an understanding of the selection process to identify potential projects. The final section of the interview included a focus on how each office used resources from other federal agencies and selected projects that fit into the overall goals of larger regional programs. This section was intended to provide a better picture on how the office operates within the larger framework of the US Government. A total of 11 participants were interviewed in this research.

4.1. Content analysis

Including the subparts of each question, there were sixteen unique questions for each of the eleven participants to answer. Many of the subparts of questions were designed to build off previous responses and provide for the interviewee to expand on previous answers. This interview design promoted some repetitive information and assisted in the development of some overriding themes. As described previously, the questions were divided into sections and will be analysed here in the same sections.

4.1.1 Personnel data

In describing the scale of the projects 72% of subjects used some form of the phrase 'small scale'. In addition, more than a quarter of respondents (27%) made reference to the use of infrastructure projects as support or supplemental to other program goals. These questions did not specifically ask about the size or use of the funded infrastructure projects. Infrastructure projects appear to be seen as support to other program goals instead of potential vehicles to drive economic improvement. Despite referencing small scale projects, the respondents did identify several sectors in which infrastructure work was being performed in the subject countries. Figure 1 above identifies different types of infrastructure projects and shows the percentage of respondents that identified each sector. In discussing the overall involvement of each subject office in the execution of infrastructure projects, the respondents were ask to identify if they were involved in construction management aspects or funding and procurement of infrastructure projects. In most cases respondents answered this question to identify the overall office involvement in the process rather than their individual involvement.

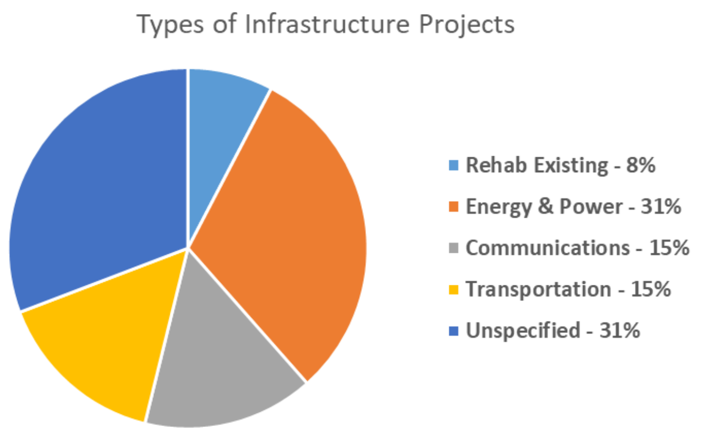

Figure 1. Types of infrastructure projects referenced

The data collected indicated that 54% of respondents identified their office as not being involved in the construction management process, as shown in figure 2. Additionally, many of the respondents use contract vehicles to manage construction activities rather than using agency personnel. The final question in this section identifies 100% of respondents as not working with other federal agencies to manage construction activities. This result is unexpected and may indicate that an agency wide policy is in place requiring that funding be used only through USAID. More research should be conducted to determine the accuracy of this information and the reasoning behind the response.

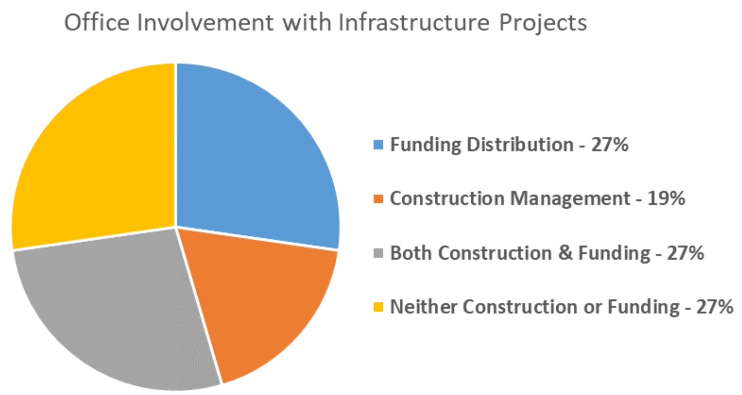

Figure 2. Office role in project execution

4.1.2 Project execution data

Three of the respondents did not indicate a level of involvement, the remaining respondents either focused on their own personal experience or identified a USAID policy that identifies the Agreement Officer (AO) as the authorized individual responsible for contracting agreements with new construction projects. In both cases, responses were very much influenced by USAID agency policy. The data shows that local governments and the private sector play an external role in identifying projects to USAID. In addition, USAID does utilize some technical expertise to identify and fund some projects. The information gathered supports the general position that respondents were satisfied with current levels of infrastructure investment but feel the subject countries would benefit from additional funding. Interviewees confirmed that once projects were identified, environmental reviews were required to allow the project to proceed.

All of the respondents confirmed that USAID followed federal contracting guidelines. One critical issue in the execution of federal contracts is the ability to execute contract modifications. Without convenient access to a contracting officer, minor construction issues have the potential to create huge delays, potentially stopping progress. However, USAID respondents indicated that access to contracting decision makers is not an issue, even in the sometime remote areas that USAID projects are executed.

Interviewees were asked about performance metrics in the execution of USAID infrastructure projects. Over 45% of respondents used the question to identify how overall offices are rated. These respondents discussed the number of projects completed and renovated. As discussed in the literature review section of this paper, there is not an agreed upon method to measure the success of foreign aid. The benefits may not be evident in analysing numbers of projects or population impacted. The intent here is to see if standard construction metrics such as schedule reviews or quality control are being implemented so the projects do not experience cost or schedule growth due to mismanagement. Some responses did indicate the use of contracting measures to manage construction, however, none of the responses referenced standard construction tools to ensure project delivery.

4.1.3 Program level data

Finally, participants were asked about how individual offices fit into the larger structure of the United States strategy for the region. The intent of this line of questioning was to determine if infrastructure projects are identified in order to support larger program and regional goals, specifically the stated strategy of the United States Government in Central America. Responses from all offices noted that projects are in line with regional goals. Most of the respondents choose not to elaborate on their responses by giving examples of how projects are selected to meet the goals of regional programs. The final question addressed interagency coordination referencing some of the other agencies or organizations involved in the distribution of United States foreign aid. Here again respondents did not provide a large amount of detail in the responses. Generally the responses indicated that projects were coordinated on an activity implementation level but not a funding distribution level. Respondents referenced program level coordination, however, two of those respondents were in positions that did not make program level decisions.

This section of questioning provides an example where the requirement to submit written questions and answers limited the ability of the interviewer to pull more information out of the responses. It is also possible that the respondents were experiencing fatigue at the end of the interview and simply rushed to complete the responses. These limitation will be discussed further in the final chapter of this research.

Overall the responses confirm that individual mission offices are aware and do track larger regional goals but they do not provide any significant insight into how individual infrastructure projects are selected based on larger regional goals. Similarly, mission offices confirmed that they are engaged with other United States Federal Agencies. However, the responses do not provide insight into how the agencies work together to effectively spend U.S. foreign aid money to accomplish regional goals.

4.2. Thematic analysis

Three predominant themes were identified in the analysis of the data collected in this research. The three themes are: Limited use of infrastructure projects, a focus on using existing USAID agency policies and procedures and limited coordination within US Government Agencies.

4.2.1 Limited infrastructure investment

One of the main themes identified through analysis of the data appears to be the limited execution of infrastructure projects. While funding data indicates that the subject countries have executed some large multi-year infrastructure projects, the majority of the infrastructure funding over the past ten years is used to fund small scale renovations of existing infrastructure. Respondents were asked to describe the role their specific mission plays in the distribution of funding to support infrastructure projects as well as the types of projects typically funded in their respective countries. Responses to these questions referenced small scale projects that are required to compliment other projects and overall program goals. Respondents described current infrastructure programs as 'extremely minimal and limited' while describing projects that involve rehabilitation and repairs to existing structures.

Responses also reinforce the idea that subject countries would generally benefit from an increase in infrastructure funding. While these responses were somewhat muted and noted that needs were largely met, they also indicated that subject countries would benefit from additional funding. As noted in the literature review section, infrastructure development is a stated goal of the US strategy for Central America. Concerning the use of environmental reviews, results did not indicate that USAID is actively using such studies to identify projects but rather as part of the analysis of a project that has already been identified. This supports the possibility that some projects may not be identified and therefor may not receive funding. While the data collected in this question does not confirm that projects are left unidentified, it suggests that reviews and studies could be used differently by federal agencies in an attempt to identify potential projects. Further research would be necessary to confirm this hypothesis.

4.2.2 Existing agency policies

When analysing the collected data with a focus on construction management and metrics the respondents often deferred to references of existing USAID policies and procedures. Participants were questions to determine if qualified personnel are involved in the management of construction activities. The requirements laid out in USAID's Automated Directives System are highlighted in the literature review chapter of this research and identify policies and procedures to minimize construction risk.

Respondents provide extensive references to the Automated Directives System (ADS) which contains the organization and functions of USAID along with policies and procedures that guide the Agency's programs and operations. When addressing oversight of construction activities, respondents specifically referenced ADS chapter 303 – USAID Implementation of Construction Activities and ADS Chapter 201 – Construction Risk Management. Program managers involved in this study consistently referenced the requirements of ADS in responses.

While this information is useful in the context of how individual mission offices manage construction projects, it is important to relate these responses to the responses to questions relevant to the volume of work responding offices execute. Responding offices generally indicated that infrastructure projects were a small percentage of the aid projects typically funded. As such, the offices may be using published agency policies to indicate how they would manage projects if the volume of infrastructure work were to increase. This hypothesis is not tested in the data collected in this research and may be a topic for further study.

4.2.3 Federal agency coordination

The subject of interagency coordination was a focus of two of the questions in the interview. This theme is a main focus of this research and can provide a first-hand account of how effectively the US Federal Government works across agencies when operating in a foreign country.

One question asked the respondent to provide direct information regarding how USAID works with other US federal agencies in the management of construction activities. Another question was more focused on the coordination of the distribution of funding across agencies. In both questions the responses were unanimous. It is clear from the data collected that USAID will coordinate the distribution of funding with other agencies to meet regional goals but does not coordinate or work with other agencies to manage construction activities.

5. Conclusions

There were three main themes identified in the data collected during this research. The first overriding theme is the limited use of infrastructure development. The second theme was the use of standard policies in the management of construction activities. The final theme was the inadequate coordination between United States Government Agencies. Recommendations for each of the three themes is outlined below.

5.1. Funding levels

Data collected strongly suggests that while infrastructure projects are funded, most countries would benefit from additional infrastructure funding, as evidenced in literature [3]. This statement is valid in most areas of the world. Even in developed countries like the United States, there is a continuous need to reinvest and support infrastructure projects. This is highlighted through recent news of issues with drinking water in Flint, Michigan and the continued low ratings for the condition of bridges in the United States issued by the American Society of Civil Engineers.

Many opponents would argue that the United States Government should focus on these internal infrastructure issues instead of spending money on the shortcomings of infrastructure in developing nations. This research did not collect data or make recommendations on the overall funding levels of foreign aid. However, the data collected does confirm that a small percentage of the overall foreign aid budget is directed towards infrastructure projects. This is true across Latin American and the Caribbean region despite the fact that infrastructure investment is a key element of the 2015 Strategy for Central America and the Alliance four Prosperity Plan. While most respondents indicated that appropriate levels of funding did exist, they also noted that additional funding would be of value. This statement is supported by data gathered on the percentages of total foreign aid used on infrastructure projects [4]. This data shows that in the Northern Triangle Countries, less than 1% of the foreign aid budget is directed to infrastructure projects in most years [5],[6],[7].

The data in this research did not identify a strong force within the existing organization of the United States Federal Government that is championing the use of foreign aid on infrastructure projects. There appears to be an opportunity to reallocate some existing funding to study and identify potential infrastructure projects. However, without an organizational focus on infrastructure issues, these projects are not likely to be identified. If infrastructure investment is important enough to be a stated goal of the regional strategy, there needs to be a central focus within USAID to study and recommend potential projects. As infrastructure development is a key focus of the regional strategies developed by the Northern Triangle Countries and the United States Government, infrastructure spending should be a larger focus of foreign aid projects.

5.2. Existing agency policies

Responses referenced several United States and USAID agency publications including the Federal Acquisition Regulation (FAR), USAID Acquisition Regulation (AIDAR) and Automated Directives System (ADS). These references are largely focused on the acquisition process. References to construction management are largely absent in these standards. While data indicates that USAID engineers are involved in some construction management activities, these functions are limited. Responses also indicate that there is an established process in place to manage active construction projects and this system is used on all projects. While standardization is necessary to maintain a consistent product, there is risk in a failure to adapt to the unique conditions that may exist in the construction environment. While many of the respondents were not involved in the field level management of construction projects, it is still notable that project specific plans were not mentioned in the responses provided. Chapter 2 of this research touches on the difficulty in assessing success of a foreign aid project. There are a myriad of factors that can impact these projects and many of these factors will be unique to individual projects. USAID appears to be effectively applying standards across construction projects but not focused on developing project specific plans to address site specific construction risks.

Based on the information gathered, traditional construction metrics such as schedule reviews, quality control and safety statistics are not tracked on projects receiving foreign aid. Instead, metrics focus on the number of structures rehabilitated or repaired and what value is being received for the number of dollars provided. The data suggests that there is a lack of oversight in the actual construction phase of infrastructure projects. Without such oversight, the potential exists for projects to be less efficient. Providing organizational standards for construction activities across USAID could result in a more effective use of existing funding.

5.3. Inadequate coordination

Data collected strongly suggests that projects and funding are not coordinated with other Federal Agencies within the United States Government. USAID respondents indicated that mission offices do identify projects based on the goals of larger regional strategies. However, construction does not appear to be coordinated with other agencies. Funding through USAID represents a significant percentage of overall foreign aid funding, there are other organizations and agencies with robust aid programs in these same countries. The projects do not appear to be coordinated between organizations at a local level.

Organizations such as the Millennium Challenge Corporation (MCC) engage and assist foreign countries in soliciting and awarding public-privet partnerships, grants and other program procurement methods to be administered by partner countries. Currently MCC is engaged with the government of Guatemala with the Guatemala Threshold Program. This is a $28 Million grant program working in part to stimulate more private funding for infrastructure projects. The Government of Honduras has a similar $15.5 Million grant to create more effective public-private partnerships in the country. In El Salvador MCC is working with the government through a $277 Million grant designed to enhance the country's competitiveness and productivity through an integrated set of investments in infrastructure education and public-privet partnerships. Data collected in this research suggests that USAID is not engaged with MCC in any of these efforts. While respondents did indicate that funding was coordinated with other government agencies, there was no involvement across agency lines in the management of construction activities. In addition to organizations such as MCC, the United States Army Corps of Engineers has an extensive network of offices involved in construction activities across Latin America and the Caribbean. The USACE program has construction offices in two of the three Northern Triangle countries as well as extensive contracting and engineering support with reach-back capabilities in the United States. The USACE program does not currently work with USAID to identify or manage projects. Several of the responses from USAID mission offices indicated that engineering and construction support are often awarded as part of a construction contract due to lack of resources. With clear construction management options currently functioning in the region, the United States Government needs to be more aware of its own existing resources. The figure below illustrates the existing footprint of USACE in Latin America. The USACE program represents an existing construction management element within the framework of the Federal Government that could be employed to implement some of these recommendations.

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Explicit Evaluation of Complexity in Construction and Real Estate Management

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Abstract

Complexity has become a major keyword when it comes to organization issues in Construction and Real Estate Management. Expressed via many different theoretical definitions, complexity in terms of management represents the part of organization which is simply not manageable. Therefore, reduction of complexity by separating a system into independent well-defined and well-controlled subsystems becomes a major task. However, since construction and real estate projects are becoming larger, encompassing higher volumes as well as higher numbers of participants and are nonetheless subjected to strongly limited time-frames and budgets on tight markets, efficient organization developed into the crucial issue to stand a competition successfully.

On this background, engineering naturally focuses on saving costly resources, where the explicit value of a single measure can easily be derived from the cost of the resource and the duration of the therewith reduced time floats. This leads to well-known concepts, e.g. just-in-time-delivery, where a system is optimized with respect to physical resources as well as virtual resources like storage space or reserve time. However, as this strategy clearly saves explicit local resources, concurrently the coupling of processes via the required availability of physical and virtual resources, ranging from pre-products to decisions, plans and responsibilities, is strongly increased and, thus, complexity is reintroduced to a significant degree.

This paper proposes an approach on the basis of Systems Theory providing an explicit measure to evaluate the increase of complexity in relation to possibly saved resources. Since cost of complexity are not given a priori but result from possible deviations, this article investigates the propagation of virtual uncertainties of real and abstract pre-products through a network of given complexity. On this basis, some general rules are derived allowing to maintain the balance between saving resources and the therewith increasing cost of the consequently rising complexity.

Keywords: complexity, systems theory, lean management, construction management, real estate management

1. Introduction

Long since, construction management suffered from the very specific task to get the production of a unique product organised [1, 2], in particular within a heavily specialised context [3]. Based on the definition of general processes, the uniqueness of products no longer poses a problem as the production as well as the planning processes become standardized [4] and the uniqueness is reduced to concatenating elements in a specific way [5]. Then, only a limited number of parameters describes the standardized processes and the task is changed to precisely determining these in advance. The processes themselves are predetermined (see e.g. [6]) and equipped with superordinate control-mechanisms ensuring the required results within the given margins of quality, cost and time [7].

So far, the overall production is formed by a system of interacting elements/objects [8] which can be described by the Theory of Systems [9, 10, 11] accordingly. Elements may be given as physical modules as e.g. in Building Information Models (BIM) [6], however, in this context they are exclusively understood as processes. Depending on type, direction and strength of coupling these objects, such systems tend to develop dynamical behaviour [12, 13], which needs to be understood and taken into account [14, 11, 15].

A well-known side-effect of the standardisation of processes is the new focus on the concatenation parameters, drifting away from the actual content of the processes as is intended. However, as a consequence, the production processes, in particular including the respective controlling structures, are expected to fulfil their task perfectly well [16].

On this background, planning is reduced to the – nonetheless demanding – task, to define the complete set of parameters coupling the numerous processes which in the end lead to the final product. So far, project management focuses firstly on the separation of the overall task into a number of processes in a well-structured way and secondly on reconnecting them into an output-oriented production system [17, 18, 19, 20].

The very engineering-like approach to optimize this with respect to the consumption of resources focuses on the total set of processes, in particular avoiding any idle running as the major wastage [21, 22, 23]. In order to do so under the pressure of tight schedules and low margins, pains are taken to couple processes as closely as possible, thus minimizing time floats and tolerance regarding perfection of pre-products [24].

Since tight and numerous coupling of a set of processes is measured in terms of complexity or connectivity [25, 26, 27, 20], this inevitably leads to an increase of complexity of the respective projects [28, 29, 30]. In contrast, it is commonly well-known that reduction of complexity is an important general goal [31, 32, 33], however, there is no quantitative description of measures and consequences available. As a significant number of current projects, in particular in construction management, teach, despite very careful planning and investing high engineering skills, these tend to fail their ambitious goals, probably due to the introduction of an unmanageable degree of complexity [34].

In general, there are two major issues to be considered in this situation. First, investing resources in controlling mechanisms allows for safely achieving given goals, however, only within well-determined limits which directly depend on the quantity of available controlling resources. Therefore, still some well-defined degree of indeterminacy remains and needs to be taken into account [35]. On this background, secondly, as the qualitative understanding of principal fuzziness grew, rules of “Lean Management” are discussed and investigated [21, 22, 23]. One of the there mentioned aspects, in very short, is to focus on the final production processes since these are generating most of the value and they are most likely to suffer most from any deviations. This is in contrast to classical hierarchical approaches which pay most attention to the processes close to the start of causal chains in order not to bring in any deviations at all.

In this paper we propose a formal model of understanding of the major balance of saving resources by ensuring very safe intermediate products and the inherent cost of complexity introduced by the therefrom resulting tight coupling of processes. On the very fundamental basis of systems theory, finally some rules to avoid unpredictable results are developed and recommended.

2. Complex network situation

The approach presented here is based on the structure of a general network of processes, where most processes are dependent on the outcome of some other processes. This structure is principally modelled as a graph comprising predecessor nodes and successor nodes connected by directed edges indicating direct dependencies. Following the principle of a graph-theoretical network plan can be safely assumed that the graph is loop-less and holds exactly one source and one sink node [17, 4, 18, 2]. Thus, a strictly causal sequence can be determined and formulated as a graph-theoretical rank [16]. Furthermore, in accordance to the definition of activities, linear production as well as linear consumption of temporal and consumable resources is given [5].

Understood as activities, these processes make use of resources, partly assigned solely to the particular process, partly shared between several processes. Under all circumstances, the activity-nodes are coupled either by the availability of shared resources or by dependencies introduced by the requirement of pre-products.

All activities are assumed to be well-defined under the responsibility of a perfectly hierarchical approach according to a graph-theoretical tree-structure and, thus, the required methods, results and resources are unambiguously given. On this basis, sensibly, all processes are equipped with appropriate control-loops making sure that possible deviations remain within a given corridor. Nevertheless, even with very tight controlling deviations will occur but remain limited [15, 16].

Finally needs to be preconditioned and accepted, that since deviations of the output of a process lead to deviating input values of the succeeding nodes they therefore travel through the network.

All types of interdependency can easily be expressed as directed edges, so that only a ranked network plan needs to be considered as the fundamental structure to be investigated.

2.1. Local deviation of a single process/activity

The result of a process can be formulated as the value of a single variable, which corresponds to some degree to the target value. In this context a varying duration D corresponds directly to a varying result since the linearity of an activity allows achieving the target value consuming respectively more or less time. Therefore, all kinds of deviation of production can as well be expressed as undertime or overtime. In order to maintain linearity and, due to no better information, the given deviation of $D \to D \pm \tau/2$ at max is assumed following a constant distribution: $P(\tau)dt = \tau^{-1}dt$

2.2. Interaction of processes (Activities)

In general, networks with no invisible deeper structure are described by some well-known parameters [10, 30, 25]: The impact ζ counts the average number of direct successors to any other node, interoperability ξ describes the average number of direct predecessors. Complexity α of a network is furthermore formulated as the information [25] within a step proceeding from a node to an average successor with respect to the maximum information: $\alpha = \ln(\xi+1)/\ln N$

For the present situation, the number ξ of direct predecessors to a node defines the precondition of the successor S to start, therefore we assume the activity S to require all ξ activities to be completed and finished to the predefined outcome and time.

As pointed out in [30] and based on a constant distribution, the relative loss to a $\xi = 1$ situation is $\hat{\tau}_{ADD}(\xi) = (\xi - 1)/(\xi + 1)$ in units of $\tau/2$, which reflects the probability of ξ activities to be all finished to perfection.

2.3. Local interaction of deviating processes/activities, separability and coupling

In order to avoid transferring any deviation resulting from a preceding activity the consequent process needs to allow for a reserve time which at least equals the maximum overtime $\tau/2$, i.e. tightness of coupling is set allowing for full reserves $\tau/2$. This situation, where each activity runs on its own, is addressed as "completely separated".

The resources required for full separability are under these circumstances given by $R_S = \tau/2 \cdot \xi \cdot \eta$, where $\tau/2$ is the possible deviation, ξ the number of required activities and η the required resources per time.

For this approach we generally assume an average value η representing cost per time which is assigned to the resources needed for production but as well stands for the generation of value on the basis of these resources.

In contrast to the fully separated situation, a complete transfer of deviations, i.e. allowing for no reserves $\tau/2$ per preceding activity, the succeeding process S is understood as "closely coupled". The therewith saved resources would be $R_S = \tau/2 \cdot \xi \cdot \eta$, however, the taken risk develops from the requirement of consuming adequate resources according to the probability of at least one pre-process to fail to some degree:

$$R_C = \frac{\tau}{2} \cdot \eta^{\xi} \frac{\xi - 1}{\xi + 1}, \tag{1}$$

where $\tau/2$ is the possible deviation, η^{ξ} the resources per time to the power of ξ due to the increase of value with joining processes, and $(\xi-1)/(\xi+1)$ the probability of one out of ξ pre-processes to fail. The background of the approach η^{ξ} as generation of value is the understanding of the value of a subsequent process being formed by predecessors as factors. Therefore, the generation of value of the predecessors are to be multiplied yielding the value of the successor.

2.4. Local interaction of deviating processes (Activities) - Balance

The balance of both the extreme situations compares the resources saved by tight coupling to the possibly taken risk earned by introducing this degree of complexity

$$R_{\Delta} = -R_S + R_C = -\frac{\tau}{2} \cdot \xi \cdot \eta + \frac{\tau}{2} \cdot \eta^{\xi} \frac{\xi - 1}{\xi + 1} = \frac{\tau}{2} \eta \left(\eta^{\xi - 1} \frac{\xi - 1}{\xi + 1} - \xi \right) = \frac{\tau}{2} \Delta_{loc} \stackrel{!}{=} 0 \tag{2}$$

As long as $\tau = 0$, i.e. no deviation is possible, meaning only perfectly stable and safe results are presented to the next rank, $R_{\Delta} = 0$ and no advantages can be taken from avoiding complexity.

3. Connectivity of network development of cost

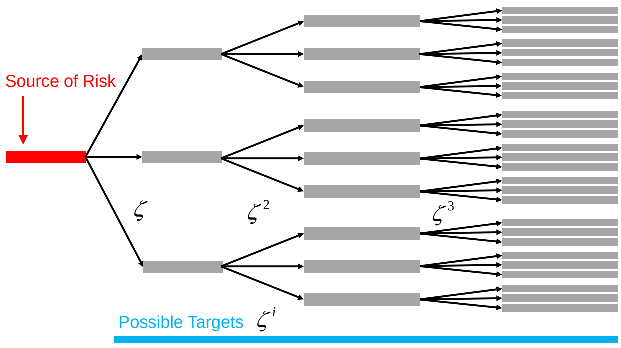

Fig.1. Development of a risk through a network tree.

Any deviation as a consequence of failed completion somewhere within the network is assumed to be carried throughout the network until the causal chains are terminated. The given interoperability $\zeta = \xi = \nu$ describes the number of affected consecutive processes per level. In this consideration, losses by delayed processes are accumulated for all affected processes, since any deviation from a pre-set schedule requires the presence of the scheduled resources beyond the scheduled time. So far, the structure of a graph-theoretical tree is assumed. Branches may in reality very well be reunited, forming an incomplete tree. However, recombining might mean recombining the same problem twice. Thus, the complete tree-structure needs to be taken into account. Therefore, the number of affected processes per level is ξ^i where the number of levels i is corresponding to the cardinality *N* of the order of the maximum rank Γ, i.e. the length of causal chains. Therewith, any deviation leads to a number of z affected processes.

$$z = 1 + \xi + \xi^2 + \xi^3 + \ldots = \sum_{i=0}^{\Gamma} \xi^i = \frac{\xi^{\Gamma+1} - 1}{\xi - 1} \tag{3}$$

3.1. Connectivity of network development of cost – Balance

In this set-up, additional loss of resources of all the affected processes needs to be considered cumulatively when balancing saving resources by increasing tightness of linkage.

$$\Delta_{net} = \eta^{\xi-1}\frac{\xi-1}{\xi+1}\cdot\frac{\xi^{\Gamma+1}-1}{\xi-1}-\xi \overset{\eta:=1}{=} \frac{\xi-1}{\xi+1}\cdot\frac{\xi^{\Gamma+1}-1}{\xi-1}-\xi \quad (4)$$

where the generation of value remains unconsidered ($\eta = 1$).

A network never consists of only tight interactions or links with sufficient separation indicating complete decoupling. The degree of coupling $\chi \in [0..1]$ reflects the percentage of links in a network being closely coupled. Since consumption of resources as well as the generation of value is linear with all low-level processes (activities), this is not necessarily the number of links but can as well describe the degree of separation for each single link j ranging from close coupling ($\chi_j = 1$) to complete separation ($\chi_j = 0$). Then, χ also holds the average degree of coupling over the complete network and stands for the probability of a risk to meet a tight interaction transferring all the deviation to the next rank.

This in particular means that only a share of $\chi\xi$ interactions are transferring the deviation and, secondly, only a share of $\chi\Gamma$ levels contribute to the transfer. Hence, we have

$$\Delta_{net} = \frac{\xi-1}{\xi+1}\cdot\frac{(\xi\chi)^{\Gamma\chi+1}-1}{\xi\chi-1}-\xi \quad (5)$$

This approach allows for some first observations:

The local saving potential (last term) is linear with ξ.

The local risk (pre-factor of first term) also runs linear with ξ.

The network impact (main factor of first term) is dominating.

From this we derive the principal criteria of balance considering the network. The non-constant term would certainly positively escalate with

$\xi\chi > 1$ implicating an escalating numerator as long as causal chains are long enough to provide high powers,

$\xi\chi = 1$ leading to a vanishing denominator and, thus, also escalating behaviour,

$\Gamma\chi > 1$ where a large size of a network segment would cause over-linear behaviour

Therefore, to keep losses from escalating, we establish some principal limits to maintain balance:

Keeping the longitudinal coupling low, i.e. $\Gamma\chi \to 1$ leads to $\chi \ll 1/\Gamma$. therewith coupling is kept to a single level, which is not applicable.

Keeping the lateral coupling low, i.e. $\xi\chi \to 1$ leads to $\chi \ll 1/\xi$, which may be used as a helpful criterion.

3.2. Connectivity of network development of cost - Balance characteristics

The explicit characteristics in close proximity to the equilibrium state can easily be derived. Holding the criterion $\xi\chi \to 1$, the development along the network is just linear infinite allowing to integrate the longitudinal coupling to the lateral coupling criterion

$$\frac{(\xi\chi)^{\Gamma\chi+1}-1}{\xi\chi-1}=\sum_{i=0}^{\Gamma\chi}(\xi\chi=1)^i=\sum_{i=0}^{\Gamma\chi}1=\Gamma\chi \quad (6)$$

This allows for further estimations to ignore the variation of the exponent $\Gamma\chi+1$ and introduce the symbolic length of effective causal chains $\Gamma=\Gamma\chi+1$. Exemplarily for $\Gamma=5$, we obtain the cost Δ_{net} in terms of saved resources or inherited risk in dependence of the connectivity ξ of the network and the degree of coupling χ.

Cost Δ_{net} are generally rising from negative values reaching an equilibrium state and then start escalating with increasing degree of coupling χ. The gradient is negligible for $\xi=1$ as expected for a single linear chain but shows significant increase with higher $\xi>1$. The yellow line indicates equilibrium, i.e. $\Delta_{net}(\chi,\xi)\overset{!}{=}0$. Figure 11 indicates the balance state for a set of different set of Γ.

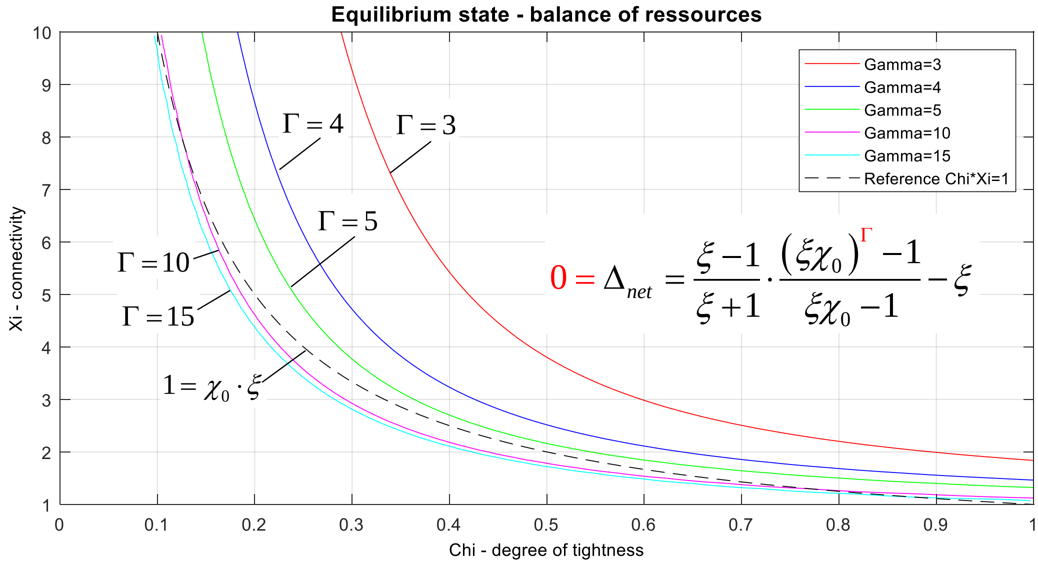

Fig.2. State of equilibrium depending on connectivity ξ and degree of coupling χ.

For comparison, the criterion $\widetilde{\chi_0}\cdot\xi=1$ is plotted as well (dashed line). For $\xi=1$ (linear chain) all deviations are averaging and therefore have no accumulating consequences. With rising connectivity, the available range of coupling is significantly reduced. Very short causal sequences allow for not much restrictions. However, clearly can be seen that for $\Gamma>5$ equilibrium can in fact be approximated by the rough rule of thumb $\chi_0\cdot\xi\approx1$, indicating for example that a connectivity of e.g. $\xi=10$ restricts the sensible degree of coupling to $\chi_0\approx10\%$.

4. Conclusion

The simple model presented here certainly does not cover all possible details of interaction and network characteristics. In particular consumption of resources and utilization of pre-products is strongly simplified here. However, as long as the linear dependency character of processes can be accepted – as is the definition of low-level activities – the principal outcome provides some inevitable reasoning.

The fundamental parameter of the network would be its complexity $\alpha=\ln(\xi+1)/\ln N$, respectively in other words $\xi=N^\alpha-1=K/N$. A completely non-complex system is characterized by $\alpha=0$ resp. $\xi=0$ indicating absolutely separated processes. As soon as interaction comes into play to some degree $0\le\chi\le1$, any possible deviation $\tau\ge0$ is carried and multiplied through any kind of network. Despite a large number of unknown effects, a limit can be provided, up to which coupling, i.e. $\chi\ge0$, leads to saving resources. Exceeding this limit quickly leads to a significant rise of cost due to the given complexity and should be avoided as a primary rule.

This limit is given by roughly a unity square with side-length of one, where the lateral dimension is $\chi\xi = 1$ while the longitudinal dimension is $\chi\Gamma = 1$. As long as the network-parameters in combination with the degree of coupling are well located within this square, a system may be considered stable and safe. Approaching this limit clearly provides the optimal situation, while exceeding leads inevitably to instable settings. Due to considering an equilibrium situation, the explicit value of the local uncertainty τ plays no role within this context as long as $\tau > 0$. In the end, the gradient at balance runs proportional to $\tau > 0$, so that any significant uncertainty allows this rule to remain applicable.

Practically speaking, any network, be it a network plan in construction or real estate management as well as a train schedule, is defined by the length of causal chains Γ and the connectivity ξ. Since fuzziness cannot be excluded generally, the degree of tight coupling χ needs to be kept beyond $1/\Gamma$ as well as beyond $1/\xi$, say a network with given connectivity of e.g. $\xi \approx 1$ allows for a maximum coupling of 10% in order to maintain a safe and stable system.

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Formal Modeling of Smart Contracts for Quality Acceptance in Construction

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Abstract

The coding and deployment of smart contracts in the construction industry are challenging because of the gap between the generality of existing modeling approaches for such contracts and the pertinence of business logic to construction management. This research proposes a formal model for smart contracts in the context of quality acceptance in the construction industry to reduce the threshold for applying smart contract technology. First, a conceptual scenario of smart contract-based quality acceptance in construction is analyzed. Second, a finite state machine-based model is proposed to formalize smart contracts for quality acceptance. Lastly, a Hyperledger-based case study is performed to demonstrate the performance of the proposed formal model. This study contributes to the industrial application of formal modeling approaches for smart contracts in the field of construction.

Keywords: blockchain, finite state machine, quality acceptance, quality management, smart contract

1. Introduction

Blockchains are one of the most high-profile technologies because of its traceability, decentralization, and tamper-proofing capability. The support for smart contract programming enables blockchain systems to automate several business processes in addition to issuing currencies [1]. Various industries devote continuous effort to technological explorations, resulting in the emergence of a batch of preliminary applications. However, the construction industry often responds slowly to innovative technologies, and studies on blockchain and smart contracts are still a novelty in this field. Perera et al. [2] stated that smart contract-enabled blockchain systems can resolve the fragmentation issues caused by the complexity of construction projects and keep the information updated and available for stakeholders in the management process. Li et al. [3] believe that smart contracts have the potential to change the organization operation and reduce disputes. Wang et al. [4] established a Hyperledger-based framework to address the challenges (e.g., poor traceability/timeliness of information) faced by the current precast supply chain and suggested that smart contracts are the sole channel for management personnel to interact with distributed ledgers. Furthermore, blockchain and smart contracts have been demonstrated to have advantages in integrated project delivery [5] and payment security [6].

Based on the functions of blockchain and smart contracts, we posit that their assembly also has advantages in quality acceptance in construction. First, quality compliance inspection, which is crucial for quality acceptance, is a knowledge-intensive task that involves a succession of regulations and industry provisions; this succession renders manual task execution cumbersome and error prone. Smart contracts can semi-automate several checking tasks and reduce the overall time consumption. Second, the substantial quality information generated during construction must be shared and stored carefully. However, a centralized database cannot guarantee data security, and data holders can tamper with the data. A blockchain-based distributed solution that allows several or all participants to have a duplicate of the ledger can effectively avoid such misdeeds. Lastly, quality compliance inspection usually becomes an afterthought in practice due to the lack of constraints on the individuals' responsibility. A system based on blockchain and smart contracts enables all participants to formulate jointly a code of conduct before a project starts and enforce it during construction. A predefined punitive measure is imposed when an inspector fails to complete the agreed operation within the time constraints.

The programming and deployment of smart contracts require specialization; thus, developers must possess computer literacy and professional proficiency. However, such requirement is impractical. Consequently, the advantages of smart contracts are hardly maximized. Formalization is an important topic in smart contract research. Smart contracts are vulnerable to malicious attacks (e.g., the attack on the Decentralized Autonomous Organization in 2016) due to the bugs caused by the negligence or limited knowledge of developers. Formalization approaches can help developers reduce faults in smart contracts and assist in software testing. Singh et al. [7] reviewed several prevalent approaches, including theorem proving, symbolic execution, model checking, formal modeling, and finite state machine (FSM). These approaches were proposed to verify contractual functionalities [8] and alleviate the security [9] and privacy [10] issues of smart contracts. However, these approaches are difficult for quality inspectors to apply because of the gap between the generality of these approaches and the pertinence of quality acceptance in construction. Thus, this study proposes a formal modeling approach for smart contracts in the context of quality acceptance in the construction industry to relax the barrier to smart contract adoption and reduce the perplexity of applying this technology to construction projects.

2. Smart contract-based quality acceptance in construction

A massive amount of quality information is generated from the measuring and testing processes during construction. However, the absence of a uniform system among the stakeholders of a construction project results in substantial "noise" (e.g., blank and tampering) in the collected quality information. Quality management systems that enable the precise documentation and tracing of quality information are desired. Blockchain technology can free quality information from exclusive control and thus promotes trust among project participants. Figure 1 presents the conceptual framework of construction quality blockchain. This blockchain, which is a distributed database for on-chain projects, preserves the complete latest records and documents regarding quality. On-chain information can be continuously utilized for project management and can be accessed by users through application clients.

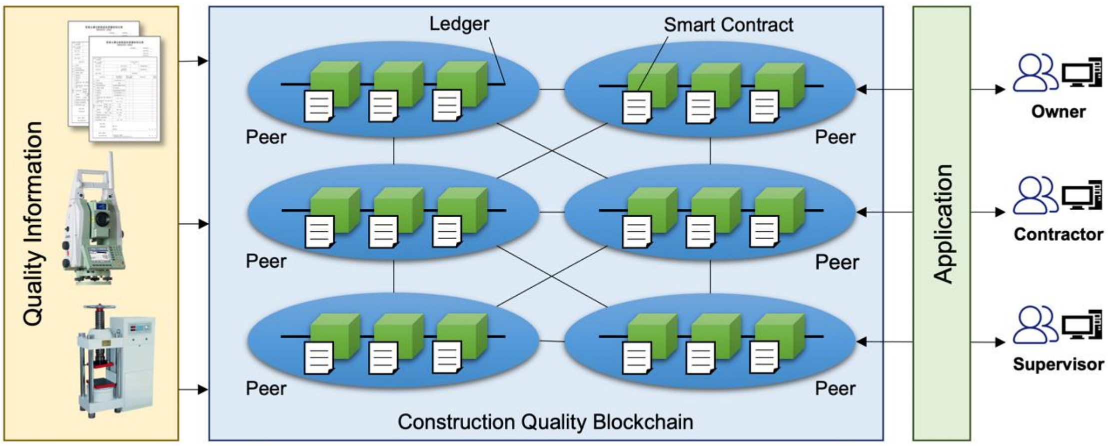

Figure 1. Conceptual framework of construction quality blockchain

Construction quality blockchain network is a peer-to-peer network composed of the stakeholders of construction projects. In such network, each participant serves as a peer. After obtaining quality information, the responsible person is obliged to upload it to the blockchain network. Through a consensus process, the uploaded information is sorted, written in the latest block, and broadcasted. Each peer downloads the block from the network and refreshes its own duplicate ledger to maintain the consistency of quality information across the network. Once updated in the ledger, information cannot be controlled by any person or entity (i.e., cannot be modified and deleted). Users can only implement quality management through the application client, which is the bridge between users and on-chain information. For example, project stakeholders, such as owners, contractors, and supervisors, can create a smart contract-based agreement regarding the responsibilities and constraints for quality management through application interfaces before the project commences. After the consensus process, this smart contract is backed up to each peer (i.e., the agreement is endorsed by the entire network). Subsequently, the participants fulfil the agreements for project delivery. For example, the contractor performs construction tasks in accordance with the schedule and uploads quality information. Meanwhile, the owner and supervisor conduct timely compliance checking and acceptance.

Smart contracts are not a new concept and have been existing for more than 25 years. In 1994, Szabo [11] defined a smart contract as “a computerized transaction protocol that executes the terms of a contract” and aims to minimize exceptions and intermediaries. However, the technological development of smart contracts was postponed because of the difficulty of establishing a trusted cooperation environment in a centralized management system. The emergence of blockchains provides a low-budget opportunity for developing and applying smart contracts. A smart contract contains the trigger conditions for responses and required actions. Once deployed, it can continuously monitor data fluctuation in the chain or external source. Moreover, it can automatically execute the predefined actions when triggered. In conventional business systems, multiple manual executions and intermediate interventions are inevitable for the same functions. Smart contracts can handle complex application scenarios because they are supported by Turing complete programming languages, such as Go for Hyperledger and Solidity for Ethereum. However, in several industries, such as construction, the large-scale application of smart contracts is challenging because practitioners must adapt to brand-new, domain-specific programming languages and logic.

The assembled technology of blockchain and smart contracts has the potential to semi-automate the procedure of quality acceptance which is a concurrent activity of the construction process, and preserve quality information in a tamper-proof and traceable manner. Figure 2 displays a graphical description of the conceptual scenario for smart contract-based quality acceptance in construction. First, the stakeholders of a construction project, such as the owner, contractor, and supervisor, must reach an agreement regarding quality acceptance; this agreement includes the inspection object, inspection task, and quality constraints, which are ultimately reflected in the contractor’s quality assurance system. Second, all agreements are transcoded from natural language to computerese; transcoding is a challenging task that is hardly handled by most frontline quality inspectors. The lack of standardization in modeling smart contracts also undermines the contracts’ anti-risk capability. After translation, the agreements for quality acceptance are coded as computer-readable logical statements, such as IF–THEN judgment statements. The functions of smart contracts are activated after being deployed to the construction quality blockchain. These contracts can continuously monitor fluctuations in quality information in the chain. When the trigger conditions are initiated, the predefined responsive actions of smart contracts are automatically executed. Then, the intermediate information is documented on the chain; this process can be fulfilled without external disturbance.

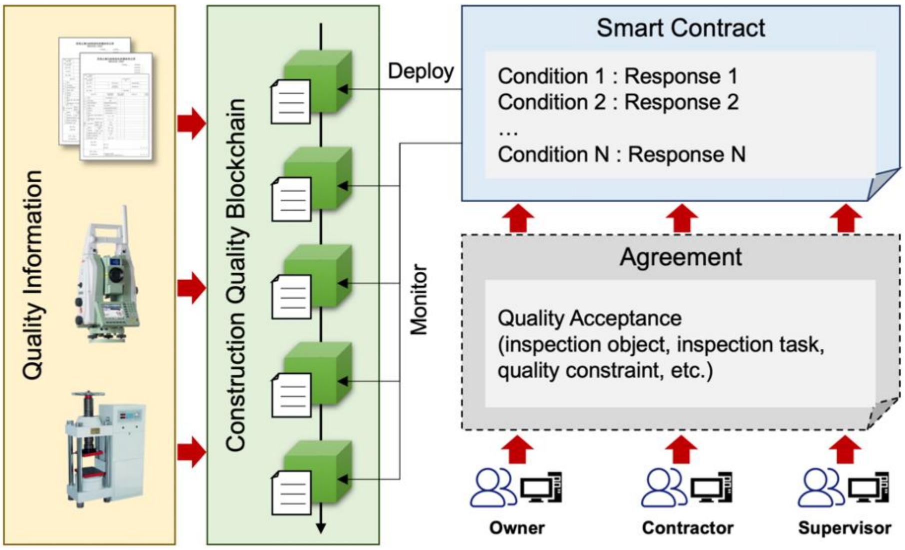

Figure 2. Conceptual scenario of smart contract-based quality acceptance in construction

3. Formal model of smart contracts for quality acceptance in construction

Formalization can avoid faults and ease the burden of inexperienced developers. Identifying and defining the fundamental constituents of the agreement for quality acceptance in construction are prerequisites of this process. Based on commercial contracts, Wang et al. [12] suggested that commitment, which they defined as a quintuple comprising a promisor, a promise, a premise, results, and time constraints, is the fundamental constituent for modeling smart contracts. However, this definition is broad and lacks pertinence for the scenario of quality acceptance.

3.1. Definition of the inspection task

In this study, CQA = {IT_0, IT_1, ⋯, IT_n} is defined as the agreement for quality acceptance that must be implemented in a construction project by the project stakeholders. IT refers to the inspection task, which is the fundamental constituent of CQA, and it can be formally defined as a sextuple.

$$IT_i = \left(R_i, A_i, CO_i, II_i, IR_i, AR_i\right) \in CQA,\ i = 0,1,\cdots,n$$

where

- R_i is the responsible person for IT_i, and this person must supervise self-inspection and issue inspection results;
- A_i is the accepter of IT_i and needs to recheck the inspection results issued by R_i and provide the acceptance results;
- CO_i is the checking object of IT_i, which can be a batch of building resources/products or a construction activity;
- II_i = {$II_{i,0}$, $II_{i,1}$, ⋯, $II_{i,m}$} is a collection of inspection items, where $II_{i,j}$ (j = 0, 1, ⋯, m) is a sole inspection item that is defined in detail hereinafter;
- IR_i is the inspection result of IT_i issued by R_i, who is responsible for the integrality and authenticity of IR_i;
- AR_i is the acceptance result of IT_i issued by A_i when CO_i can be accepted.

The sole inspection item $II_{i,j}$ is defined as

$$II_{i,j} = \left(R_{i,j}, QA_{i,j}, QC_{i,j}, QI_{i,j}, IR_{i,j}\right) \in II_i,\ j = 0,1,\cdots,m$$

where

- $R_{i,j}$ is the responsible person for $II_{i,j}$ who needs to capture and truthfully report on-site data and provide the inspection result of the inspection item;
- $QA_{i,j}$ is one of the quality attributes of CO_i that must be inspected in $II_{i,j}$;
- $QC_{i,j}$ is the quality constraint that $QA_{i,j}$ must satisfy to achieve the holistic quality goal of the project; related regulations, construction plans, and other items are the main sources and references for setting this constraint;
- $QI_{i,j}$ is the raw quality information captured for $II_{i,j}$ that should be documented in a traceable and tamper-proof manner for project management;
- $IR_{i,j}$ is the inspection result of $II_{i,j}$ issued by $R_{i,j}$.

3.2. Formal definition of smart contracts

CQA must be further encoded as a language-specific (e.g., Go- or Solidity-based) smart contract before deployment to the construction quality blockchain. The programming and deployment processes vary among different underlying blockchain infrastructure. Nonetheless, smart contracts are executable programs that switch between states on the basis of the data input, which can be described using FSM, a discrete mathematical method for modeling the state transition of a system [8]. In this study, FSM is used to formalize the smart contracts.

A smart contract for quality acceptance in construction (SC_CQA) is an FSM, which can be formally defined as

$$SC\_CQA = \left(S, s_0, F, \Sigma, \delta\right)$$

where

- $S = \{s_0, s_1, \cdots, s_n\}$ is the state set of SC_CQA involved in its smart contract life cycle;
- s_0 is the initial state of SC_CQA ($s_0 \in S$);
- F is the set of terminal states of SC_CQA ($F \subset S$);
- Σ is the set of input events of quality information;
- δ is the set of state transition functions ($\delta: S \times \Sigma \to S$).

Figure 3 presents the state transition diagram of SC_CQA. The diagram can describe the various states and transitions between the states of SC_CQA during its life cycle. SC_CQA has a composite state, which is composed of multiple concurrent substates (as shown in Figure 3) because several inspection tasks of a CQA are performed concurrently without interfering each other. Each concurrent substate of SC_CQA is used to describe the state of an inspection task. These concurrent substates are activated synchronously under certain conditions; if and only if they are all completed, then the SC_CQA enters the next state. Similarly, an inspection task also has a composite state because an inspection task has multiple concurrent inspection items, and each inspection item has multiple states. The state set and the input event set of SC_CQA are defined in Tables 1 and 2, respectively.

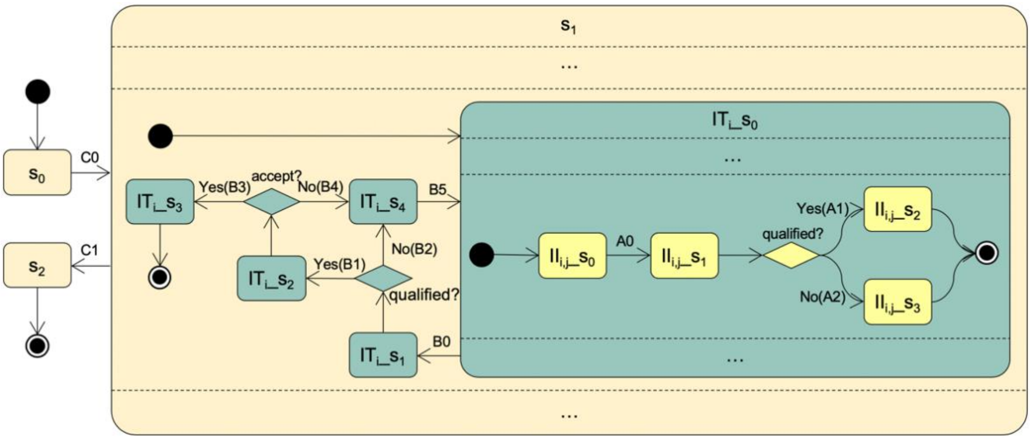

Figure 3. State transition diagram of the SC_CQA

Table 1. State set of SC_CQA

State	Description
II_s_0	Uncompleted state where the on-site checking information of $II_{i,j}$ is being collected and documented
II_s_1	Completed state where the requisite checking information of $II_{i,j}$ has been fully documented on the construction quality blockchain
II_s_2	Qualified state where $QA_{i,j}$ can satisfy $QC_{i,j}$ and therefore receives a "qualified" inspection result from $R_{i,j}$
II_s_3	Unqualified state where $QA_{i,j}$ cannot satisfy $QC_{i,j}$ and therefore receives an "unqualified" inspection result from $R_{i,j}$
IT_s_0	Uncompleted state where at least one more inspection item of IT_i has yet to be completed
IT_s_1	Completed state where all inspection items of IT_i are completed and waiting for the overall inspection result to be issued by R_i
IT_s_2	Qualified state where R_i issues a "qualified" result for CO_i and IT_i is waiting for the acceptance result from A_i
IT_s_3	Accepted state where A_i issues an "accepted" result for CO_i
IT_s_4	Rectified state where CO_i is identified as unqualified by R_i or A_i and must be rectified and checked again
s_0	Initial state
s_1	Running state where at least one inspection task of CQA has yet to be completed
s_2	Completed state where all inspection tasks of CQA are completed and accepted

Table 2. Input event set Σ

Event	Description
A0	All requisite checking information has been submitted.
A1	$II_{i,j}$ passes the quality compliance inspection.
A2	$II_{i,j}$ does not pass the quality compliance inspection.
B0	All inspection items have been completed.
B1	IT_i passes the overall quality inspection.
B2	IT_i does not pass the overall quality inspection and must be rectified.
B3	IT_i passes the acceptance.
B4	IT_i does not pass the acceptance and must be rectified.
B5	The rectification of IT_i is completed and reinspection begins.
C0	SC_CQA starts to run.
C1	All inspection tasks of SC_CQA are completed.

4. Case study

Support for smart contracts has become the fundamental function of blockchain infrastructure. This study takes the Hyperledger Fabric blockchain framework as a case study to demonstrate the implementation of SC_CQA. Hyperledger is an open-source project launched by the Linux Foundation for blockchain-based industrial applications, and Fabric is one of the permissioned blockchain frameworks in the Hyperledger project.

On the basis of the Hyperledger Fabric framework, a consortium blockchain can be established among the stakeholders of construction projects in a specific region to manage quality information. Using the real-name registration provided by the built-in membership service provider module rather than maintaining anonymity allows the information in the construction quality blockchain to be traced to specific individuals. The certificate authority module allows the establishment of a permission hierarchy in a project, such that each person's permission can be predefined by his/her superior. Many modularized consensus algorithms, such as Kafka and practical Byzantine fault tolerance, can ensure the consistency of quality information among peers in the construction quality blockchain.

Furthermore, chaincodes (i.e., smart contracts in the Hyperledger-based blockchain) enable the blockchain to perform the complex business logic of quality acceptance (Figure 4). Project stakeholders can deploy a chaincode for quality acceptance through the user interface of the construction quality blockchain. Once deployed, the chaincode acquires a unique address and exclusively runs on the blockchain network. In the subsequent management process, the project stakeholders cannot directly process the quality information in the blockchain, and the chaincode serves as a bridge. Through the user interface, a project stakeholder can send an input event to the deployed chaincode in accordance with the needs of the management. Then, the chaincode switches to a new state on the basis of the current state, and the predefined state transition rules and sends the relevant quality information to the latest block for documentation. For example, during the construction of a cast-in-situ bored pile inspection lot, the quality inspector of the contractor must measure the hole depth and input the data through the user interface. Subsequently, the state of the hole depth inspection item, which is in the chaincode of the cast-in-situ bored pile inspection lot, switches from uncompleted to completed, and the hole depth is sent by the chaincode to the latest block. Figure 5 presents a code snippet of a chaincodes for quality acceptance based on the Go language, which defines the input events of SC_CQA, as well as the starting and terminal states of these events.

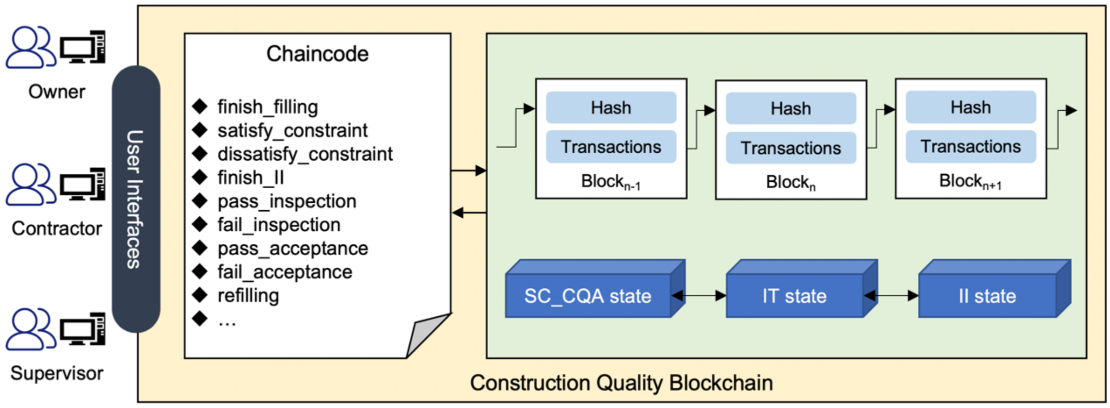

Figure 4. Smart contract for quality acceptance in construction

```
func InitFSM(initCQAStatus string, initITStatus string, initIIStatus string) *fsm.FSM{
    CQA := fsm.NewFSM(
        initCQAStatus,
        fsm.Events{
            {Name: "start_IT", Src: []string{"Initial"}, Dst: "Running"},
            {Name: "finish_IT", Src: []string{"Running"}, Dst: "Completed"},
        },
        CQA.Callbacks{},
    )
    IT := fsm.NewFSM(
        initITStatus,
        fsm.Events{
            {Name: "finish_II", Src: []string{"Uncompleted"}, Dst: "Completed"},
            {Name: "pass_inspection", Src: []string{"Completed"}, Dst: "Qualified"},
            {Name: "fail_inspection", Src: []string{"Completed"}, Dst: "Rectified"},
            {Name: "pass_acceptance", Src: []string{"Qualified"}, Dst: "Accepted"},
            {Name: "fail_acceptance", Src: []string{"Qualified"}, Dst: "Rectified"},
            {Name: "refilling", Src: []string{"Rectified"}, Dst: "Uncompleted"},
        },
        IT.Callbacks{},
    )
    II := fsm.NewFSM(
        initIIStatus,
        fsm.Events{
            {Name: "finish_filling", Src: []string{"Uncompleted"}, Dst: "Completed"},
            {Name: "satisfy_constraint", Src: []string{"Completed"}, Dst: "Qualified"},
            {Name: "dissatisfy_constraint", Src: []string{"Completed"}, Dst: "Unqualified"},
        },
        II.Callbacks{},
    )
}
func (s *SmartContract) Init(APIstub shim.ChaincodeStubInterface) sc.Response {
        return shim.Success(nil)
    }
func (s *SmartContract) Invoke(APIstub shim.ChaincodeStubInterface) sc.Response {
   function, args := APIstub.GetFunctionAndParameters()
   if function == "Initial" {
      return s.Initial(APIstub, args)
   }  else if function == "start_IT" {
      return start_IT(APIstub, args)
   }  else if function == "finish_IT" {
      return finish_IT(APIstub, args, "finish_IT")
   }  else if function == "finish_II" {
      return finish_II(APIstub, args)
   }  else if function == "pass_inspection" {
      return pass_inspection(APIstub, args)
   }  else if function == "fail_inspection" {
      return fail_inspection(APIstub, args)
   }  else if function == "pass_acceptance" {
      return pass_acceptance(APIstub, args)
   }  else if function == "fail_acceptance" {
      return fail_acceptance(APIstub, args)
   }  else if function == "refilling" {
      return refilling(APIstub, args)
   }  else if function == "finish_filling" {
      return finish_filling(APIstub, args)
   }  else if function == "satisfy_constraint" {
      return satisfy_constraint(APIstub, args)
   }  else if function == "dissatisfy_constraint" {
      return dissatisfy_constraint(APIstub, args)
   }
   return shim.Error("Invalid Smart Contract function name")
```

Figure 5. Code snippet of the smart contract for quality acceptance

5. Conclusion

Blockchains and smart contracts are promising tools for improving quality management in construction. The former provides quality information and tamper resistance, and the latter can (semi-)automate the business logic of quality management. However, the coding and deployment of smart contracts for quality management are high-threshold tasks for quality managers. To address this issue, this study proposes an FSM-based formal model of smart contracts for quality acceptance in construction. A Hyperledger-based case study is performed to demonstrate the functions of the proposed model. However, the effectiveness of the proposed model requires further evaluation using practical evidence, which is a limitation of this research.

Smart contract technology is still a novelty in the construction industry, and our work provides insights into the industrial application of smart contracts. Our future work will include the method of generating smart contract codes for quality management by mapping the FSM model and smart contracts. Such an investigation would further lower the application threshold of smart contracts for quality management personnel.

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How Organization Will Enhance Benefits Realization by Using Innovation Project Managment and AI (Artificial Intilligence)

The Influence of Innovation Project Management on Project Success within Projects-Based Organizations

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Abstract

The importance role of innovation and technology is widely recognized in the corporate change, growth and profitability, but the main challenge is how to facilitate the innovative process and tools for practices and research, especially in project-based organizations. Where, conventional project management methods are oftentimes insufficient for managing innovation projects. In project-based firms, innovation is almost lost under the pre-determined scope and predicted environments of traditional project management. There is tremendous pressure on organization to innovate and the project managers are responsible to manage these innovation projects effectively. Therefore, innovation project management calls for providing the tools and technology (AI), perceptions, and metrics needed; in order to manage innovation projects successfully; helping PM's and stakeholders to identify problems in their organization, conceive elegant solutions, and, when necessary promote changes to their organizational culture. Thus, for this paper, authors attempt to conceptualize the innovation project management; to facilitate the innovation within project environment and to gain the ultimate corporate goals through their projects accomplishment.

Keywords: project-based organization, project management, innovation management, innovation project management, project success

1. Introduction

All companies desire growth. But without some innovations, the opportunities may be limited and even if the firm does have a successful innovation, failure can still occur if the company focuses on past successes without developing a culture for continuous and sustainable innovations, Today industry leaders can become tomorrow's failures without constantly challenging results [12].

If continuous and sustainable innovation is to occur, then innovation leadership and project management must be integrated together and with a clear understanding of each other's roles. Innovations defines what we would like to do, and project management determines if it can be done. The integration also may require that both parties learn new skills and create a corporate culture that support ideas management practices. Understanding each other's roles is the first step in making a company more innovative. This requires that the project managers and other innovation personnel understand what they do not do now but must do for long-term successful innovation. *"The Future is a direction, not a destination", as quoted by Edwin Catmull* [5,12,25].

Over the past three decades, there has been a great deal of literature published on innovation and innovation management. Unfortunately, innovation projects may not be able to be managed effectively using the traditional project management philosophy we teach in project management courses. Innovation varies from industry to industry, and even companies within the same industry cannot come to an agreement on how innovation project management should work. Part of disagreement comes from the fact that there are several forms of innovation, each one with different characteristics and possibly requiring different tools [5,12,25,26].

It is inevitable that, over the next several years, professional organizations such as the Project Management Institute (PMI) will recognize the need to begin setting some standards for innovation project management and possibly partner with organizations, such as the Product Development and Management Association (PDMA), with offer a certification programs related to innovation. There may also appear an Innovation Project Management Manifesto like the Agile Manifesto. The greatest innovation in the next decade may be the recognition and advancement of innovation project management such as a specialized project management career path position [5,12,25].

There are difference between traditional and innovation project management. People have avoided using the words "innovation" and "Project Management" in the same sentence because of these differences. There is limited research on examine the link between innovation and project management. Innovation is often unstructured and requires people to utilize those portions of the brain that focus on freethinking, creativity, brainstorming, and alternative analysis. Project Managers, on the other hand, is very structured, with a well-defined scope, and often with a very tolerance for any creativity or brainstorming that is believed to be out of scope [12].

Also, in past days, project management research has focused a lot on practices that related to get projects done rather than on conceptual or strategic issues like innovation where reasons for success, exposes that the most common subjects for project management research are those linked to initiating, executing and closing projects [9].

There are several types of innovation, ranging from small, incremental changes to product to very new products and processes that are the result of a breakthrough in technology that disrupts the market. Incremental innovation may follow some of the standard project management processes. Radical or disruptive innovation may require playing a different set of rules. All assumptions must be challenges, even if they appear in a business case. Innovation requires the identification of the right problems and thinking about elegant solutions. All of these factors may require that the organizational culture change. *"If you want something new, you have to stop doing something old", as quoted by Peter Drucker* [12].

Therefore, this paper purpose is to fine the linkage between the project management and innovation management and attempt to map them together; to assess their merging influence on project success and to improve the business outcomes, in order to compete and survive in this new market place.

2. Theoretical background

A different type of forces drive the innovation process, for instance the demand for radically new types of structures or buildings, especially during the 80s and 90s. This demand for new types of buildings was developed by the diffusion of information and communication technology, growth of the service sector, and new methods of manufacturing. All that, to enhance flexibility to meet unforeseen changes in demand and to improve lifecycle performance characteristics [7].

Moreover, global business is susceptible to changes in technology (ex. Artificial Intelligence), demographics, a turbulent political climate, industrial maturity, unexpected events, and other factors that can affect competitiveness. Taking advantage of these changes will be challenging. Companies need growth for long-term survival. Companies cannot grow simply through cost reduction and reengineering efforts that are more aligned to a short-term solution. In addition, companies are recognizing that brand loyalty accompanied by a higher level of quality does not always equate to customer retention unless supported by some innovations [12].

2.1. Project-based organizations characteristics

Project-based firms definition according to many literature as firms that are organized around projects [7] and that produce knowledge-intensive services or complex integrated systems by order of their clients [9].

Based on many studies related to project-based management, there are at least four exceptional features, comparing to other practices of management [19]:

- Project-based management is focused toward activities to accomplish goals of time, scope, and cost [20] and, gradually, toward wider business and customer objectives. In previous study, management by objectives has been considered as an organizational innovation, also as goal-oriented agendas.
- Project-based management induces replacing the old organizational structure or utilizing a temporary organizational structure [20]. In the past, matrix or M-form organizational structures, and flow manufacturing in multiple plants have been studied as organizational innovations.
- Project-based management can contain both organization-specific and standardized tools and good practices [20]. So earlier, studies on ISO 9000 and total quality management (TQM) have been considered as organizational innovations.
- Project-based management endorses distributed and project specific responsibilities in the organization [20]. Each project has a dedicated project manager and project organization that dissolves as the project ends. New management system has earlier been considered as organizational innovation in somewhat different settings.

Organizational innovation may cover new services or products, new organizational structures or administrative systems, new process technologies, or new plans or programs relating to organizational participants [19].

Project-based organizations must manage uncertainty and technological across whole organization, within networks of interdependent regulatory bodies, customers and suppliers. Project-based firms therefore need to manage in multi-technology environments, responding to changes in engineering, software, information and materials technologies, increasing costs, and the need to deal with growing complexity because of political and social situations. However, management of innovation is complicated, since there is a discontinuous nature of project-based production in which, often, there are broken learning and feedback loops [7].

Likewise, according to [6] most actions in recent business world are planned and organized in projects still there is no universal project procedure that fits all organizations. Specially, that innovation are frequently applied via projects. Therefore, innovation project is a novel way to do so and aims to take something that has been planned, created, or developed and then utilizes processes to them in some way to realize a specific outcome. Consequently, the need for innovation in project-based organization is desirable.

2.2. Innovation and management

According to [23], innovation studies are derived from some important studies of Joseph Schumpeter in the 20s and 30s, whose ideas started to gain popularity in the 60s, as the general interest among policymakers and scholars in technological change, R&D and innovation increased. The field formed as a distinctive academic discipline from the 80s.

Basically, the innovation process model with a standard decision points of five-stage model is consist of creativity, selection, incubation, implementation and learning. First, the creativity stage involves examining the internal and external environment: customers' needs, competitors' products and in-house R&D can all be sources of creativity. Second, selection stage follows as the company assesses the relative merits of competing ideas, considering the organization's strategy and operational constraints. Third, the incubation stage, where the company develops a prototype, using it to identify problems and resolving them before progressing to the larger scale activity of the following stages. Finally, during implementation stage, the company scales up the prototype to full production and launches the product in the market [14].

And, in order to understand innovation further more, it is required to know the source of the innovation or where they come from. Thus, the seven sources of innovation were listed as following [6]:

The first four represent the organizational internal sources:

- Innovation based on process need- Based on specific tasks within a business rather than overall operating strategy.
- The incongruity– Is the variance between actual reality and perceived/assumed reality.
- Changes in industry structure or market structure that catch everyone unawares.
- The unexpected– The unexpected success, failure or outside event.

Whereas, the next three describe organizational external sources of changes:

- New knowledge, both scientific and non-scientific.
- Changes in perception, mood and meaning.
- Demographics- population changes.

In 2016, [6], have identified five types of innovations:

- New sources of supply - input innovation
- New production methods (process)
- New forms of organization
- New product
- New market

Based on [15] (p. 229) realized that there is a strong link between innovation and management, accordingly, the following description about innovation and management have been provided: "Management is to some extent a cross-disciplinary field by default and firm-level innovation falls naturally within its portfolio. So between innovation studies and management there clearly is some common ground" [23]. Therefore, the next sections will provide more description about project management and innovation management concepts and their relationships.

2.3. Project management

According to PMI's *A Guide to the Project Management Body of Knowledge (PMBOK® Guide)* [20] a project management, is the application of knowledge, skills, tools, and techniques to project activities to meet the project requirements. It has been practiced as a distinct profession in the mid-20th century. Project management processes fall into five clusters: initiating, planning, executing, monitoring and controlling, and closing. Moreover, project management knowledge areas are: integration, scope, time, cost, quality, procurement, human resources, communications, risk management, stakeholder management. All management know clearly about these very well. However, project management considers bringing a unique focus shaped by the goals, schedule and resources of each project.

Therefore, a project can be considered as an endeavor in which financial, human, and material resources are organized in a unique manner to commence an exclusive scope of work, of given specification, which constraints of time and cost, in order to accomplish valuable change that can be defined through quantitative and qualitative objectives [23].

2.4. Innovation project management

In this section, a brief literature review exposed the crossing point amongst project management and innovation studies, in which, there are number of important associations between project and innovation.

Thus, based on Keegan and Turner (2002, p.385), "A revision of traditional project management guidelines may be necessary given the potential of conventional approaches to managing (innovation) projects to stifle innovation" [23].

Besides, according to other scholars, the term of innovation project is used and the common definition is:

Innovation projects are systematically managed activities that use inputs in order to transform them into outputs with a certain scope and aims at achieving something new, in a new way or at improving something existing [26].

Consequently, innovation project management will be focused on a process for creating and executing management decisions that are in linked with the defined organizational strategic objectives and the organizational structure, formation of actions and monitoring their execution. In sum, focusing on all the implementation process of an innovative idea [1]. Moreover, many authors like [12] put three critical innovation interfaces as: organization, technology, and markets.

However, several researches indicates that innovation projects set the requirements that must comply with tools to manage them in the long-term period. Herewith, innovation project management must be reflected within three features, in specific, as a management decision process, as a functional system of, and as an organizational system in terms of the functional approach in the innovation project management [16].

On the other hand, authors like [1] described some more approaches related closely to innovation project management in a further comprehensive way as following:

- The system approach that refers to the management process, in which it consist of two subsystems that includes the "input" and "output" of the system, 1) the external environment, where it is communicating with the external environment, 2) and the internal environment, where it is a set of consistent mechanisms that ensure the process by which the management subject govern the process, the translation of an "input" into an "output", the system approach needs support on a number of applicable systematic sets, combined models, means, standards, processes and tools that are used for managing projects in several areas of activity.
- The process approach that refers to the management functions of project progress, planning, organization, motivation, controlling, coordination, and regulation to be interrelated and establishing a management cycle.
- The behavioural approach that refers to the actualization of the human resources and number of the principles of inspiration to accomplish the objectives of both the individual and the organization.
- The prescriptive approach that refers to the guideline of functions of the management elements by normative of the task, programs, plans, region, national government, the founder, and the organization itself.
- The integration approach that refers to the improvement of collaboration between management, expanding the relations among the gears of a management system, amongst the life cycle phases of the management object and between the management structural levels.

Based on these methods, innovation project management is managed as a process of advanced execution of an agreed set of management phases - initiation, planning, execution, analysis and regulation, monitoring and control, and closing - that guarantee meeting or even exceeding the project success [1].

2.5. Classification of innovation projects

There are number of classification and typologies of projects have been developed. Thus, for this paper and for the purposes of the study it is aimed to define the location of innovation projects and to state their specific groupings, see Fig. 1. There are two types of projects; the conventional projects, which is the traditional project that include the commonly executed ones like operational projects, constructions projects, or as infrastructural ones [6,23].

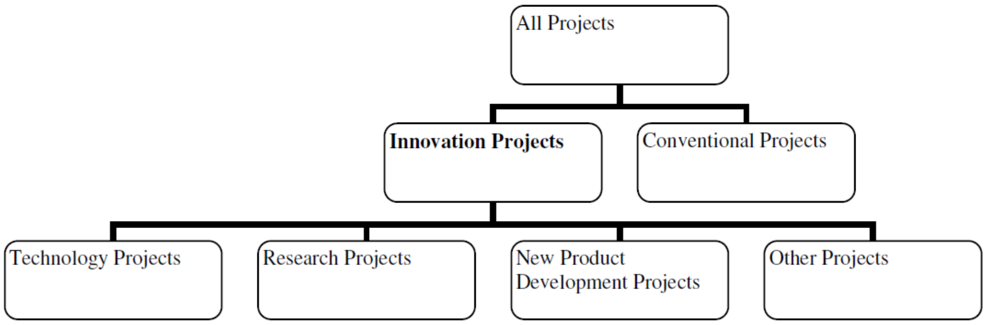

Fig. 1. Classification of projects [23]

The second type is the innovational projects that includes technology project, new product development projects, research projects, and other projects. Technology projects are refer to R&D projects, especially in such industries as defence, aerospace, etc. In addition, research projects are refer to the projects that involved in various research, for instance for social research, not necessarily as a technological projects [6,23].

2.6. Mechanism of innovation project management

As previously mentioned that the innovation project is a set of organizational, technical, planning, calculation and financial documents needed to achieve the project objectives. Consequently, the innovations implementation process can be defined as a collective of organizational, production, financial, technological, research, and commercial processes, which can be taken in a precise arrangement and producing innovations [16].

Likewise, the right organizational focus will be looking at projects as labs to test innovation in all dimensions. Innovation will include selecting the right mix of team members, experimenting with the right balance of virtual and collocated teams, testing new ways of working, experimenting fast with outcomes, innovating the use of data analytics in making faster and more effective decisions, and sensing very differently while engaging with the customers often and fast for best creative outcomes [12].

According to [12,16] the mechanism of innovation project management had been developed in stages, as:

- Stage (1): the project objective and goals with targeted results are developed, the forecasts of the project results are well-defined, the competitive capacity and possible economic consequence are projected, activities with a complex project measurements are shaped, and the project is displayed and planned. Where, the most important step for this stage is assessment of the project excitability.
- Stage (2): the selection of organizational form of management, activities related to measure, forecast, and estimate the developed operational state to achieve required results, spending of cost, time, and resources, analysing and removing the causes of elapsing from the established plan, then plan modification are done accordantly. Fig. 2 displays the innovation project management mechanism.

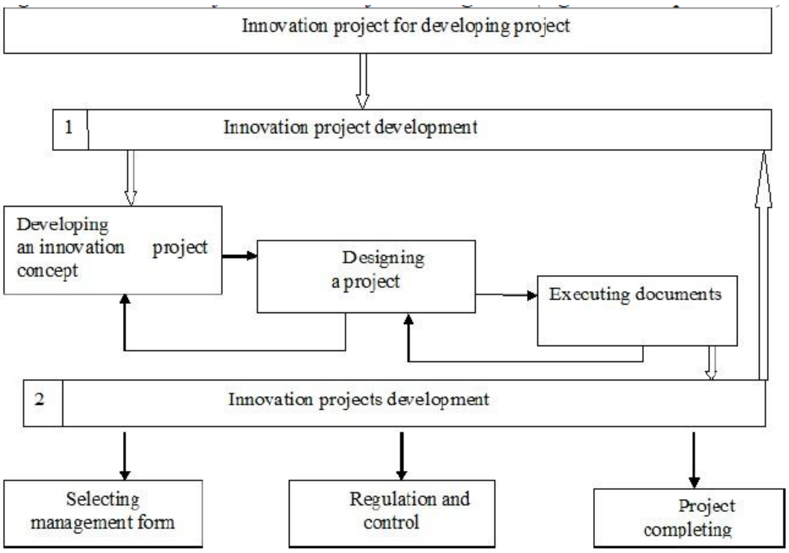

Fig. 2. The mechanism of innovation project management [16]

2.7. Characteristics of conventional and innovation project management

There are many characteristics can be considered when likening innovation with conventional projects. As mentioned by authors like [6,23] that innovation projects by their nature are vary from conventional projects in many aspects like:

- Objectives, whereas conventional projects tend to have clearly defined goals and targets. On the opposite, innovation projects often do not. Innovation is often intangible end goals and the commercial success of an innovation project can be highly uncertain. In fact, innovation is often a result of trial-and-error.
- Expenditures for research and innovative activities are considered as long-term, with increased insecurity regarding the eventual amount of generated earnings.
- Resources in traditional project management is designed via the accuracy, precision, and optimal use of resources. However, for innovation part since it is a creative process related to uncertainty aspect it is required slack resources.
- Risk-taking is low in conventional projects since the objectives are clearly defined and processes are established. While, in innovation projects the risk-taking is high; since their objectives are lightly identified and vague, and processes are more exploratory and experimentally.
- Project teams leading innovation projects are made up of people with diverse backgrounds, and that reflect the complex nature of innovation.

2.8. Project managers and innovation personnel challenges

Project managers that are using innovation projects must understand that the environment of innovation is significantly different from the traditional project environment, where some critical problems and challenges may occurs like for instance [12]:

- The alignment issue of the project and decision-making toward business strategy and strategic business objectives.
- Many of the team members may be made up of partner and consumers organizations, especially if co-creation is being used.
- There is a connection among innovation project management and strategic development.
- Benefits of success may look like another way from the traditional project management.
- Project managers may be predictable to create a major amount of business decisions.
- There are variances between innovation and traditional project management.

- Innovation project management is consider as a strategic capability.
- A long-term rather than short-term thinking might be required.

Hence, when linking the project with innovation, the biggest challenge facing project managers possibly, particularly qualified project managers, is knowing that innovation projects may need a full different set of gears and tools than they have been familiarized with [12].

2.9. Innovation project management skills tools

As commonly recognized from previous literature that innovation has arisen as the engine of social cohesion and national success but come with it new challenges. However to preserve global competitiveness and people's regular of living and to accommodate new challenges, efficiency needs to advance, new businesses need to be produced and people required to gain the skills that employers want. This lead to more acceptance by individuals receive change, grip new ideas, and improve new capabilities and skills. Hence, the required tool that measures the skills needed for innovation, are developed mainly to measures five general skills, which support innovative behavior and procedure an agreed number of characteristics that clearly linked to the innovation process: leadership, energy, creativity, risk-propensity, and self-efficacy [8].

In details, and compare to traditional project management, where all actions depend more in the organizational guidelines, policies, and procedures. As well as, for the project management methodology the project manager simply directs the project team to complete all the needed forms and checklists related to the project. Whereas, for innovation project management there are different skills required because of the innovation nature [12].

Few literatures identified the characteristics of innovators, but some of these studies focuses on creativity as a personality trait. Moreover, the studies assumed that innovative behaviors and skills may be gained from experience and experimentation. however, innovators may developed more skills through appropriate education and training [8,13]. Thus, here are some of important skills take into account for an innovation project manager like [12]:

- Knowing the firm's intangible and tangible assets (capabilities and resources)
- Willing to work under up normal pressure, risk and uncertainty
- Link the team objectives with the firm's growth objectives
- effective team building that includes external resources
- Let team members to be accountable to their actions
- Innovation Leadership and Good communicator
- Have a wide insight, see "the big" picture
- Have a design thinking skills
- Creative Problem-Solving
- Will to take responsibility

One of the most critical dimensions for projects success over the years has always been executive support. In innovation, several firms are recognised that the most critical to start from the top. For example, boards of directors and executive leaders of the future are not going to play a very different role, however they are improving, innovating, changing the business for the better, as well as, strengthening the excellence of implementation that derives from innovative project management [4,12]. Moreover, innovation in project management requires a good degree of autonomy. Specially, that today's dynamic workplace, teams are luckily becoming more self-directed. This is necessary to enhance the opportunity of creativity, the flow of ideas, and the assurance that the teams will produce the innovations desirable for the style engaged to track projects [12]. In sum, innovation is initially ran by human attempts, the appreciation and improvement of an idea adjudged to bring economic and social welfares. The process is clearly rational in that it draws on individuals' involvement and skills to translate their ideas and knowledge into something unique that will be valuable by others [8]. Fig. 3 shows the journey of the ideas until it turns into innovation.

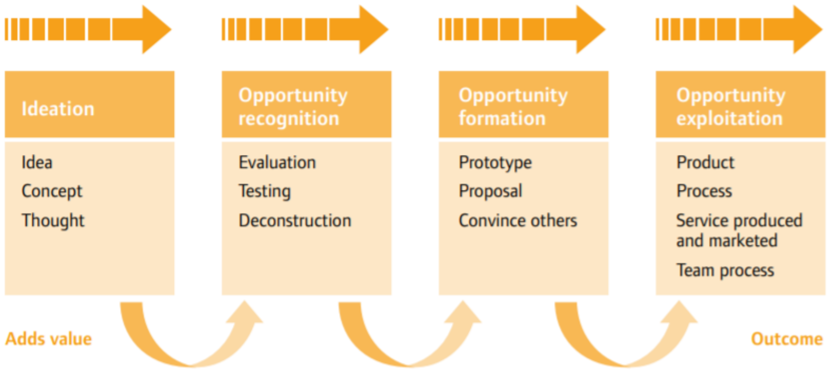

Fig. 3. How the ideas are turned into innovations [8]

2.10. Artificial intelligent (AI) technologies

Technological Innovation influences organizations capability to try to win effectively in a progressively more global market [2], and one of the most popular technological innovation notion in a current business world is the artificial intelligent (AI), which it dramatically reshape enterprise project management. Artificial intelligence (AI) tech such as deep learning and process automation is changing how projects are managed today and will have an even greater effect tomorrow. Artificial intelligence (AI) has permeated enterprise operations to the point that it now determines an organization's success, including in the area of project management [20].

According to [2] there are several essential advantages for this kind of innovation, as could computing, forensic accounting, mobile accounting, enterprise resource planning, social media, optical character recognition, and reducing errors through Tax software.

Likewise, based on [21] report found that in the next three years, project professionals expect overall AI usage to jump from 23% to 37% and the majority of respondents (81%) said their organizations are currently being affected by AI technologies. The growth in AI usage will require changes in how projects are managed, and how organizations implement strategy.

The [12] report identified six AI technologies that are affecting organizations around the globe:

- Decision management: Creates an intelligent process or set of processes based on rules and logic to automate decision-making. Project managers predict that in the next three years, the impact of the following three AI technologies will grow:
- Knowledge-based systems: Understands the context of the data being processed, helping support human learning and decision-making.
- Machine learning: Analyzes data to build models by detecting patterns, yielding improved decision making with minimal human intervention.
- Deep learning: Builds, trains and tests neural networks that predict outcomes and/or classify unstructured data based on probabilities.
- Expert systems: Emulates and mimics human intelligence, skills or behavior in a particular field, topic or skill.
- Robotic process automation: Mimics and automates human tasks to support corporate processes.

2.11. The innovation culture

Many authors like [10] utilized the common definition of the culture for their studies, as the shared beliefs, values, norms, attitudes, ideas, and performances that define a group of people and their behavior. Organizational cultures are intangible assets that can lead to failure or success. The failure can happen when innovation makes people tense. Some people consider themselves as not creative people. Also, there are many people conclude that the innovation is not part of their job description and the innovation is the only related to research and development people. Some are not even convinced that innovation is significant to validate a major initiative. Therefore, the importance of an organization and or project's culture is often underestimated. As a result, the organizational innovation culture need to be boosted and acknowledge by all people within the organization; to allow people to freely contribute ideas [12].

[12] Proven that an effective innovative cultures must allow within the organization the following habits: risk taking, curiosity, failure tolerance, everyone to tap into their own level of creativity, freedom to follow one's intuition, avoid or defer from rapid judgment, collaboration (informal), active listening, being team players, managing tensions rather than just trade-offs. In another words, without the safety that is needed to innovate, organizations miss out on the right amount of innovation enablement. The culture to support innovation in project management must be adaptive. No longer would a classic view of the slow build-up of phases of a given project be suitable for generating and testing the best ideas. Much higher iteration would be needed. Teams must be encouraged to take risks and the organization must have a high tolerance for mistakes that can occur at a higher rate than ever before. The appetite for risk-taking and the courage that is required to fail and learn is the new normal. Fail fast and learn will become part of the new DNA of most organizations. The learning culture that this creates is priceless. Executive leadership will play a big role here too, as they will have to walk the talk frequently and will have to use a high level of emotional intelligence to manage the stress related to the risk taking required. Leaders will have to relate to their project managers differently to instil a new sense of trust.

2.12. Knowledge management

A Knowledge management definition as per [17] (p 3), is 'the deliberate and systematic coordination of an organization's people, technology, processes, and organizational structure in order to add value through reuse and innovation. This coordination is achieved through creating, sharing, and applying knowledge as well as through feeding the valuable lessons learned and best practices into corporate memory in order to foster continued organizational learning".

In 2016 [18], studied and examined the association among core requirements of innovation, knowledge management implementation, and organizational performance in a mobile telecommunications sector. The results indicated that knowledge management implementation had a statistically significant and direct positive effect on innovation. In addition, it indicated that the innovation had a positive and statistically significant effect on organizational performance. Thus, the knowledge management aspect will be consider in this paper; to control the process of innovation project management.

2.13. Innovation project performance (success)

In order to evaluate and to assess the innovation project success, there is a need to check the external market-related performance items. In addition, it is required to capture the match with client needs, the impact of the innovation on competitive advantage, adherence to revenue targets, and adherence to profit targets. Besides, the perceived gain in reputation in the area of the new product or new service was included, since this is an important aspect of performance in project-based firms [3,9,24,25].

2.14. Innovation project management models/measurements

A study by [3] explored a number of themes derived from the innovation literature innovation for project management perception that consist of the following:

- Organisation of work
- The type of structure used to manage innovation projects
- The level of formality in that structure
- Patterns of authority
- Communication patterns
- Evaluation of outcomes

Another study by [11] put a model to examine the correlation between the four dimensions of innovation management (organization culture, strategy, and structure and innovation means and tools) and the influences of internal and external factors for two detailed case studies in two medium-sized contractors. This model finding allowed a suitable management of innovation in construction companies and improved the companies' ability to innovate, see Fig. 3.

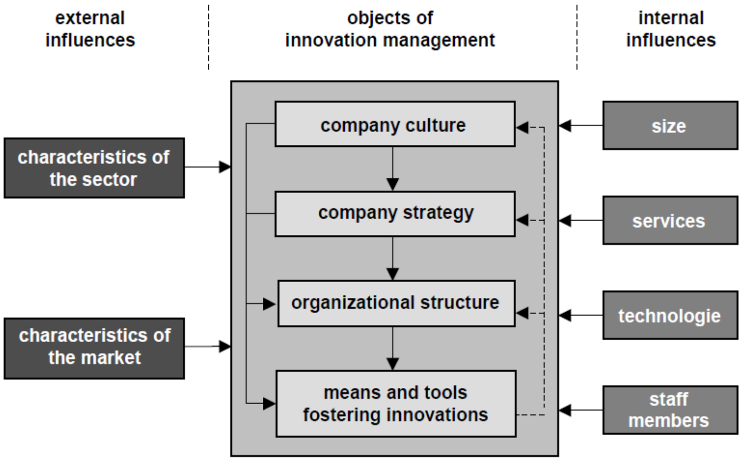

Fig. 4. The integrated model of innovation management in construction companies [11]

Then a study by [22] proposed a seven-dimensional conceptualization of the innovation management phenomenon and applied it to an examination of the measurement problem. The innovation management process consisting of seven categories: inputs management, knowledge management, innovation strategy, organizational culture and structure, portfolio management, project management and commercialization as table 1.

Table 1. Innovation management measures aspects [22]

Framework category	Measurement areas
Inputs	People Physical and financial resources Tools
Knowledge management	Idea generation Knowledge repository Information flows
Innovation strategy	Strategic orientation Strategic leadership
Organization and culture	Culture Structure
Portfolio management	Risk/return balance Optimization tool use
Project management	Project efficiency Tools Communications Collaboration
Commercialization	Market research Market testing Marketing and sales

An integration between project management processes and innovation management concepts and components was developed; since project management alone cannot support radical innovation projects. Fig. 5 shows the mapping between PMBok process including initiating, planning, execution, controlling and closing phases with Innovation methodology process groups that consist of problem definition, critical analysis, solution development, validation & decision, governance, detailed design, implementation, and optimization. This supports in revealing important innovation project successes and sustain companies development and competitive advantage [5].

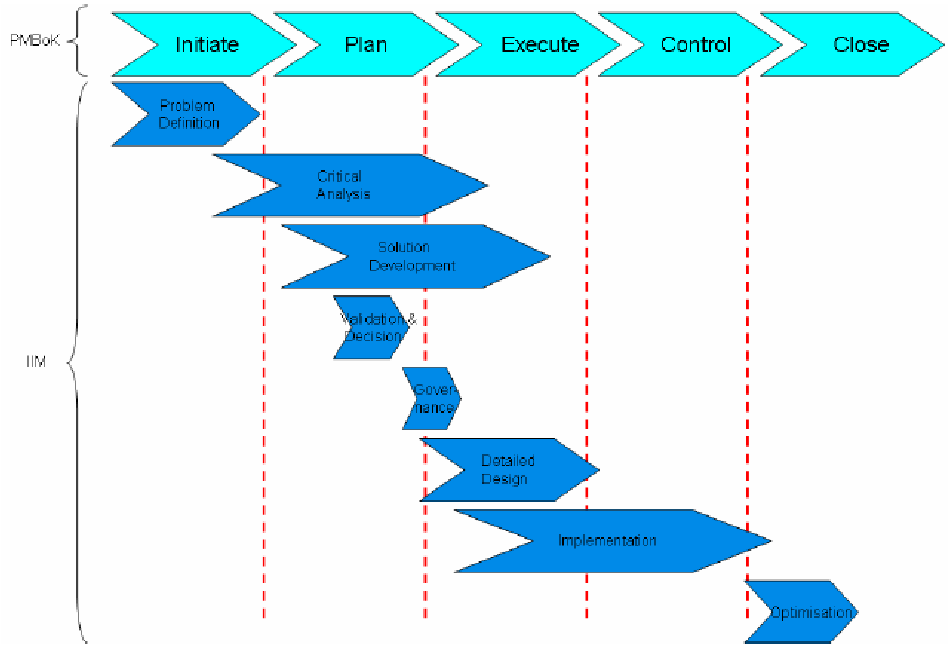

Fig. 5. Integration of the PM and IIM components [5]

After that, a model was developed for four common mmanagement practices for innovation projects consist of planning, senior management support, multidisciplinary teams, and heavyweight project leaders, and the influence of these practices on project performance. Moreover, the characteristics of project-based firms are investigated, how these affect management practices for innovation projects, and the influence of these practices on project performance. the firm characteristics consist of project-based firm, collaboration level, autonomy level, service firm, firm size, and firm strategy. Then the project characteristics consist of newness, planning, project autonomy, multidisciplinary team, and senior management support [9]. See Fig. 6.

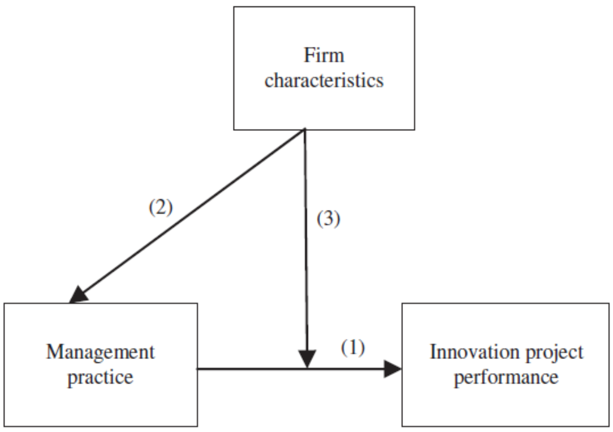

Fig. 6. Firm characteristics influence on the innovation project management practices [9]

Moreover, an innovative framework was designed for project management, which included innovation processes to enhance the project management processes. This framework described a structured method to integrate integration innovation management processes with project management processes. Project management processes take account of the five Course Clusters: Initiating, Planning, Executing, Monitoring and Controlling, and Closing, as cleared in PMBOK® Guide. Importance is given to scope management, human resource management, opportunity management, and requirements management processes.

Equally, innovation processes contain discovery (ideas for solutions), open innovation (all possible ideas and solutions that can be an opportunities for innovative processes, products, or services), seek innovation partners (all stakeholders), idea management (create and evaluate all ideas, converge into one solution), knowledge brokering (sustain innovation), and innovation opportunity management [25].

Besides, a conceptual framework was created where they integrated strategic project management for product innovation projects, through business model, resource-based view, value proposition, contingency theory and dynamic capability theory. These strategies aimed at business value creation and enhancing the commercial product innovation achievement. The Strategy Project Management framework is essentially an input-output process, as shown in Fig. 7, and it illustrates that project managers should analyse [24]:

- Firm-level strategy and capabilities
- Internal project characteristics and external contingencies
- Project-level resources and capabilities
- Key project success factors
- Expectations to project value deliverables

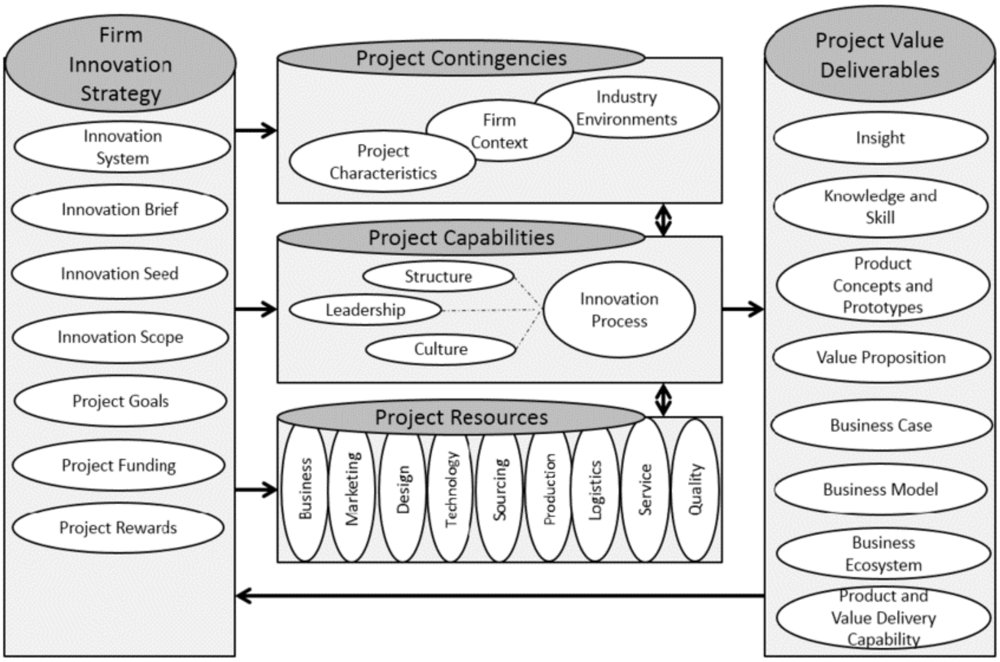

Fig. 7. The Strategy Project Management framework [24]

Then, [26] presented a paper about the innovation project tool, which aims to outline the main characteristics of innovation projects in terms of project management, then to use these facts for developing a tool for categorisation of innovation projects. These specific characteristics of innovation projects are defined thorough usage of knowledge areas of PMBOK project management methodology. Moreover, the findings were ranked the most ten innovation factors; and used them for testing the Innovation project tool.

3. Research framework

Based on a comprehensive literature review done in this paper, the proposed framework is established, which attempted to contribute in improvement of the innovation projects performance; in order to support project managers and innovation managers to facilitate their tasks.

The proposed framework, as shown in Fig. 8, contains of dimensions related to innovation and project management aspects that consist of:

- Company innovation strategy refers to strategic orientation and strategic leadership [11,22].
- External innovation factors refers to characteristics of the sector and the commercialization [11,22].
- Internal innovation factors refers to size, services, technologies, collaboration and staff member [11,9].
- Company innovation culture [11,12,22].
- Company structure [3,11,22].
- Innovation stakeholders refers to all innovation partners [25].
- Innovation tools refers to all tools needed for innovation like [11].
- Artificial intelligent refers to technological innovations [2].
- Knowledge management refers to idea generation, knowledge repository, and information flows [17,18,22].
- Project inputs refers to people, physical and financial resources, communication, technology and tools [22,24].
- Project characteristics refers to newness, planning, project autonomy, multidisciplinary team and senior management support [9,24].
- Project capabilities refers to project structure, project leadership, and project culture [25,24].

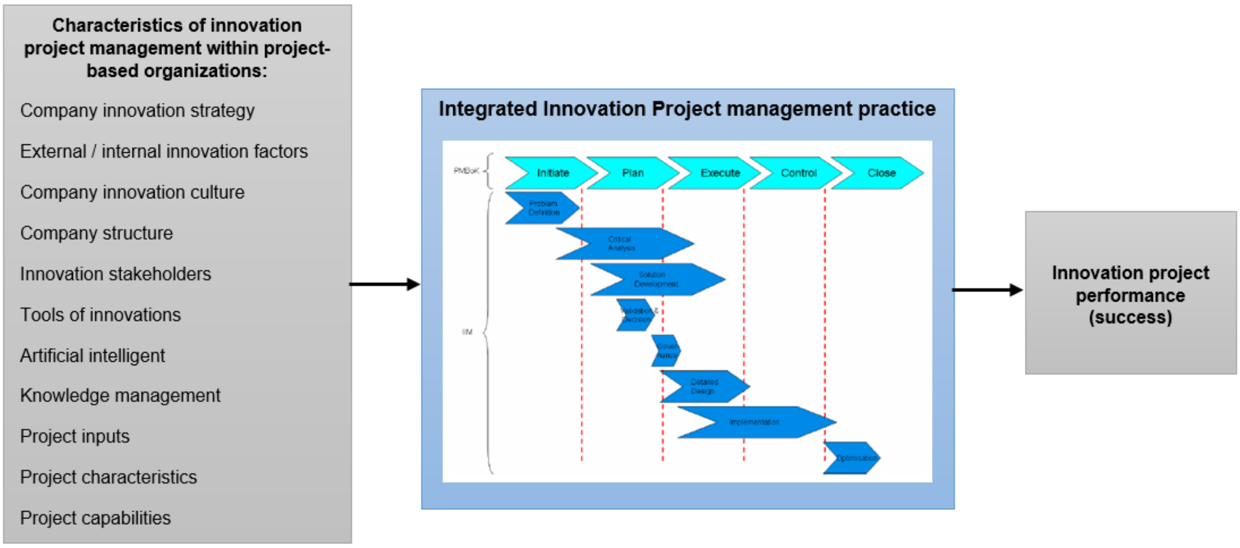

Fig. 8. The proposed conceptual framework

These twelve characteristics/dimensions had impact on the integrated innovation project management practice that leads to enhance the innovation project performance. Where the integrated innovation project management is an arrangement of project management stages with innovation management approach adopted from authors like [17,25,26].

4. Research methodology

To test the paper's proposed conceptual framework, a cross-industry sample of firms in UAE will be utilized. Where, a deductive quantitative approach based on a proportionate stratified random sampling technique will be used. Therefore, an administrative on-line survey will be sent to the main members of the project management from internal interested party of these companies. The components that need to investigated are: The characteristics of innovation project management, as an (independent variables) measuring: company innovation strategy, externa/internal innovation factors, company innovation culture, company structure, innovation stakeholders, innovation tools, artificial intelligent, knowledge management, project inputs, project characteristics, and project capabilities. The integrated innovation project management practice as an (independent variables). The innovation project performance (success) as a (dependent variable) measuring: the external market-related performance, to capture the match with client needs, the impact of the innovation on competitive advantage, adherence to revenue targets, and adherence to profit targets, and the area of the new product or new service.

5. Conclusions and future work

As projects became the best chance to innovate, more than any time in history, as well as, projects were intended to change the business by nature. And since projects are no longer simply considered as operational actions. Thus, they are now very strongly contribute in enabling changes from a current state to a future state [12].

As a result, this paper developed a robust innovation framework for project management for project-based organizations. In which, innovation processes has been integrated with project development/management processes that can significantly leads to enhance the innovation in project-based organization, which as a results will achieve all the organizational short-term and long-term goals and realize a competitive benefits for the business. The innovation project management framework provides a structured approach for project managers to use in starting and delivering innovation projects with considering the entire related characteristic around the innovation project management aspect.

Finally, in future, extra investigation is required for project management approach to innovation, and to embed flexibility in innovation project management approaches. Moreover, considering that at this stage the present project management practice does not have enough or robust characteristics of innovation, so there is a need to identify further characteristics of innovation. Another suggestion is to use the agile concept in project management approach. Finally, it would be very valuable to have researches that are more empirical on the usage in other types of industries and different innovation projects [6].

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Identifying Motivators and Challenges to BIM Implementation Among Facilities Managers in Johannesburg, South Africa

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Abstract

The use of technology such as building information modelling (BIM) during the operational and management phase of a building helps to improve facilities and asset performance. However, the slow uptake of building information modelling (BIM) in the facilities and asset management industry diminishes the value derivable from properties and assets in general. The current study examines the motivation to adoption of BIM in the facilities and asset management industry and identifies barriers or challenges to BIM implementation in the sector. A field questionnaire survey was used to collect data among facilities management firms in Johannesburg South Africa. Empirical data from 17 participants were analysed to output frequencies on the challenges of BIM implementation. Findings revealed that competitive advantage, innovativeness, peer-push, as well as organisational image and objectives were motivators for adopting BIM in facilities management. The challenges of BIM implementation were mostly a lack of knowledge (trained personnel) on how to use BIM in facilities management, data management quality, lower data management standards (quality) at the operational stage, inadequate data provision for maintenance and management of facilities. Other issues included limited coordination or cooperation from team members and stakeholders on projects, absence of guidance on best practices to ensure performance optimisation and facilities management support using BIM, and financial commitment and infrastructure involved.

Keywords: assets, BIM, facilities, management, performance

1. Introduction

Facilities management has been around for ages. The aim of facilities management is to enhance performance of existing buildings and assets. As real estate development involves a number of participants who enter and depart at different times from design through construction, to occupation and operational stages, loss or distortion of knowledge or information is a concern [1]. One of the ways of ensuring efficient management of information and other processes to enhance the performance of buildings is through the adoption of new technologies such as building information modelling (BIM) [2]. BIM is a comprehensive system, which integrates the various aspects of the life cycle of a project [3]. It is an advanced process by which information about buildings and assets is generated, stored, managed, transferred and shared in an interoperable and reusable way, and thus enhancing performance and improving efficiency of facility management functions throughout the life cycle [4], [5]. The use of new technologies in facilities management functions is important given that value is created at the operational stage during the use of an asset [6]. Therefore, ways to ensure that the value in use is sustained warrant consideration.

Value can be improved through different ways in facilities management including the use of new technologies to improve information transfer, design, construction and visualisation of management needs prior to the operational stage. Studies have shown that adopting BIM increases operational efficiency, competitive advantage, performance and cost benefits, improves maintenance management and ultimately, building value [3], [7]. However, it appears that the focus has mostly been on the design and construction stages, in research and in practice [8]. Despite emphasis on the importance of ensuring improved performance of existing buildings and facilities, it is surprising that the uptake of BIM is less emphasized and applied at management and operations stage, as opposed to the design and construction stages. The slow adoption of new technologies in the management of facilities and assets is thus of great concern as it affects operational, strategic and organisational management [9]. The benefit of BIM for maintenance and information management within facilities management organisations has not been explored greatly [8].

Previous studies have focused on motivating factors, for example, the study by [3] highlighted motivators to adopt BIM, and discussed ways to encourage adoption of BIM in the construction industry in Iraq. [2] investigated the advantages of 3D laser scanning technology over the current technologies available for the built environment. [10] identified challenges of BIM implementation in the architecture, engineering and construction industry as organisational factors, lack of knowledge and skilled personnel, high cost of implementation, but without particular focus on the operational stage. [11] conducted a review of BIM implementation challenges. Other studies have been conducted in the United Kingdom [5], in China [12], and in the United States [13]. It appears that there is little evidence of the challenges faced by facility managers in South Africa. Research on BIM adoption and challenges or barriers to implementing BIM in facilities management in South Africa is therefore warranted.

Consequently, for the facilities management sector to enjoy the associated benefits, there is a need to identify what could motivate or drive facilities managers to adopt BIM as a new way of practice, as well as the challenges or barriers that may hinder BIM implementation. The current study therefore identifies the motivators and challenges to BIM implementation in the facilities management sphere using a quantitative approach. A literature review and thematic analysis was conducted, followed by a questionnaire survey on the challenges or barriers to BIM adoption in facilities management practice. A review of related literature on BIM in facilities management is presented hereunder, followed by the methods employed in conducting the study, findings and discussion, as well as the conclusions drawn from the study.

2. BIM-enabled facilities management – Motivation and challenges

Facilities management encompasses multiple interdisciplinary functions and integrates people, place, process and technology required to coordinate with organisation strategies and achieve set goals and activities including preventive maintenance and retrofits, space management, energy use monitoring and decision-making [12], [14], [15]. Achieving the goals of an organisation, efficiently, therefore requires effective processes in place. New technologies such as BIM can be used in facilities management functions to cut down operations, boost efficiency, enhance the quality of the facilities and ensure sustainability and overall performance of the organization, which encompasses the aim of facilities management [15]. In the same vein, the goal of BIM is total resource management which aims to reduce waste and costs, increase productivity, improve service delivery, cash flow and profit [16]. A BIM is a 3D digital description of a building, comprising an individual building, its site or GIS objects with attributes that define their detailed description and relationships that specify the nature of the context with other objects [2]. A BIM has robust geometry, comprehensive an extensible object properties, integrated information system (holding all information in one repository), and supports data over facility life cycle from conception to demolition [2]. It therefore contains data that can be assessed and exported for use at a later stage in the life of a project, that is, the maintenance and operational stage and ddecisions can be made more efficiently with visual information made available to all parties, for example in Figure 1.

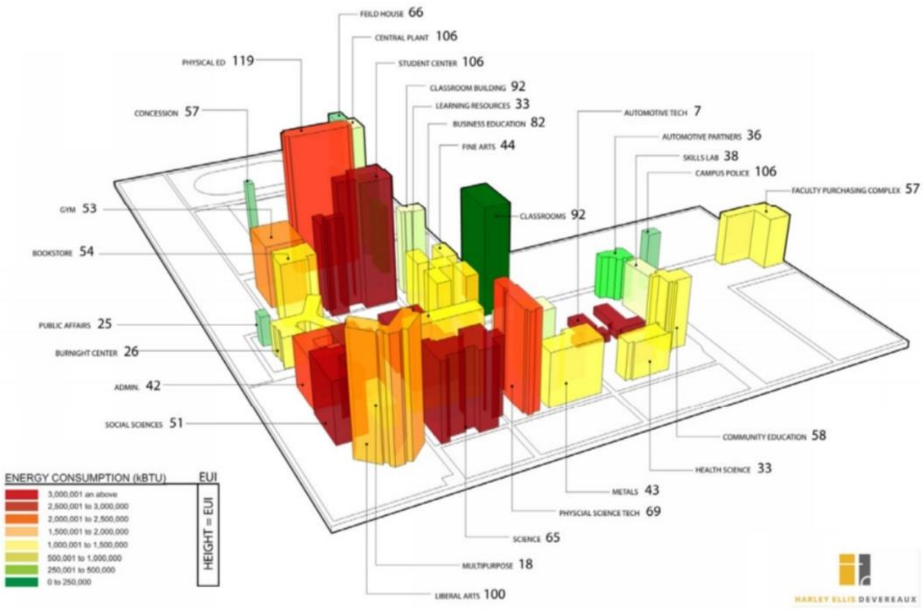

Fig. 1. Prioritising maintenance based on energy-efficiency [14]

As real estate development involves a number of participants who enter and depart at different times from design through construction, to occupation and operational stages, loss or distortion of knowledge or information is a concern [1]. Nonetheless, it does not suffice to have data. Sometimes the information in reality exists, but this fact is not known, or it is not easily accessible or compatible, or coherent, and thus leading to the unnecessary duplication of efforts and resources [2]. Therefore, practitioners might be motivated to reduce or prevent loss of information and other inconvenience that may arise (such as delays). In addition, problems in facilities management as identified by [17], which can occur can be alleviated with the implementation of BIM. Such problems include inadequate technical knowledge and expertise, lack of participation from all relevant departments due to lack of understanding on the importance of providing a comprehensive facilities management in order to achieve set objectives, lack of proper facilities management guidelines and requirements and performance indicators to standardize the practice and implementation of BIM [17]. Good quality and performance in facilities management should be demonstrated to address technical aspects and to achieve clients' satisfaction [12]. Further, operational efficiency, improved building performance, faster and more effective processes, better production quality, controlled whole life costs and environmental data, better integration of planning and implementation processes, and a more effective industry, are motivators for the adoption of BIM technologies in facilities management practice [2], [3], [7], [8].

Notwithstanding its benefits, some challenges associated with the adoption of BIM in FM were identified as either process-related (for example market-readiness, project phase applied, training costs) or technology-related [7]. Other studies suggest that the following may hinder the implementation of BIM in facilities management:

- information management standards at the operational stage falling behind those in building design [9];
- limited coordination between the designer and operator in defining the provision of data to support operational management [9], 17];
- market-readiness [7];
- the absence of detailed guidance in how BIM could be best utilised to support ongoing building performance optimisation [9], [17];
- the difficulty in accurate modelling of complex high-performance features, ineffective use of those optimisations and inaccuracy of predictions, which could increase the chances of performance disparity [9];

- legal/ contractual and data ownership issues [4], [7];
- personnel inadequacies in terms of training, and skills or competence in the use of BIM application and requirements [4], [17];
- costs of training and provision of required infrastructure (including tools and license) to implement [2], [4], [7]; and
- a lack of real cases where BIM application is demonstrated in a replicable form or context-specific information [4], [7], [8], [9].

Further, interoperability and enhancement of data integration; augmented knowledge management and enriched training and competence development for facility managers can hinder the extent to which BIM is adopted and utilised among facilities managers and practitioners [1]. The current benefit of BIM in operations among Dutch semi-public and public clients was marginal as a result of a lack of alignment between the supply and demand for information as well as the context-dependent role of information [8]. In addition, [4], [11] argue that the lack of methodologies that demonstrate the tangible benefits of BIM in FM as well as determining who owns the data are challenges.

In summary, the tangible and intangible benefits from the use of BIM in facilities management cannot be realised fully if the barriers to BIM implementation in existing buildings are not given consideration. The next section presents the results of survey conducted on the barriers/challenges of BIM implementation among facilities management entities in Johannesburg, South Africa.

3. Methods

The study adopted a quantitative approach to determine the challenges or barriers, which facilities managers may face in the adoption of BIM in their operations. A questionnaire, developed from a review of literature, containing ten questions on a 5-point Likert scale, was used. The ethics committee of the researcher's department approved the study prior to self-administration of the questionnaire. The participants, identified through a database of facilities managers in South Africa identified through a Google search, using purposive and convenience sampling techniques, were contacted in person, telephonically and via email. Although effort was made to include more participants in the study, twenty-one respondents participated in the study. The empirical data were analysed using the statistical package for the social sciences (SPSS). The outputs were descriptive statistics (mean and modal scores) regarding the perceived challenges with BIM implementation in facilities management practice. The Cronbach alpha test was used to assess the internal consistency reliability of the measures. The alpha value of 0.951 indicated excellent internal consistency reliability [18]. The following section presents the findings on the challenges of BIM implementation among the sampled facilities management organisations.

4. Findings and discussion

4.1. Demographic characteristics

The respondents included twelve practitioners from public and four from the private sectors, respectively. One of the participants did not indicate the type of organisation they worked with. Six of the respondents were from government entities, three were from educational institutions, and two were from the healthcare sector and professional facilities management organisations, respectively (Figure 2). One of the respondents was from the IT sector and three were from "other" organisations, comprising state-owned enterprises. They included repairs and maintenance managers, technical advisors, managers, real estate lead, facilities management specialists and senior surveyor, with years of experience mostly between 10 – 14 years.

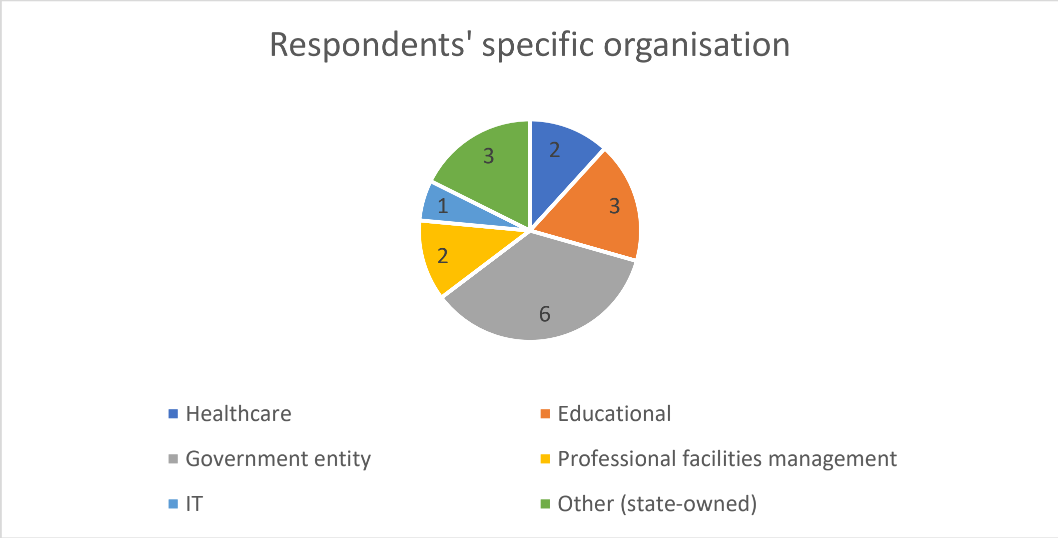

Fig. 2. Respondents' specific organisation type

4.2. Challenges of BIM implementation

Respondents were asked their perceptions on the benefits of BIM implementation in facilities management. Table 1 showed that they were mostly in agreement regarding the statements as listed, with the modal scores of 4.0. However, *lack of knowledge (trained personnel) on how to use BIM in facilities management* had the highest mean score (MS= 4.06), followed by *lower data management standards (quality) at the operational stage* (MS= 3.94). These findings are in line with the views expressed in [9], [10], [15], that the lack of best practice and guidelines on how BIM can be used to support facilities management functions hinder adoption and implementation of BIM. In addition, poor information quality and issues around data exchange and transfer have been highlighted. The quality as well as suitability and accuracy of BIM information and flow is crucial for facilities management decision-making [15]. However, most models created for design and construction phases contain significant quality issues including inaccurate (in terms of spatial association), incomplete, or unnecessary information [15].

In addition, respondents were in agreement that *limited cooperation from team members on projects* (MS= 3.76), *lack of guidelines on how BIM could be used to support building and facilities management* (MS= 3.71), *BIM infrastructure including license is expensive* (MS= 3.71) *and poor information transfer from design and construction teams to the facilities management team* (MS= 3.71). These findings also correspond with results in [9], [11], [15]. The time and cost of hiring trained personnel or training on the use of BIM, as well as acquiring the license and tools for implementation are hindrances to adopting BIM in facilities management practice.

The results also showed that the respondents tended to be neutral with the statements, *difficulty in accessing original design data due to technological advancement and development of new BIM software*, and *difficulty in accessing design data due to network security* with the modal scores of 3.0. Although these factors ranked the least, with mean scores of 3.41 and 3.35, respectively, they were identified as barriers to BIM implementation in facilities management practice [11]. However, these problems were associated with the 2D plane models which designers used in the past and it was difficult for some professionals to understand [14]. Interoperability and access can be achieved with a 3D and 4D model and through the use of specific requirements such as Revit plugins which enables easy updating of information and reports on facilities management status [14], [19].

Table 1. Challenges of BIM implementation in facilities management

S/No.	Measures	Mean	Mode	Rank
1	Lack of knowledge (trained personnel) on how to use BIM in facilities management	4.06	4	1
2	Lower data management standards (quality) at the operational stage	3.94	4	2
3	Inadequate data provision for maintenance and management of facilities	3.88	4	3
4	Limited cooperation from team members on projects	3.76	4	4
5	Lack of guidelines on how BIM could be used to support building and facilities management	3.71	4	5
6	BIM infrastructure including license is expensive	3.71	4	5
7	Poor information transfer from design and construction teams to the facilities management team	3.71	4	5
8	Lack of real cases where BIM application is clearly demonstrated	3.47	4	8
9	Difficulty in accessing original design data due to technological advancement and development of new BIM software	3.41	3	9
10	Difficulty in accessing design data due to network security	3.35	3	10

5. Conclusion

The study set out to investigate the motivators and challenges of BIM implementation among facilities management firms in Johannesburg, South Africa. The findings from literature review showed that the motivators for BIM implementation in facilities management include competitive advantage, innovativeness, and organisational image. Findings from the field survey revealed that the challenges of adopting and implementing BIM, among the sampled organisations, include a lack of knowledge (trained personnel) on how to use BIM in facilities management, data management quality, lower data management standards (quality) at the operational stage, inadequate data provision for maintenance and management of facilities. The findings of the study are envisaged to assist facilities management organisations in identifying ways to overcome the challenges identified and ultimately achieve their objectives efficiently and effectively sin e adopting new technologies in this era of the fourth industrial revolution is pertinent. The sample size limitation of the study warrants mention. Data could be collected from a larger sample to explore the challenges of BIM implementation in facilities management entities.

6. Acknowledgement

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Identifying the Factors Affecting Sustainability Cost Toward Optimization of the Project Selection Process

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Abstract

The dialogue that competes with politics and societal issues is becoming about sustainability. Sustainability has been drawing more attention now after many years of focusing solely on technology and development and neglecting the green aspect significantly, due to the growing resource constraints and the balanced requirement of environmental, economic, and social objectives. It is becoming increasingly important for all companies across all industries. The adoption of sustainability drives stakeholders to sustain their business success in the long-term. Therefore, they have to consider more factors than profit or loss when building their strategies and change their policies in the decision-making process to prevent environmental damages. Accordingly, decisions should be dictated according to the principle of sustainability, and the impact of these decisions should be planned for years and decades. According to the researchers and experts, the adoption of sustainability is facing two major obstacles, which are the increased cost of capital or perceived cost associated with sustainability and the lack of stakeholder's demand on sustainable projects due to the wrong perception that sustainability causes cost increase. Therefore, they can take sustainability costs as a primary concern in project selection. In this regard, the purpose of this study is to explore essential factors that have an impact on sustainability cost, which in turn, affects the project selection process, based on the theoretical backgrounds from the literature. To take the sustainability costs would help us to build a cost model, including the sustainability cost of the projects and their returns, which helps stakeholders to select the optimal sustainable project from several candidate projects in the project selection decision-making process. Thus, it can lead to an increase in the potential for creating win-win situations contributing to both stakeholders and sustainability value.

Keywords: project selection, decision making, sustainability cost, sustainable project

1. Introduction

There is a growing interest in the world on sustainability in light of protecting the environment, reducing energy consumption, optimizing the use of natural resources, and relying more on renewable energy sources. Therefore, sectors are coming under intense pressure to respond quickly to environmental, economic, and social issues that have increased significantly in the last few years, and to involve sustainability in their goals, policies, plans and project decision-making process [1]. The concept of sustainability is not limited to the relationship of environmental development but goes beyond that to the relationship of development with economic and social dimensions. Sustainability is known as the capacity to conserve and sustain. It means identifying, developing, and fostering sustainable mindsets, practices, and policies to preserve a healthy, economically sound, and socially viable environment [2]. It is known as the triple bottom line (TBL) approach. It promotes management concentrating not just on generating value for stakeholders but also on generating environmental and social value [3].

2. Sustainability in the construction sector

The construction sector is considered as one of the largest sectors that has an important role in the movement of the national economy of any country. It has a significant impact on the environment, economy, and society. Statistics show that the construction industry is losing 57 % of its resource inputs (compared to 26% in other industries) during the construction process, consumes 40% of energy, and releases approximately 40% of CO_2 in the USA and other developed countries [4][5]. Therefore, sustainability is gaining greater prominence in the construction sector, and ignoring it could potentially lead to reputational or litigation risk [6]. The United Nations Global Compact (UNGC) and Accenture conducted a survey on sustainability comprising 1000 CEO's from 103 countries and 27 industries. According to the survey, 93% of CEOs considered sustainability as a key component to the future success of their business. Besides, 76% of CEOs said they believed that integrating sustainability approach into their core operations would lead to new opportunities and revenue growth [7]. Construction sector development is associated with the initiatives to encourage the development and growth of the EU economy as a whole. Europe 2020 vision for the 21st century puts forward three mutually reinforcing priorities:

- Smart growth: developing an economy based on knowledge and innovation.
- Sustainable growth: promoting a more resource-efficient, greener, and more competitive economy.
- Inclusive growth: fostering a high-employment economy delivering social and territorial cohesion. [8]

The headline goals under these priorities for 2030, which directly impact the construction sector, are as follows: minimize greenhouse gas emissions by 40% (from 1990 levels), increase the share for renewable energy by 32%, and achieve improvement in energy efficiency by 32.5% [9]. People anticipate a sustainable project to be more costly. However, the sustainability concept challenges this misperception and clarifies that it could be profitable in the long term, especially when cost and environmental strategies, and program management are integrated right from the beginning into the development process [10][11]. Therefore, many sustainable projects show lower operational costs compared to conventional projects, and they prove that the high construction costs are recovered within a reasonable payback period through reduced energy and water use, and lower long-term operations and maintenance costs [11]. According to USGBC sustainable projects use 26% less energy, 13% lower maintenance costs, 27% higher occupant satisfaction, and 33% less greenhouse gas emissions [12]. In addition to direct cost savings, sustainable construction industry offers indirect economic benefits for both building owners and society [10]. Recent researches studied the relationship between economic and sustainability performance, and they prove that sustainability brings a lot of benefits to business success. Therefore, high sustainability performance contractors can expect higher international revenue growth, and sustainability performance is likely to become a competitive advantage in the international construction market [13].

Two benefits could result from the adoption of sustainability in the construction sector, which are process benefits and product benefits. Process benefits include materials savings due to reuse, recycling, conversion of waste into valuable forms, savings from safer working conditions, reduction of the costs of the activities associated with discharges, waste handling, transportation, increasing energy, and water consumption efficiency during the production process. Product benefits include higher construction quality, lower life cycle costs, and safer construction process [14]. Additionally, it improves the quality of indoor living, strengthens the culture of sustainability and its application in society, and reduce environmental pollution inside and outside the building.

The internationally recognized environmental assessment systems for buildings (e.g., LEED (Leadership in Energy and Environmental Design, USA), and BREEAM (Building Research Establishment Environmental Assessment Method, UK) are mainly focused on environmental criteria with little consideration for economic and social criteria, such as energy-saving, efficient water use, reduced CO_2 emissions, improved quality of indoor living, and resource management [15]. Therefore, there is a tremendous demand in the construction industry to develop a tool that allows assessing the sustainability of the project which is considering all dimensions of sustainability. Fernandez-Sanchez and Rodrýguez-Lopez recommend criteria list to measure sustainability for infrastructure projects in Spain. They classified and prioritized sustainability indicators based on risk management standards, which resulted in a list of 30 essential criteria that include health and safety, economic cost/economic benefit, public participation and control on the project, Life cycle cost, project governance, and strategic management [16]. Dobrovolskiene and Tamosiuiene developed a tool to measure the sustainability of a business project in the construction industry. The authors studied 56 criteria and identified the essential 15 criteria according to the prioritization via questionnaire survey comprising six environmental, five social, and four economic. That helps the decision-makers to compare projects and make rational decisions regarding resource allocation in a project portfolio [1]. W. Der Yu proposed a construction project sustainability assessing system that comprises 4 levels with 31 sustainability indicators in order to manage and control the sustainability process for a construction project [5].

On the other hand, there is a lack of researches on sustainability cost of construction and value, which means that stakeholders cannot make the right decisions concerning sustainability. That, in turn, drives to Choose the wrong projects, which lead to wasted resources and loss of profits that could have been achieved by concentrating on other projects. Furthermore, the question of the effect of sustainability costs on net income needs to be solved [10] [17].

3. Sustainability cost

To build a solid foundation for any sustainable and environmentally friendly project, we must think outside the framework of the axiom factors that affect the building life cycle. The concerned parties can achieve higher returns on their investment in sustainable projects by determining the size of the gains that will be achieved through improving the performance of the project users due to the quality of the internal environment and by employing sustainability cost. Managing and controlling these elements helps in achieving financial goals in addition to environmental goals. Sustainable projects added additional costs from 1-10%, due to the efficient mechanical systems that required for sustainable projects which are quite expensive and complex extended designing process [18]. Ross et al. developed a financial model emphasis that LEED-certified projects added 10% more to the costs because of the high materials and labor cost, which accounts for the largest percentage of sustainable project costs [19]. On the other hand, research indicates that saving from the sustainable project can be cover the incremental cost of the project.

Researchers have recognized the uncertainty of construction cost predictions and the need to improve the potential of cost prediction models [20]. Alshamrani developed a model to estimate the initial cost of conventional and sustainable buildings with a maximum of three floors in North America. The input variables were building area, types of structure and envelope, number of floors, and floor height [21].

Kudratova et al. developed a corporate sustainability driver model by integrating sustainability cost measurements into the traditional selection of projects. The authors found that sustainability cost estimation in traditional project selection methods produces positive returns on investment and produce positive trade-off results for both the environment and sustainability [17]. They also proposed a sustainability optimization model that considered sustainability cost and reinvestment strategy. The net present value is used to estimate the return of the project. They found that stakeholders project selection decisions and the maximum objective value obtained at an optimal 3% sustainability cost range [22]. Recently, investors in the construction sector are becoming more attracted to the sustainability concept due to the potential of higher cost-saving benefits and higher returns [23]. Unfortunately, these benefits can only be achieved over a long period of time [24].

Attracting investors for sustainability adoption can be achieved by ensuring that sustainable projects can be executed without additional cost. Construction project costs can be divided into three categories: land, hard, and soft cost [16][17]. Land costs include land acquisition expenditures that include land purchase, transfer of title, clearing of sites, etc. Land costs are affected by factors such as location, land price and taxes, legal fees but not by the decision to be sustainable [27].

Hard costs defined as actual costs of the construction. It is a direct cost that is often influenced by the client, engineer, architects' decision. It is related to the project's physical aspect, such as architectural, civil, structural, mechanical, and electrical works [28]. It could be in the form of materials, tools, equipment and plants, workforce, etc. In contrast, Soft costs defined as costs generated by non-physical aspects of the construction project such as planning, management, marketing, and documentation [29]. In other words, soft costs are any other costs than building costs and are not related to construction work or materials or labor. The factors that would affect the cost of the sustainable project should be studied to understand why the cost difference occurs, thus would promote to minimize the cost increase and making the sustainable project more interesting. These factors are:

3.1. Professionals and experts

Professionals and experts' competence and engagement would have a significant impact on the quality and cost of a sustainable project. That is why professionals are seen as crucial players to deal with the increasing issues for vitality to live, which takes up around 3-5% of the life cycle cost. Professionals are likely to be charged extra fees due to additional duties and responsibilities, have green experience and skills, understand environmental risk, and advise the client on sustainable projects [27].

3.2. Technical

From the technical and technological perspective, a sustainable project is fundamentally different from the conventional [30]. Technical factors refer to the methodological aspect of sustainable project implementation. The additional rules and regulations in sustainable projects, procurement issues, process conflicts, the availability of sustainable materials, and the skills to manage them can create a problem in sustainable projects [31][32]. The challenges associated with a complex technical requirement show the need for creating awareness, demonstration of techniques, and educational materials about sustainability to develop skills and gain experience, learn more about the process, etc. The difficulties of permits and approvals of the process for sustainable projects can also cause delays, as many building standards are not tailored to current environmentally friendly systems. These delays lead to higher risks and increased costs which in turn leads developers to think twice to build green [33].

3.3. Technologies

Technologies refer to the product used during the implementation process, and it divided into soft and hard technologies [34]. Soft technologies improve the construction process by using suitable structures, models, and resources to support decision-making, controlling, and evaluation activities. In contrast, hard technologies include equipment, materials, and construction processes [35]. Material price fluctuations are one of the risk factors which lead to cost overruns problems [37]. The soft costs, such as design, certification, modeling, and consulting, are taking a large part of the increased costs of sustainable projects [36]. Therefore, it is essential to concentrate on how to make these technologies widely and easily available at an acceptable cost level, which is affordable by stakeholders.

3.4. Special requirements

A sustainable project is likely to include additional design experts, as the green dimension of the project needs to be implemented [37]. Sustainable projects must be rigorously assessed using a sustainability performance tool and using sustainable project evaluation criteria to be certified, and a certain certification fee will be applied. This fee will be charged differently depending on the project type, project size, and assessment tool. Due to incremental demands on architects and engineers, and the additional green consultant, the sustainable project requires additional effort and time to the design and implementation phase of the project. Means estimates that the cost of designing the sustainable project will cost 5% more than the typical design cost of the conventional project [38].

4. Conclusion

Sustainable development transcends the narrow economic view that is sought to achieve rapid profit and increase it, to discuss means of preserving natural resources in a way that guarantees its investment for the most extended possible period, and improve the quality of the interior environment to enhance the performance of building users. Therefore, sustainability is becoming a source of competitive advantage in the international construction market, which increasingly focusing on the benefits that would be achieved after a period of time, which in turn, can lead to higher revenue growth, new market opportunities. This paper sheds light on sustainability in the construction sector, and since there is a massive demand in the construction industry to develop a tool that allows calculating the sustainability cost of the project, therefore, essential factors that have an impact on sustainability cost have been identified. Focusing on the sustainability aspects would help us to build a cost model, including the sustainability cost of the projects and their returns, which helps stakeholders to select the optimal sustainable project from several candidate projects in the project selection decision-making process.

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Implementation of the Common Vulnerability Scoring System to Assess the Cyber Vulnerability in Construction Projects

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Abstract

The utilization of new technologies coupled with the digitization and automation of the construction industry (known as Construction 4.0) comes with many advantages. For example, it will make the Architecture Engineering and Construction (AEC) industry more connected, accessible, and transparent. However, the inherent nature of these connected systems will make construction networks more vulnerable and prone to cyberattacks. That will compromise not only the confidentiality of sensitive information but also the security of physical assets and project participants. With this background in mind, it is crucial to measure the security of construction networks. There are different systems to evaluate security vulnerabilities of a system, network, organization, or process; one of the most common is the Common Vulnerability Scoring System (CVSS), which provides a numerical score that reflects the severity of a given vulnerability based on specific identified metrics. This paper examines the application of CVSS to quantify and evaluate the vulnerability of project participants that can be used as the groundwork to determine the security vulnerability of construction networks. The objectives of this paper are 1) to examine the advantages and disadvantages of different scoring systems and their applicability to the AEC industry, 2) to systematically apply the identified system to determine scores for some of the most significant construction participants such as the owner, contractor, and worker. The proposed approach will help to assess the vulnerability of project participants and, eventually, the security level of construction networks.

Keywords: construction automation, CVSS, cybersecurity, security score, vulnerability assessment, vulnerability metrics

1. Introduction

Construction project networks include the interaction between a wide range of participants, equipment, and assets. Such interaction often refers to the exchange of design specifics, work instructions, and information about the assets and participants of the project. The rapid rise of communication and information technologies has led the construction industry to progressively move towards the digital ecosystem, which is referred to as Construction 4.0. The aim is to have connected systems during all the phases of construction, starting from project inception till the end of life. This enables the utilization of data, which in many cases, contains highly confidential, sensitive, and proprietary information. This includes competitive bidding information, design specifications, engineered calculations, intellectual property-related information, pricing, profit/loss data, banking records, employee information, quality, safety, and productivity-related standards and practices, to name a few.

As has occurred in other industries, operating in a digital environment raises significant security concerns and vulnerable to cyberattacks. Within a computer system, a vulnerability is typically defined as a weakness that can be exploited by an attacker to perform unauthorized actions. In the context of this paper, vulnerability is referred to as a state or quality of being attacked or harmed because of a weakness in the system or user actions (e.g., weak software, unencrypted file sharing) [1]. Consequently, the actions performed by taking undue advantage of these vulnerabilities are referred to as attacks [2]. Most of the cyberattacks are either unreported because it causes damage to the reputation of the firm or unknown because the attacker uses sophisticated mechanisms to hide it [3]. A few examples of such reported cyberattacks concerning the construction industry include a) stolen design files of the highly sensitive Australian intelligence headquarter building [4]; b) attackers tried to steal proprietary related information of a robotic bricklayer [5]; c) an operational facility's (Target, a very well-known retailer in the United States) network was compromised, and attackers gained access to customers personal information through a vulnerable HVAC vendor who worked on the facility during the construction phase [6] and many more.

One of the fundamental ways to improve security is by quantifying the vulnerability of these organizational or project related networks [7]. Quantifying the network vulnerabilities enables identifying those that pose the highest risk, thereby assists in prioritizing and implementing network security solutions. By defining the security level of individual project participants and combining the individual scores into an overall measure for network security, we can identify the most vulnerable connections given a target participant and further suggest possible security solutions to improve the network. Some studies in the related fields like intelligent urban infrastructure systems, power grid systems, and water facilities proposed metrics to help quantify and assess the vulnerability of the respective networks (thereby the security of the network) [8] [9] [10]. However, these metrics are context and application-specific and do not apply to construction. For example, some of the context-specific metrics include the efficiency of the power grid, the power supply of the load stations, and the rate of pipe deterioration.

To summarize, none of the existing studies proposed a systematic approach for quantifying the security of individual participants and thereby the security of the entire construction network. This study serves as an initial step towards this direction. Specifically, the focus of this study is to a) explore different existing scoring systems and identify a suitable one for construction projects, and then b) systematically apply the scoring system to determine scores for some of the most significant construction participants such as the owner, contractor, or worker. The rest of this paper is organized as follows. Section 2 provides a review of the different scoring systems. In Section 3, the selected scoring system, namely the Common Vulnerability Scoring System (CVSS), is used in an example to determine the vulnerability score for different construction participants. Finally, Section 4 provides the conclusions and summarizes ongoing work by the authors in this area.

2. Review of vulnerability scoring systems

There are several existing vulnerability scoring systems managed by governmental, commercial, and non-profit organizations. Each of these scoring systems focuses on different aspects of measuring vulnerability. For example, CERT/CC (Computer Emergency Response Team) considers whether the Internet infrastructure is at risk and establishes a procedure to examine the preconditions required to exploit the vulnerability [11]. The System Administration, Networking and Security (SANS) vulnerability analysis scale considers whether the weakness is found in default configurations or client or server systems [12]. Microsoft's proprietary scoring system reflects on the difficulty of exploitation and the overall impact of vulnerability [13]. While relevant and useful, these scoring systems assume that the impact of a vulnerability is constant for every individual and organization. This limits the usage of these systems for construction projects and networks which have different participants and varying security levels [14]. For example, vulnerability levels vary significantly between a contractor, worker, and owner. It is also possible that, depending on the type of the project (e.g., high-security government facility vs. residential project), the security level of these participants vary. Hence, it is necessary to quantify these based on customized networks rather than assigning constant values.

Unlike the systems mentioned above, the Common Vulnerability Scoring System (CVSS) "*provides a way to capture the principal characteristics of a vulnerability and produce a numerical score reflecting its severity*"[1], or in other words, it assigns numerical scores to each identified vulnerability. This is a widely adopted system which is based on the relative security levels and, hence, enables security analysts, industry professionals, organizations, and researchers to adopt a common language in scoring the vulnerabilities. This is actively used by many organizations, including the United States (US) federal government systems and the National Institute of Standards and Technology (NIST). The US federal government uses this to rate the severity of vulnerabilities within their system [14]. The NIST National Vulnerability Database (NVD) provides a comprehensive database of CVSS vulnerability scores validated by the US government [14]. These scores enable organizations to understand and rank the impact of the vulnerabilities of individual subsystems and participants level.

Furthermore, there is a possibility to adjust the estimated scores and specifically tailor this scoring system to the target environment based on environmental metrics such as damage to the asset, revenue, or productivity. In addition, CVSS is also one of the six vulnerability management standards that comprise the Security Content Automation Protocol (SCAP). SCAP is a method to enable automated vulnerability management, measurement, and policy compliance evaluation (e.g., Federal Information Security Management Act[2] (FISMA) compliance). U.S. government agencies and other organizations use SCAP to determine the presence of vulnerabilities and provide mechanisms to score the results of these measurements to evaluate the impact of discovered security issues. Therefore, considering all these advantages over other systems, in this study, the CVSS (version 3.1) [14] is systematically applied to different construction participants. Details regarding different elements of the CVSS, along with the quantitative evaluation of the score range is described in the following section.

3. Applying CVSS to participants in construction projects

The scores in the CVSS are estimated based on the three metrics, namely base metrics, temporal metrics, and environmental metrics. The base metrics capture the characteristics of the vulnerability that are consistent over a period of time and among different user environments. An example in the context of this study could be the vulnerability of construction entities due to the connected systems such as the Internet of Things and wireless networks on the job site. Optionally, the base score can be adjusted with temporal and environmental metrics to reflect time-variant and environment-specific factors, respectively. The temporal metric captures the readily available methods and techniques to exploit a vulnerability. A relevant example in construction could be an attacker remotely exploiting the vulnerability of a progress monitoring system (e.g., drone, camera) through a sophisticated attack (e.g., executing an automated agent software that allows the attacker to use target systems as attack platforms to perform malicious unauthorized actions). The objective of the environmental metrics is to understand the importance of the affected asset based on measuring the confidentiality, integrity, and availability. For example, in the context of construction, the environmental metric could relate to the effect of loss of confidentiality or integrity on the specific construction entity (e.g., contractor, worker, designer, and owner). Based on the examples mentioned above, it can be said that these three metrics are relevant to the AEC industry. However, for this study, only base metrics are considered. It has to be noted, however, that the same approach would apply for the inclusion of temporal and environmental metrics. For this study, it is assumed that the scores from the CVSS can be used to assess the severity of the vulnerability of the different participants in construction projects.

Acknowledging that the level of vulnerability varies depending on the construction participant (i.e., a small local contractor versus a large international contractor), this study uses a public owner (PO), a local contractor (LC), and a construction worker (CW) as the construction entities (i.e., participants) used to illustrate the implementation of the CVSS. This selection encompasses a varied range of security levels in the descending order assuming that a PO is expected to have a high amount of security (or conversely low

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[1] Common Vulnerability Scoring System Special Interest Group (CVSS-SIG) [https://www.first.org/cvss/]
[2] The act recognizes the importance of information security to the economic and national security interests of the United States.

vulnerability) compared to that of an LC or a CW. The following sections describe the implementation of the CVSS to determine the vulnerability scores for each of the participants (or entities) indicated.

3.1. Base metrics

The score calculated using the base metrics is called the base score, which ranges between 0 and 10. A higher base score refers to a higher exposure or higher vulnerability. Ranges from 0, (0.1 – 3.9), (4.0 – 6.9) (7.0 – 8.9), and (9.0 – 10) represent none, low, medium, high, and critical severity of vulnerability, respectively. There are three types of base metrics: exploitability, scope, and impact (as per the third version of the CVSS [14]). Each type is further divided into categories with different metric values and corresponding scores. Table 1 shows an overview of all the categories, metric values, and the corresponding score values for each of the three base metric types, as indicated in the CVSS guide. Each of these metric types, categories, and metric values are briefly defined as per the CVSS, and its relevance to the construction is illustrated with the help of the identified construction entities (PO, LC, and CW) previously introduced. For further in-depth details regarding each of the metric value definitions and scoring schema, the readers should refer to the CVSS guide [14].

Table 1. Scores for each of the base metric types, categories, and metric values according to the CVSS (adopted from [14])

Base Metric Type	Category	Metric Value	Score	Base Metric Type	Category	Metric Value	Score
Exploitability Metrics	Access Vector (AV)	Physical (P)	0.20	Scope (S)	-	Unchanged (U)	-
		Local (L)	0.55			Changed (C)	-
		Adjacent Network (A)	0.62	Impact Metrics	Confidentiality (C)	None (N)	0.00
		Network (N)	0.85			Low (L)	0.22
	Attack Complexity (AC)	High (H)	0.44			High (H)	0.56
		Low (L)	0.77		Integrity (I)	None (N)	0.00
	Privileges Required (PR)	High (H)	0.27* or 0.50**			Low (L)	0.22
		Low (L)	0.62* or 0.68**			High (H)	0.56
		None (N)	0.85		Availability (A)	None (N)	0.00
	User Interaction (UI)	Required (R)	0.62			Low (L)	0.22
		None (N)	0.85			High (H)	0.56

*Note: *for Scope = Unchanged (U); **for Scope = Changed (C)*

3.1.1 Exploitability metrics

The objective of this metric is to measure the relative difficulty of exploiting a particular vulnerability. In the current context, it is to measure the vulnerability of a particular construction entity that could lead to a successful attack. The following paragraphs go over the four categories that comprise the exploitability metrics.

a) Access Vector (AV) category measures the distance accessibility required for the hacker to exploit a vulnerability. That is, how far the attacker can be and still manage to attack the entity. For example, in the case of construction, does the attacker need to be physically present on the job site? Can the attacker launch an attack on the autonomous equipment remotely? The more remote an attacker can be to launch an attack, the more vulnerable the entity is, and hence the higher the vulnerability score of the entity. The AV levels are divided into four metric values, namely Physical (P) access (e.g., physically access the target system), Local (L) access (e.g., local account required or intended or unintended user interaction such as trick a user to open a malicious document), Adjacent Network (A) access (e.g., accessible from local subnetworks), and Network (N) access (e.g., accessible through the Internet). For example, to attack a sophisticated entity like a high profile PO, an attacker needs to have physical access (i.e., Metric Value = 'Physical' and Score = 0.20 from Table 1), considering that the PO has stringent cybersecurity policies and procedures in place. However, the attacker could potentially attack a CW's mobile phone or any device where work-related information is stored remotely through the internet (i.e., Metric Value = 'Network' and Score = 0.85 from Table 1). It is thus reasonable to assume that an average LC lies in the middle of the spectrum (i.e., between 'Physical' and 'Network'), and hence local access is considered (i.e., Metric Value = 'Local' and Score = 0.55 from Table 1).

b) Attack Complexity (AC) category measures the complexity of the attack required to exploit the vulnerability once the access is made. That is, how complex should the attack be to compromise any specific construction entity. For example, a Common Data Environment (CDE) managed and controlled by a contractor (or designer) is considered highly vulnerable if all the users (e.g., painting subcontractor) have complete access and rights to the structural, mechanical, electrical, and plumbing shop drawings. Possible metric values, as suggested by the CVSS, include High (H) (e.g., admin/root privilege required) and Low (L) (e.g., no specialized access condition required). As can be seen from the corresponding scores in Table 1, the lower the required complexity, the higher the vulnerability score. For example, the attacker would need an admin or root privilege to access or modify any of the information if he/she gets access to any of the PO's network. Hence a value of 'High' is considered for the PO (Score = 0.44 from Table 1), and correspondingly, 'Low' (Score = 0.77 from Table 1) is considered for both the LC and CW.

c) Privileges Required (PR) category relates to the level of exclusive rights an attacker is required to possess to exploit a vulnerability. In the context of this study, that means how much privilege will an attacker require to compromise any construction entity's network (e.g., PO's subnetwork), equipment (e.g., CW's tablet interface), or repository (LC's CDE repository). Possible CVSS metric values include High (e.g., administrative control required), Low (e.g., user control required to impact the settings and files owned by the user), and None (e.g., does not require any prior access but still can launch an attack). Considering that a PO will have multi-layer security, high privileges would be required to hack his/her systems, components, or networks. That is why 'High' is chosen for the PO, and correspondingly a score of 0.27 (if Scope = Unchanged) or 0.50 (if Scope = Changed) is assigned depending on the Scope (which is described later in this section of the paper). Furthermore, it is reasonable to assume a 'Low' type for both the LC and CW. This is because of the bare minimum security every entity has, starting from the usage of their mobile phones to work laptops or tablets. Therefore, a score of 0.62 (if Scope = Unchanged) or 0.68 (if Scope = Changed), depending on the Scope, is assigned for those participants.

d) User Interaction (UI) category captures the requirement of an internal or external user, other than the attacker, to assist in successfully launching an attack on the vulnerable component. In the current context, it relates to an external or an internal user (e.g., existing employee) assisting a potential attacker in compromising any construction entity. This category is further divided into two metric values: Required (R) and None (N). For example, to successfully exploit a PO, an attacker might need the help of a network administrator. However, none of such user interaction might be required to launch a similar attack on the LC and CW considering the technology readiness of these entities. For instance, an attacker might not need administrative privileges to be able to hack an LC or CW's personal device, which might have been frequently used to access work-related information. Hence values of 'Required' (Score = 0.62 from Table 1) were assigned to the PO and 'None' (Score = 0.85 from Table 1) to the LC and CW.

3.1.2 Scope (S)

This metric captures whether a component's vulnerability can impact resources and components beyond its scope. In the context of this study, it is to capture whether the vulnerability of a specific construction entity can impact components such as the assets, information, and resources of other entities. This metric type has two metric values: Unchanged (U) and Changed (C). As the name suggests, a metric value of 'U' suggests that there will be no change in scope, and conversely, a value of 'C' means that there will be a change in scope. Due to the inherent nature of construction, almost all the entities are interrelated and hence can compromise and impact each other with very few exceptions. For example, [15] showed how the vulnerability of an individual entity impacts the whole construction network due to the existing information and communication exchange channels. An example of an exception can be when a potential vendor who is not part of the construction project yet, might not have any communication or association with the existing entities (e.g., contractor), and hence the vulnerability of such a potential entity might not have any impact. In the context of this study, all the participants considered can either have a major or minor impact on the other entities. Hence a metric value of Changed (C) is assigned for the PO, LC, and CW. As briefly discussed in 3.1.1 c), the score for some of the values for the Privilege Required (PR) category varies depending on the metric value used for the Scope. Since we are assuming a 'Changed' metric value for Scope, the metric values for the PR category corresponding to the Changed condition should be used. Therefore, the PR values, in this case, are 0.50 for PO and 0.68 for LC and CW.

3.1.3 Impact metrics

The idea of the impact metric is to capture the effect of exploiting a vulnerability. That is, in the current context, measure the impact an attacker can have on the specific construction entity if an attack is successfully launched. As can be expected, the increased impact increases the vulnerability score. The following paragraphs go over the three categories that comprise the impact metrics.

a) Confidentiality Impact (C) category measures the impact on information confidentiality. That is, to measure the impact of disclosing or revealing the information of a construction entity. For example, an attacker steals the private encryption key of a contractor's or a CDE's server. This could lead to gaining access to the design files, contractual documents, and sensitive personal records of the employees, visitors, or workers. Possible metric values are 'None' (e.g., no impact), 'Low' (e.g., considerable disclosure of information), and 'High' (e.g., total disclosure). Considering the three participants, it is reasonable to assume that, even though the attacker somehow accesses the PO's systems, he/she might have a 'Low' confidential impact (i.e., Score = 0.22 from Table 1) because of the possible defense mechanisms that might already be in place. However, a similar attack on the LC or CW will have a 'High' impact (i.e., Score = 0.56 from Table 1).

b) Integrity Impact (I) category measures the ability of the attacker to modify, tamper, or delete an entity's information. In the context of this study, it is to measure the extent of modification an attacker can perform once the construction entity is hacked. Considering a similar example as in the Confidentiality Impact above, the attacker not only has access to the restricted information related to the design, contract, construction, and operation but also can modify or erase it. Possible metric values are 'None' (e.g., no impact), 'Low' (e.g., modification of some information), and 'High' (e.g., complete loss of system protection). Similarly, a value of 'Low' (i.e., Score = 0.22 from Table 1) is considered for the PO, and a value of 'High' (i.e., Score = 0.56 from Table 1) is used for both the LC and the CW.

c) Availability Impact (A) category measures the ability of the attacker to impact the availability of the target system. In the context of this study, it measures the amount of control an attacker can have once the specific entity or the entity's resources. Possible metric values are None (e.g., no impact), Low (e.g., reduced performance or interruptions in resource availability), and High (e.g., total shutdown of the affected resource). For example, if an attacker hacks the tower crane on site, which is usually controlled by the LC, it is possible to take over that resource and render it completely dysfunctional. Considering the cyber awareness and readiness of the CW, it could also happen the same for any of the resources he/she might be operating. Therefore, a metric value of High is considered for both these participants, and a score of 0.56 is assigned. However, a PO might have an existing defense mechanism in place that might usually block a hacker from doing so and might end up with some loss of functionality. Hence, a value of low (i.e., Score = 0.22 from Table 1) is considered.

All the scores for the three construction entities (PO, LC, and CW) and the different categories are summarized in Table 2.

3.1.4 Base score calculation

As shown in Table 1, each of the metric values is mapped to the corresponding numerical score. With the help of these scores, a CVSS base score can be calculated using equations 1 to 4 from the CVSS guide [14]. While equations 2, 3, and 4 help estimate individual base metric type scores, equation 1 aggregates all these to estimate the final base score. The corresponding values calculated for the PO, LC, and CW are shown in Table 2. As can be seen, the PO, LC, and CW have total base scores of 4.28, 8.71, and 9.89, respectively. Those scores represent a medium, high, and critical vulnerability, respectively, based on the 0 to 10 score range mentioned at the beginning of this section.

$$BaseScore\ = 0, if\ (Impact\ Score \leq 0), else$$

$$= Roundup\{Minimum[(Impact\ Score\ +\ Exploitability\ Score), 10]\ if\ (Scope = Unchanged)$$

$$= Roundup\{Minimum[1.08 * (Impact\ Score\ +\ Exploitability\ Score), 10]\ if\ (Scope = Changed) \quad (1)$$

$$Exploitability\ Score\ =\ 8.22 * AccessVector * AttackComplexity * PrivilegesRequired * UserInteraction \quad (2)$$

$$Impact\ Sub\ Score\ (ISS) =\ (1 - (1 - Confidentiality) * (1 - Integrity) * (1 - Availability)) \quad (3)$$

$$Impact\ Score =\ 6.42 * ISS\ if\ (Scope = Unchanged)$$

$$=\ 7.52 * (ISS - 0.029) - 3.25 * (ISS - 0.02)^{15}\ if\ (Scope = Changed) \quad (4)$$

Table 2. Base metric score calculations for each of the construction entities considered

Base Metrics	Category	Public Owner (PO)		Local Contractor (LC)		Construction Worker (CW)	
		Metric Value	Score	Metric Value	Score	Metric Value	Score
Exploitability	AV	P	0.20	L	0.55	N	0.85
	AC	H	0.44	L	0.77	L	0.77
	PR	H	0.50	L	0.68	L	0.68
	UI	R	0.62	N	0.85	N	0.85
Scope	-	C	-	C	-	C	-
Impact	C	L	0.22	H	0.56	H	0.56
	I	L	0.22	H	0.56	H	0.56
	A	L	0.22	H	0.56	H	0.56
Exploitability Score (Eq. 2)			0.22		2.01		3.11
Impact Sub Score (ISS) (Eq. 3)			0.53		0.91		0.91
Impact Score (Eq. 4)			3.73		6.05		6.05
Total Base Score (Eq. 1)			**4.28**		**8.71**		**9.89**

4. Conclusion and ongoing work

Construction is progressively moving towards adopting automation and digitalization technologies. This will inevitably increase the number of cyberattacks that occur in the industry. Based on the amount of available scientific literature, it seems that the issue of construction cybersecurity is at a very nascent stage. Though several standards and policies exist for risk assessment and mitigation in the construction project management domain, a widely accepted cybersecurity assessment is mostly unavailable in the construction. One of the fundamental steps towards analyzing and addressing the cybersecurity concerns include the ability to quantitatively measure and understand the security, or conversely, the vulnerability of participants (e.g., owners, architects, and contractors) and networks (e.g., combined group of participants, equipment, and assets). This study provides an impetus towards research in this direction and explores different systems that exist in the cybersecurity domain. Preliminary analysis of different available systems suggests that the Common Vulnerability Scoring System (CVSS) has several advantages compared to that of others and allows customizable scores for different entities.

The CVSS was systematically applied to determine the total base scores for three of the construction participants, namely a public owner (PO), a local contractor (LC), and a construction worker (CW). For the sake of simplicity, only the base metric scoring was shown in this study. This could, however, be extended to adjust the base scores and incorporate the temporal and environmental metrics. Based on the ranges of the base scores defined by CVSS, the PO, LC, and CW had a medium, high, and critical vulnerability. These scores need not necessarily be an exact representation of all the owners, contractors, or workers, and caution should be exercised to avoid generalizing the results from this study. Instead, this study should be used as an example to implement the CVSS to determine the vulnerability level of each of the entities by considering the individual characteristics of the entity (or participant) in a construction project. Further investigation, such as comparing attack history and assessing the security of different systems within the network or subnetwork, can be done to assign more precise metric values.

Ongoing work of the authors extends this scoring system to define and analyze the overall vulnerability of construction networks. This is done by adopting the CVSS aggregation approaches suggested in the literature. Such an analysis could greatly assist the existing risk assessment (e.g., comparing the cyber risks of different project delivery methods or supply chain structures) and management approaches (e.g., investigating the cyber vulnerabilities of introducing drones or 3D printers on construction sites).

5. Acknowledgment

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Improving But-For Delay Analysis and Concurrency Assessment

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Abstract

But-For analysis is one of the popular techniques for apportioning the responsibility for project delays among the project parties (owner, contractor, and third party). Despite its acceptance by courts, one of its known drawbacks is that it produces conflicting results when adopting different party's viewpoints. Moreover, But-For analysis is not able to identify the concurrent delays caused by multiple parties. Despite some literature modifications to address those shortcomings, Modified But-For (MBF) analysis persistently does not consider event chronology and thus can produce wrong results. This paper thus discusses the concurrency assessment method of the MBF and introduces implementation improvements to divide the analysis into multiple windows to increase the analysis resolution, account for critical path fluctuations, and consider the chronology of different-party events, which is a requirement by recent delay analysis guidelines of professional bodies such as AACE and ASCE. A case study is used to show a detailed procedure for applying multiple-window MBF analysis to produce more accurate and repeatable delay analysis, considering concurrent delays.

Keywords: but-for, collapsed as-built, concurrent delay, construction, delay analysis

1. Introduction

The risky and uncertain nature of construction projects frequently leads to schedule delays, cost overruns, and disputes [1]. Delay analysis techniques are the main forensic tools to fairly apportion construction delays, settle disputes, and avoid its undesirable effects such as lawsuits and contract termination [2]. Among several existing delay-analysis methods, the But-For (or collapsed as-built [3]) technique is one of the most widely used and accepted techniques [4, 5, 6] because of its simplicity and its use of the as-built schedule (the real schedule already executed) [7, 8]. However, the traditional But-For method exhibit four main drawbacks: (1) it produces different results when adapting different parties' viewpoints [9, 10, 11]. This shortcoming made the technique easy to manipulate [12] to support different parties' claim argument [13]; (2) it is unable to identify the concurrent delays that occurred during execution[14, 15]; (3) it is insensitive to the specific timing of parties' events on the schedule; and (4) it is insensitive to the fluctuation of the critical path(s) during construction. In the literature, the common misinterpretation of results in the traditional But-For were explained and resolved by Bhih and Hegazy [9]. Also, Mbabazi et al. [16] introduced the Modified But-For (MBF) method to address the first two drawbacks, thus producing consistent results irrespective of the adopted viewpoint, and accurately identifying concurrent delays. Despite the improvements introduced by the MBF, the two latter drawbacks (3 and 4) still persist due to the fact that MBF uses a single time window (the whole as-built schedule) for the analysis [17]. To support schedule forensic analysis, several professional bodies have established general industry guides. Currently, three schedule-analysis guidance documents are available [18]: the Delay and Disruption Protocol of the Society of Construction Law (SCL) in the UK [19]; the Forensic Schedule Analysis Recommended Practice 29R-03 of the AACEI in the USA [20]; and the Schedule Delay Analysis (ANSI/ASCE/CI 67-17) of the ASCE in the USA [21]. These guides, however, provide generic guidelines to promote balanced and fair assessment of compensations and time extensions rather than specific steps to perform delay analysis.

This paper, first discusses the MBF method and how it improves concurrency assessment of the traditional But-For method. Afterwards, the paper introduces improvements to the MBF to address the insensitivity to event chronology and critical path fluctuations. Example applications are used to discuss and validate the developments made.

2. Modified But-For method

The MBF methodology [16] allocates project delays in the general case of three parties (owner, contractor, and third party). In this paper, for simplicity, the case of two parties is used. MBF was introduced to resolve the drawbacks of the traditional But-For of producing different results when different parties' viewpoints are adopted [11, 16, 22] and its inability to identify concurrent delays [9]. A small case study of four activities (adopted from literature [23]) is used to explain MBF benefits. The as-planned and as-built schedules are shown in Fig. 1. The project was planned to finish in 10 days (Fig. 1a). The as-built schedule (Fig. 1b) exhibits simultaneous owner and contractor delays so the project finished 2 days behind schedule. The owner event to activity B shifted the remaining portions of activities B and C to a period of lower productivity, thus taking longer time than planned and delaying the project.

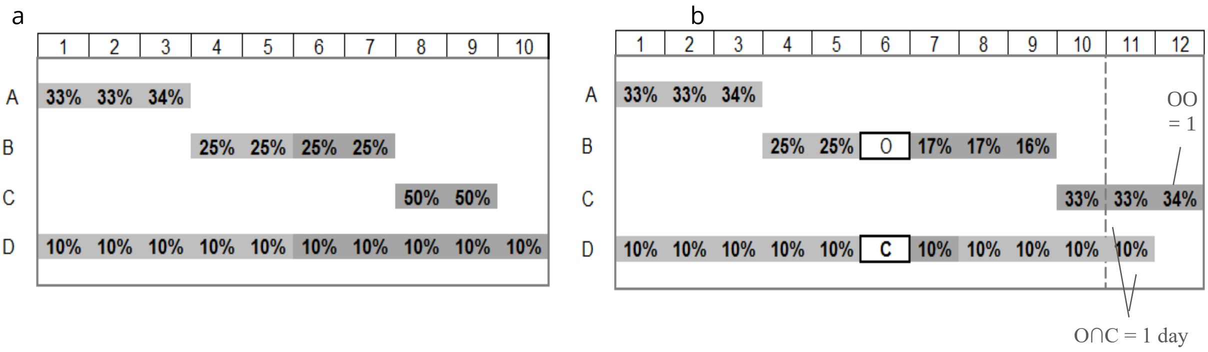

Fig. 1. Case study schedules (a) As-planned schedule, (b) As-built Schedule (Scenario 1)

In traditional But-For analysis, parties' events are removed one at a time from the as-built schedule to investigate its impact on the project duration. From the owner's perspective, by removing the owner-caused events from the as-built schedule it collapses 1 day; so the owner accepts responsibility for only 1 day project delay, and the remaining balance of project delays (1 day) is attributed to the contractor. Thus, Owner's viewpoint results are (Owner responsibility = 1 day, Conctractor responsibility = 1 day). From the contractor's perspective, on the other hand, since the as-built schedule does not change after removing the contractor events, then the contractor's responsability is 0 days and the remaining balance (2 days) is attributed to owner. Thus, Contractor's viewpoint results in (Owner responsibility = 2 day, Contractor responsibility = 0 days). As such, the difference in results and the inability to identify concurrent delays have become serious drawbacks to the traditional But-For method.

To resolve these issues, the MBF method [16] utilizes Venn representation and set theorem to allocate delay responsibility among project parties, as shown in left side of Fig. 2. The two intersecting circles represent the project delays caused by Only-Owner (OO), Only-Contractor (OC), and the intersection area of their Concurrent Delays (O∩C), as shaded in the figure. Using set theory, a formulation of all segments in the Venn representation can be made to calculate the three areas of delay responsibilities, which add up to the total project delay, as follows:

$$\textit{Total project delay} = OO + OC + O\cap C \tag{1}$$

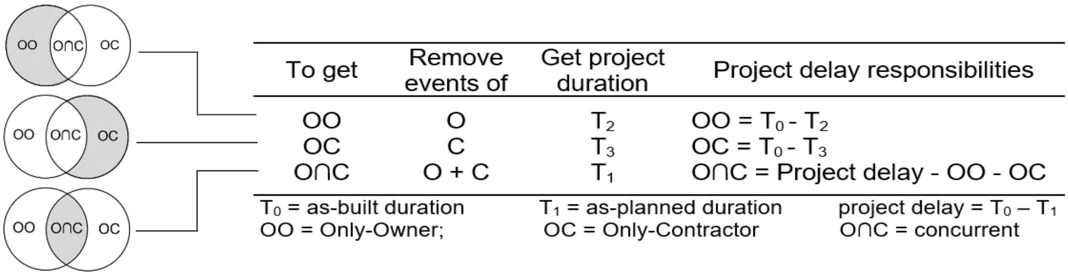

Fig. 2. MBF methodology

Applying the MBF method to the case in Fig. 1 is shown in the steps of Fig. 2. The MBF process basically removes three combinations of delay events from the as-built schedule, one at a time, and the resulting project duration is used in the delay responsibility calculations. Having the as-built duration of T_0 = 12, the first MBF step is to remove all the Owner (O) events from the as-built schedule. Accordingly, without any owner events, the schedule becomes T_2 = 11 days. Therefore, the Only-Owner (OO) responsibility is directly evaluated as the difference between T_0 and T2, i.e., OO = T_0-T_2 = 12 -11 = 1 day. In the second step, removing all the Contractor events from the as-built, the schedule duration becomes T_3 = 12 days, thus, the Only-Contractor (OC) responsibility = T_0 - T_3 = 12 - 12 = 0 days. Also, in the third step, removing both the owner and contractor events results in the as-planned duration T_1 = 10 days. Accordingly, using Equation 1, concurrent delays O∩C = Project delays - OO - OC = (T_0 – T_1) - OO - OC = 1 day. Summary results are shown in Table 1 (OO = 1 day, OC = 0, O∩C = 1 day) and these values can be easily observed on the as-built schedule of Fig. 1b. This analysis, as such, is repeatable and does not depend on any party's viewpoint. Furthermore, it does not ignore concurrent delays.

Table 1. Case study MBF calculations (scenario 1)

To get	Remove events	Project duration (days)	Project delay responsibilities (days)
OO	O	T_2 = 11	OO = T_0 – T_2 = 12 – 11 = 1
OC	C	T_3 = 12	OC = T_0 – T_3 = 12 – 12 = 0
O∩C	O+C	T_1 = 10	O∩C = Project delays - OO - OC = T_0 – T_1 - OO - OC = 1

T_0 = 12

3. Improving MBF sensitivity to event chronology

As the MBF method uses the entire project as a single analysis-window, by nature, it cannot respect events' chronology, i.e., the specific timing of the events. Furthermore, the MBF only considers the final critical path(s) of the as-built schedule, overlooking path fluctuations over the course of the project, which affect the analysis results. To highlight this issue, the as-built schedule of the case study is slightly altered as shown in Fig. 3. In this scenario, the contractor and owner events were shifted so that each one is happening on different day, thus are no longer simultaneous.

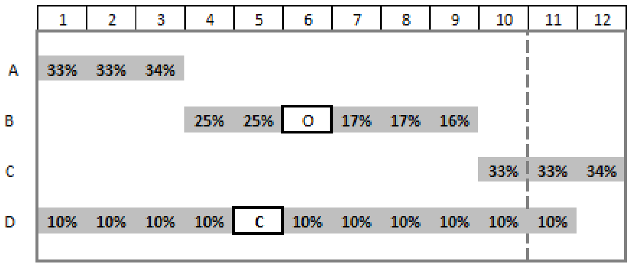

Fig. 3. Case study as-built Schedule (Scenario 2)

Using a single-window MBF, scenario 2 was analysed by following the step-by-step process explained earlier. The results are shown in Table 2 being (OO= 1 day, O∩C = 1 day). These results are identical to those obtained for the original case study (scenario 1) in spite of the difference in the timing of events. This shows that the MBF analysis is not sensitive to the timing of delay events.

Table 2. Case study MBF calculations (scenario 2)

To get	Remove events	Project duration (days)	Project delay responsibilities (days)
OO	O	$T_2 = 11$	$OO = T_0 - T_2 = 12 - 11 = 1$
OC	C	$T_3 = 12$	$OC = T_0 - T_3 = 12 - 12 = 0$
O∩C	O+C	$T_1 = 10$	O∩C = project delays – OO - OC = 2 - 1 - 0 = 1

$T_0 = 12$

Irrespective of the identical results of the two scenarios, they represent two cases of concurrency, namely “true concurrency” versus “concurrent effect”, as defined by the SCL protocol [19]. This protocol defines concurrent effects as "two or more delay events arise at different times, but the effects of them are felt at the same time”. As shown in the above analysis, single-window techniques such as MBF suffers from its inability to differentiate between true concurrent delays (as in scenario 1) and concurrent effects (as in scenario 2) due to its inability to consider event chronology. Because this drawback can seriously affect delay analysis results, the ASCE proposed standard [21] and the AACEI recommended practice [20] require that project delays be assessed chronologically and cumulatively.

3.1. Analysis considering event chronology

To correctly analyze the project delays of scenario 2, the chronological order of events is considered. Starting from the as-planned schedule of Fig. 1a, the schedule has one critical path (task D) and one near-critical path (A-B-C) with 1 day of float. As shown in Fig. 4, the contractor event on day 5 caused 1-day project delay, resulting in an expected project completion on day 11, and this also increased the float of the near-critical path (A-B-C) to 2 days. Afterwards, on day 6, the owner event on path (A-B-C) not only consumed all the float but also caused an additional project delay, ending in day 12. Thus, the correct responsibility for scenario 2 is (OO = 1 day, OC = 1 day, O∩C = 0 days). Such logical analysis cannot be done manually for large and complex projects, and modifications to the MBF are needed.

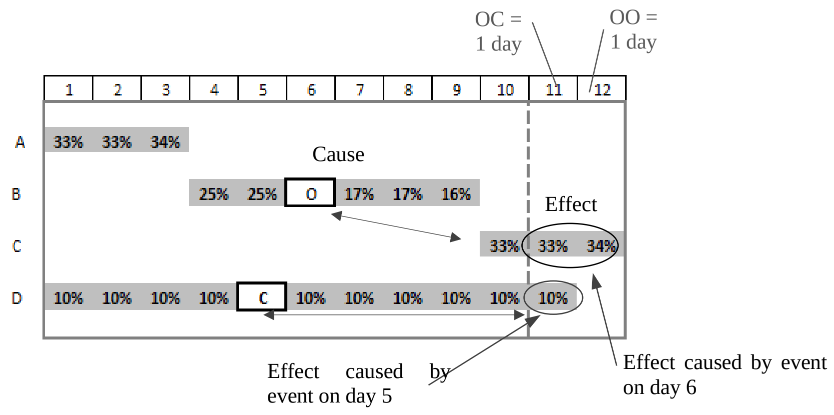

Fig. 4. Analysis based on event chronology

3.2. MBF with multiple-window analysis

To overcome the MBF insensitivity to the timing of events and facilitate accurate concurrency assessment, this paper proposes to use multi-window MBF analysis. Multi-window MBF analysis will also improve the tracking of critical path(s) fluctuations. The analysis windows should be selected carefully as the window size could affect the results. Since the MBF method can assess project delays based only on effects regardless of its causing events, having different parties’ events in separate analysis windows will ensure that their effects will be assessed separately, unless the events happened simultaneously or very close in time. For instance, in scenario 2, if a literal concurrency is adopted (i.e., concurrent events must ha happen on same day), using two analysis windows (Window 1: days 1 to 5; and Window 2: days 6 to 12), as shown in Fig. 5, will ensure arriving at the correct answer.

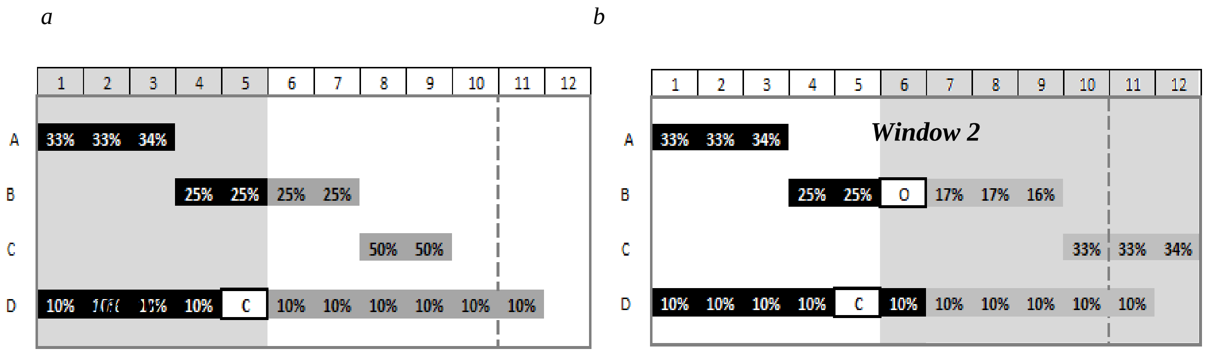

Fig. 5. Analysis of scenario 2 (a) Window 1, (b) Window 2

Applying the two-window MBF analysis to scenario 2 is shown in Table 3. Each window is analysed separately and the result is shown in the corresponding row; finally the analysis results are accumulated to obtain the project delay responsibility. The results obtained using this multi-window analysis are identical to the correct logical results obtained considering event chronology and those obtained by Zhang & Hegazy [23] using the more accurate daily-windows analysis. As such, applying multi-window MBF analysis can produce accurate results by properly separating the different parties' events in different windows. This in fact increases the analysis resolution and makes the MBF analysis capable of better tracking of the critical path(s) fluctuations and the chronology of delay events.

Table 3. Case study MBF multi-window calculations (scenario 2)

Window	Days	As-built without party(ies) events (days)				Project delay responsibilities (days)		
		As-built T_0	O and C T_1	O T_2	C T_3	OO	OC	O∩C
1	1-5	11	11	10	10	0	1	0
2	6-12	12	11	12	11	1	0	0
						1	1	0

4. Concluding remarks

Traditional but-For technique has been criticized for its highly subjective nature and its inability to assess concurrent delays. The Modified But-For method, therefore, uses Venn representation to overcome those drawbacks by reconciling the opposing viewpoints of project parties, and having the ability to apportion concurrent delays. However, the MBF method, due to its single-window implementation, suffers from its inability to respect the chronology of delay events and to capture the critical path(s) dynamics. In this paper, the MBF methodology was used to arrive at repeatable independent results that compiles the view points of all parties and identify concurrent delays. Furthermore, a multiple-window MBF analysis is proposed to improve the analysis resolution and produce more accurate results considering events chronology and critical path fluctuations. A simple case study is presented to demonstrate the improvements made in multiple-window MBF analysis.

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Investigation of Possible Dominance of Factors Affecting Project Success

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Abstract

The bottom-line of project management is to produce the deliverables successfully. However, the various participants may interpret the term 'success' differently, and they assess the result of the project along with different indicators. A traditional, widespread, and clear set of indicators for the project managers are the time-cost constraints with the goal achieved in the right quality. Since the prediction and interpretation of success is a far more complex problem, researchers and experts have long been trying to answer the most critical questions relating to the success and failure of projects. Firstly, this paper provides a summary of how the traditional success approach evolved and how the researchers tried to extend the basic model and to grab its complexity. Secondly, the research goal is to formulate a research question on the possible dominance and effects of the factors. Finally, the authors develop the process and collect the possible mathematical-statistical tools supporting the previously mentioned goals. The founding of the research question in this article can lead to original assumptions, which highlights an area of research on the success that has not been explored so far. According to our intentions, this article lays the foundations for a thorough and comprehensive analysis for understanding better

Keywords: success criteria, success factor, perception of success

1. Introduction

The authors briefly review the conceptual foundations of project success based on previous works on this particular topic [1]. The aim is to develop further the role of perception described in the literature so far and to examine its dominance. Is perception able to overwrite other elements grouped in the literature when assessing project success?

The purpose of this research is to establish a statistical analysis by making groups of project participants based on their opinions about the project. Then, if these research goals are justified, the opinions of independent and homogeneous groups will be compared with the traditional project evaluation aspects. We conclude this article with a few thoughts on data collection and further potential research we intend to do. The ideal follow-up of these founding steps to identify those subjective opinions of participants, which have the most influence; and to create a model that can predict whether the project will be perceived successful.

2. Approaches to project success

The success of the project is assessed by taking into consideration the general goals of the project (or enterprise), while the success of project management is assessed based on traditional factors such as cost, time and quality. Many researchers concentrate on these two directions exclusively when researching the causes of success. The literature commonly distinguishes the success of the project from the success of project management (e.g., [2]). Nevertheless, there is an apparent relationship between them –successful project management leads to a successful project.

The paths of analysis can be arranged into three classes: the factors affecting success have to be determined, the criteria of success defined, and their relationship examined [3]. The traditional cost-time-quality triangle appears in every project definition. Project managers consider these as criteria for success as an industrial standard. The shortcomings of the traditional approach, which can be considered the standard for project managers, have been addressed in several development attempts in recent decades. The result of these studies was a more sophisticated system of criteria or factors [4]. Some researchers build models that can handle many existing factors, but the irrationally large size of the model makes the problem unmanageable.

Many have realized that human assets have to be included in success criteria, in addition to the easily measurable technical parameters. Since these are not easy to quantify, less research has been done in this area compared to traditional factors [5]. Researchers have begun to introduce criteria connected to persons such as flexibility and adaptability, enthusiasm, spontaneity, aggressiveness, confidence, preferences related to initiative and leadership, ambition, verbal abilities, etc. On the human side, Yang and his colleagues suggested examining how the international character of the project and the leadership style affect success, in addition to the factors recommended by technical literature, such as teamwork, project type, sector of the industry, team size, etc. [6].

In researching the financial dimension of success, researchers have gone from supplementing traditional fundamentals and criteria with value creation to being able to measure overall success with a comprehensive financial indicator. While numerous extensions to the basics can be found in the literature, one of the most important is that the traditional triangle of criteria should be extended with the notion of creating and transmitting value. The final goal of the project manager was identified by some researchers to create business value [7].

3. Role of perception

Verma (1995) stated that in addition to the accomplishment of traditional technical performance (specification) and the mission, success is also a function of communication, teamwork, and leadership [8]. Compared to the classical approach, Verma provided an entirely new approach to include perception and satisfaction into success factors. The roots of the idea go back ten years earlier. Several authors before Verma included perception as a new element in several ways (e.g., Baker, Murphy and Fisher in 1983 suggested taking into account the perception of project performance [9]).

Different stakeholders can, therefore, perceive success differently. Although the term stakeholder appeared in management literature as early as in the 1960s (e.g., Stanford Research Institute), almost twenty years passed before it was used in a sense used today. Freeman (1984) defined stakeholders as groups or individuals who are affected by and also affect the achievement of organizational goals [10]. The idea to examine stakeholders from the point of view of success appeared around the end of the 20th century [11]. Consistent with the principles of quality management, the "happy user" appeared among success factors.

Some papers of fundamental importance, however, have been published in this field in recent years. Originally a single stakeholder, the client was identified as a vital participant in addition to CSFs, and Jugdev and Müller (2005) investigated communication with the customer [12]. A step forward was when the owner and the sponsor were also identified as important stakeholders. Gradually it became clear for everyone how important the concept of perception is in the case of every stakeholder. Recently Davis (2013) added senior management, the project core team, and the project recipient stakeholder groups to the group of stakeholders relevant from the point of view of success [13]. Williams et al. (2016) evaluated project success in two areas: customer satisfaction and client relationship quality in project management [14]. This proves that the importance of perception also features prominently in up-to-date research.

The idea of perception has become common in the last decade and has appeared in many aspects in the fields related to project management. Marzagão and Carvalho (2016) included the perceived project performance as a critical success factor in their simplified Six Sigma model. They revealed independent latent variables, including project success perception. The research evinced that the Six Sigma Method (SSM) has an impact on project success perception [15]. Koops et al. (2016) identified four different perspectives on project success, each with their specific set of most and least essential success criteria with differences of opinion within the four groups. Also, the challenge revealed is to understand each other's point of view on the importance of the specific elements of product success: satisfies the needs of shareholders and stakeholders, fit for purpose, and specific political and social factors [16]. Fowler and Walsh (1999) realized the conflicting perceptions of success. The satisfaction was used as a measure of success, which raised the issue of the different perspectives of participants involved [17].

While doing a literature review, a clear trend is observed. The literature on the study of the effect of perception, in addition to the general presentation of the phenomenon, can be classified into two distinct, well-separable groups. A group of works examining the topic has raised the importance of perception in doing research on risk management. Wang et al. (2016) examined the influence of personality and risk propensity on risk perception along four proven hypotheses related to risk perception (personality vs. perception) [18]. Wu et al. (2019) assessed the perceptions of risks as well. They introduced the relative importance index analysis and examined the internal consistency analysis involving Cronbach's Alpha [19]. Gürcanli (2015) investigated risk perception with the likelihood and severity assessments of the participants. The paper claims that employee participation and the perception of safety risks could be valuable for determining and eliminating hazards. It evaluates the risk perception of construction equipment operators. [20]

Another well-distinguished group of articles focusing on stakeholders introduced the phenomenon of perception. Davis has addressed the relationship between stakeholders and perception in several publications (e.g., [21]). Davis demonstrated that success depends on stakeholders and perception, and it changes over time. Also, a method to measure success dimensions relating to individual stakeholder groups was developed. Success is related to the multiple stakeholders, and to project structure. New success dimensions are linked directly to the perception of project success. Stakeholder perception influences the perceived project outcome as a success, and others demonstrated that the time point used to analyze success could change the outcome to perceived failure. Three stakeholder groups identified were investigated to evaluate why perceptions of success dimensions differ. McLeod et al. (2012) investigate how project outcomes are subjectively perceived in one IS case study project by senior management and the project core team [22]. A project can be perceived as successful by one stakeholder and a failure by another, but the stakeholder who evaluates it provides the final judgment. Turner and Zolin (2012) recognized that projects have various stakeholders and that perception can change over time, so the project manager needs to address this. Stakeholders have different perceptions of the success dimensions because they focus on factors related to the criteria they perceive as important [23]. Failure can be a result of different interpretations of the criteria and factors used for success by multiple stakeholder groups [24]. Failure is a result of different interpretations of the criteria and factors used for success by multiple stakeholder groups. There is no recorded theory to determine project success within the project management literature, which includes both the perspective of multiple stakeholder groups and the shared use of success dimensions for a given project. Studies were focusing on evaluating on how senior management, project core team and project recipient stakeholder groups perceive project success [25], [26]. Turner and Zolin (2012) proved that stakeholders could have different perceptions of success criteria because they will focus on factors related to the criteria they perceive as necessary [23]. There is no significant discrepancy between the perceptions of different stakeholders about the sustainable project risks [27]. Rafindadi (2014) concluded to the opposite of the hypothesis, which was that different stakeholders would prioritize risk sources differently, the findings suggest there is no significant discrepancy between the perceptions of different stakeholders about the sustainable project risks. A conclusion is that although different stakeholders might define goals and success on projects differently and they are engaged in different project life cycle phases, they all share the perception of the sources of highest risks within phases.

Maddaloni and Davis (2018) investigated the project manager's perception of the local communities' stakeholders in megaprojects [28]. It is on how the local communities' stakeholder is perceived, defined, and categorized by project managers. Zhao (2016) investigated stakeholder perceptions of risk in construction and found that there is a discordance of risk perceptions among critical stakeholders [29]. Ramos and Mota (2014) demonstrated that there are differences of opinions and perceptions among stakeholders as well [30]. The management of a project and its success are not directly related [31]. Poor communication among stakeholders, managers, and the project team causes a project serious problem. Bryde (2008) realized a positive correlation between project sponsor activities and perceived levels of project success (project outcomes) [32]. Goodenough et al. (2017) provided a review of stakeholder management performance attributes in construction projects and presented the diverse perspectives of what should be regarded as ‘construction project success’ exist. The diverse needs, interests, and objectives of stakeholders are expected to be fulfilled in the project to contribute to satisfaction [33]. Mei-Yung Leung et al. (2008) measured construction project participant satisfaction. There is a significantly positive relationship between commitment and satisfaction in construction project management, while a high level of conflict is stimulated in the goal-setting process amongst the participants [34].

Now it is evident, the topic of perception has emerged indeed in the project management literature. Approaching it from the risk management side, on the one hand, and from the stakeholders on the other hand. There is a lot to research, to analyze in terms of perception, with which we could implement a higher level of managing projects, and with which we would have a better understanding of project management processes.

4. Data analysis

To answer the research questions, we conducted a questionnaire survey, which was completed by a total of 114 responses, of which 111 can be used for research purposes. The main focus of the research is on projects where one of the participants feels that although the project may perform well on the basis of traditional project evaluation criteria (total project time, budget, and compliance), it seems to one or more project stakeholders that it is not successful.

The first question was, therefore, whether the project has a participant who perceives success differently from the others. Because we conducted a targeted survey in this regard, two answered ‘no’ to the question, and one respondent did not want to answer. Data collection lasted from early November 2019 to early March 2020. Current research is fundamentally exploratory, targeting an unidentifiable population. The sampling procedure was snowball sampling of nonprobability sampling, which is not statistically representative sampling, but given the topic of the research, a representative sampling method would not be appropriate. Descriptive statistical processing of the responses shows that we have managed to reach a relatively wide range, from small and medium-sized companies to large companies, and from small projects of 1-9 people to large projects employing more than 250 people. We believe that the sample is suitable for the analysis of the research question, and the study of the phenomenon of perceptual overwriting or dominance. Considering that we want to examine an issue that is not precisely defined, unknown or not interpreted in the same way even among professionals, we already placed great emphasis on the explanation and precise identification of concepts in each question when preparing the questionnaire, and we also asked whether the questions were understandable to the respondents or not. Based on the textual answers, it seems that the respondents understood the questions, they also know the phenomenon they want to explore. This is also supported by the item analysis of the responses to the assessment of the subjective success of the projects.

Based on the project literature, we identified ten actors, from the customer to the project members, through the project manager to the influencers, whose opinions were measured on a Likert scale ranging from 1 to 5 about the given project. The Cronbach’s alpha value for the answers to these questions is 0.91, which is above the generally accepted range of 0.7 to 0.85. This indicates that the responses are consistent; however, a value above 0.85 also indicates that there is a risk of redundancy. The evaluation of the 10 participants is not independent of each other; there may be a close relationship between the evaluations of two or more participants. We classified the project participants into groups according to their opinion.

These groups are expected to develop according to the roles they play in the project, whether it is an internal or an external stakeholder, customer or performing organization of the project, or even it has a financial interest in the success of the project, etc. In addition to the previous analyses, which were typically one-variable descriptive statistical characterization of the answers to each question, as well as the examination of the relationship between the qualification criteria with the chi-square test of independence, we plan to use multivariable exploratory statistical methods for further analyses. With this statistical analysis process, we can get an answer to the connections between the evaluations of the project participants, as well as to our basic hypothesis that the difference between the traditional project evaluation indicators and the subjective evaluation of the participants really exists and can be statistically justified. For this, we primarily use hierarchical multivariable regression analysis, factor analysis, and agglomerative clustering.

5. Conclusion

According to the traditional approach, the most important set of indicators for the project managers are the time-cost constraints with the goal achieved in the right quality. Researchers and experts try to find and answer the most critical questions relating to the success of projects. This paper gave a summary of how the traditional success approach evolved and how the researchers tried to extend the basic model. A research goal on the possible dominance and effects of the factors come round. In conclusion, the possible mathematical-statistical tools supporting the research goals were developed and presented. After the statistical analysis, we group the project participants based on their opinions about the project, and we compare the opinions of these hopefully independent and homogeneous groups with the traditional project evaluation aspects. In the case of successful group formation, and if the phenomenon of perceptual overwriting can be verified in a statistically justified way, we plan to create a model that can be used to judge which participants' opinions are decisive in assessing the success of a project, and which subjective opinion of the given participant is most influenced by the objective factors.

We hopefully can get closer to the area of research on the success that has not been explored so far. This article review enables a future analysis for understanding better the success of projects.

6. References

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Knowledge Management and BIM Technology in Construction Project Management

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Abstract

Knowledge systems and knowledge technologies are an important tool for resource efficiency in the management of construction projects. The exploitation of the knowledge systems is essential throughout the construction period, starting with designing and ending the building management. BIM technology represents another progressive technology in the management of construction projects. Last decades, it's a lot of information and assumption about the connection of BIM technology and knowledge-based technology in constriction project management. This research discusses the issue of knowledge management and uses BIM technology in constriction project management. The main aim of the research is to analyze the level of exploitation of BIM technology and knowledge-based technology in construction project management in selected countries in Europe.

Keywords: knowledge management, BIM technology, construction project management

1. Introduction

Progressive technologies push the possibilities of working in every industry. Architecture, engineering, and construction (AEC) is no exception. The importance of the implementation of information and communication technologies has probably never been more important than it is now [1]. On the one hand, it is the current situation that has also affected the construction sector. On the other hand, there is a long-term need to manage processes in construction projects and automate management activities [2]. Already in the last century, there has been an effort to automate some processes in the management of construction projects and thus achieve efficiency. Innovative technologies in the management of construction projects are often the impetus for starting automated processes, which has a positive impact on the efficiency of construction projects.

The present time places great emphasis on information. The information constitutes valuable assets of the company [3]. Based on timely and relevant information, it is also possible to achieve a high degree of success in the management of construction projects. The need for information is indisputable. This is stated by several researchers dealing in The Knowledge management field [4]. Effective tools for managing and working with information must be applied as far as possible at every stage of the construction project. Various information systems and decision support tools work with large amounts of data. After processing, they often have great potential for making the right decisions. This information is translated into the knowledge of managers, which leads to the right decisions. These decisions often affect the outcome and success of a construction project. When solving a successful solution of construction projects, it is necessary to use the human side for the needs, which is always at the input and finally the output of the process.

Knowledge technologies managed by the human factor are a potential tool that in many cases can define the outcome of construction projects. This means the need to find the right technologies and people who can achieve a synergistic effect [5]. This all leads to another goal, which is closely related to the use of knowledge technologies and BIM technologies, and that is the possibility of education [6]. The need for education in the field of knowledge technologies and BIM technologies is indisputable and several researchers are addressing this [6], [7].

2. Problem statement

Knowledge management and project management theory are important to participate in a project [8]. Despite this fact, the development and introduction of digital skills usually only answer to the current problem. There are only a few cases when it is supported by a long-term strategy [9]. Knowledge management (as well as KM) is now a usual concept in the architecture, engineering, construction (AEC) industry, and the effective management of project knowledge, it is acknowledged, is necessary for improved performance. KM deals with the organizational optimization of knowledge through the use of various technologies, tools, and processes to achieve set goals [10]. In the case of the AEC industry, these goals include improved efficiency and innovation in project delivery. KM is also seen as a means to prevent the 'reinvention-of-the-wheel' for every new project [11].

A reached of what knowledge is top to its effective management. E.g. knowledge is considered to be interchangeable with information, then the focus tends to be on the management of information systems as a proxy for knowledge management [12]. However, the various definitions of knowledge suggest that it is much more than information. According to some authors, knowledge can be defined as a dynamic human process of justifying personal belief toward the "truth" (i.e. a justified true belief). Knowledge has also been defined as 'know-why, know-how, or an intangible economic resource from which future revenues will be derived [13]. Attempts to distinguish between data, information, and knowledge have also geared towards the understanding of the latter [14]. However, it is necessary to view knowledge based on its final use and/or based on the context of its use. This underscores the fact that knowledge can be viewed as a component of a task performing system. That is a state of that system which warrants task completion, and the future repetition of this task. The lack of this component implies a failure when completing a task. If this lack is sustained over time, it means that this system ceases to exist. Knowledge is built from data, which is first processed into information (i.e. relevant associations and patterns). Information becomes knowledge when it enters the system and when it is validated (collectively or individually) as a valid, relevant, and useful piece of knowledge to implement in the system [15].

Due to the new threats and challenges faced by the construction industry today, construction enterprises have to accept challenges and new solutions in order to remain ahead of the competition. Knowledge has been identified to be a significant organizational resource, which if used effectively can provide a competitive advantage. A lot of emphasis is being put on how to identify, capture, and share knowledge in today's organizations. It has been argued over the years that due to the fragmented nature of the construction industry and ad-hoc nature of the construction projects, capture and reuse of valuable knowledge gathered during a construction project pose a challenge [16]. Last year there has been no structured approach to learning from construction projects once they are completed. Actually, the construction project management is adapting concepts of tacit and explicit knowledge management to improve the situation. Generally, top managers assume that professionals in companies already possess tacit knowledge and experience for specific types of projects. Such knowledge is extremely important to organizations because, once a project is completed, professionals tend to forget it and start something new. Therefore, knowledge multifield utilization is a key factor in productively executing a construction project [17].

Knowledge Management (KM) has become an important term in the construction industry. Knowledge management involves many activities like creating, securing, capturing, coordinating, combining, retrieving, and distributing knowledge. Most know-what, know-how, and experience exist only in the minds of individual participants during the construction phase of construction projects. The knowledge can be reused and shared among the engineers and experts involved who participate in projects in order to improve the construction process and reduce the time and cost of solving problems. Sharing and reusing knowledge depends on acquiring and preserving both tacit knowledge and explicit knowledge as the property of a corporation. Effectively using information and web technologies during the construction phase of a project enables knowledge to be captured and managed to the benefit of future projects [18]. Construction Project Management (CPM) has a strong tool trough knowledge technology and BIM tools. BIM technology is valuable in each stage of the construction project. In the context of knowledge management, it is a solution for construction project participants (investors, designers, contractors, and other participants). Knowledge technology gives some advantages for construction project management. It's the first step to the automation of processes and some activities. Connection of BIM technology and knowledge technology can be helpful in many routine activities and it's possible to manage all information. The problem statement is actually the rate of exploitation of these technologies in construction project management. The level of exploitation in other countries is not different. It depends on many factors, but specifics and many characteristics of the construction market and industry are very similar.

3. Methodology and research sample

3.1. Hypothesis and research aim

Construction Project Management is a difficult process and its success depends on many factors. Enterprise size is one of them. It's an assumption, that the exploitation level is different in each country. The subject of research were three countries in the middle of Europe. The main aim of the research is to analyse the level of exploitation of BIM technology and knowledge-based technology in construction project management in selected countries in Europe. The main hypothesis was set: The exploitation level in selected countries is not different. The research was done in Slovakia, Poland, and the Czech Republic. The research sample includes the main participants of construction projects, which means investors, designers, constructors, and sub-constructors. According to enterprise size, the research was done on the SMEs (small and medium-sized enterprises) and large companies. The research sample is detailed described in Tab. 1. and Tab. 2.

Table 1. Research Sample according to size of construction enterprises

An example of a column heading	SMEs	Large Companies
Slovakia	51	4
Poland	47	12
Czech Republic	58	7

Table 2. Research Sample according to Participants of Construction Projects

An example of a column heading	Investors	Designers	Contractors	Sub-Contractors
Slovakia	21	11	8	15
Poland	14	13	15	17
Czech Republic	13	21	18	13

3.2. Research steps, data collection and processing

After the determination of the final hypothesis and the established research problem and the goal of the research, the phase of data collection followed and last but not least the evaluation of data on the basis of selected statistical methods.

To confirm our hypotheses about mean ranks, the Mann-Whitney U test was used. It is nonparametric alternative to t-test and it does not assume any assumptions related to the distribution of scores [20]. This test is used to compare two sample means that come from the same population and used to test whether two sample means are equal or not. It gives the most accurate estimates of significance, especially when sample sizes are small.

Equation (1) for calculation of the Mann-Whitney U:

$$U = n_1 n_2 + \frac{n_2(n_2+1)}{2} - \sum_{i=n_1+1}^{n_2} R_i \quad (1)$$

where

U = Mann-Whitney U test

n_1 = sample size one

n_2 = sample size two

R_i = rank of the sample size

4. Results and discussion

Computation of this test was done in MATLAB. We have tested samples individually and also differences between each measurement (Slovakia, Poland, and the Czech Republic) were tested. These results were obtained:

Table 3. Results of Research Sample distribution

An example of a column heading	Slovakia	Poland	Czech Republic
Mean	2.876	3.125	2.987
Standard Deviation			
Number of respondents	55	59	65
Skewness	0.928	-0.023	0.972
Kurtosis	0.498	-1.097	0.765

According results, samples were not equal. In addition, mean of ranks were numerically compared so According to results, samples were not equal. Also, the mean of ranks was numerically compared so we could assume that really and results were different for each country's results.

Generally, the exploitation level of BIM and knowledge technology for each country divided according to participants od construction projects a Mann-Whitney ranking are described in Tab. 4.

Table 3. Results of MU test

An example of a column heading	Slovakia	Poland	Czech Republic
Impact rate	2.88	3.22	3.00
Number of Valid responses	0.928	-0.023	0.972
Code	1	2	3
p			0.1189

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Based on detailed results and testing, these results and considerations can be presented. The basic premise was the consideration that the construction market in Central Europe and thus also in the V4 countries are very interconnected and similar. The conditions in construction are similar. For example, the following facts can be considered as the most basic common features:

- The greatest construction boom is in capital cities and large cities, or its immediate surroundings;
- Infrastructure and road construction are largely under government control and planning;
- For the implementation of large projects, it is necessary to have experience and competitions are usually won by large companies, which represent a guarantee and ability to complete the project;
- SMEs make up 80% or more of enterprises;
- The standard of living of the population is approximately at the same level.

Of course, each construction industry has its specifics and small differences, which, however, do not represent a diametrically different situation with general characteristics. From this point of view as well, it was assumed that these countries have the same level of use of BIM and knowledge technologies. These results also indicate the results of the survey. However, in the exact measurement, several facts need to be pointed out. The results show that the assumption that individual countries have the same or similar degree of use of BIM technologies and knowledge technologies is correct. The results of the survey do point to this trend. The spacing of the difference was less than 0.3 which represents the minimum deviations.

On the other hand, the Mann-Whitney test did not confirm this at the level of alpha significance. P-value has reached 0.1189 and these results also point to the closeness of the statement that the results are similar, but the statistical test did not directly confirm this and therefore, from an exact point of view, the established hypothesis cannot be accepted. We can discuss why, although all indications point to similar use of technology, this has not been confirmed by tests. However, as already mentioned, these countries also have certain specifics for the market and the conditions of their country. This means that even though the legislation is similar, it is not the same. On the other hand, consumer psychology is also an important aspect. The requirements of investors are a little different in each country.

5. Conclusion

The issue of using BIM and knowledge technologies have recently become very popular and important. It is necessary to analyse and compare the degree of use of these technologies in individual countries. This research was aimed at comparing results in countries that have many similar features. This was the main assumption that the rate of use of these technologies will not be different. This means that their range will not be greater than 0.5 points and at the same time this will be confirmed by a statistical test. The results that point to this point to a trend. The initial assumption and reasoning were relatively correct. Respectively, the results point to the given trend. However, the exact statistical measurement did not unequivocally confirm this and therefore the established hypothesis cannot be accepted exactly. In terms of future research, it is important to obtain data for another V4 country and extend this research to Hungary and then compare it. It would also be interesting to make a comparison between different sizes of companies, where, for example, only large companies in individual countries would be compared with large ones in another country. These are interesting considerations and space to continue to address this topic.

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Learning Curve for Improved Productivity in the South African Construction Industry

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Abstract

The South African construction industry has battled with productivity for years despite being the key contributors to the economy of the country. This paper aims to remedy this problem by introducing the learning curve tool into the South African construction industry. The study sought to deduce the level of awareness of the learning curve and determine the benefits of adopting the learning curve tool in the South African construction industry. The Quantitative Methodology was adopted for this study and participation from construction professionals was obtained through a well-structured questionnaire. A total of 106 questionnaires were sent out and 62 were received back representing a response rate of 58.5%. The findings revealed that there is a moderate awareness of the learning curve tool in the South African construction industry. Additionally, the findings revealed that the workers would become familiar with their job and sharpen their skills which would result in a higher quality of construction work and the reduction of time taken to complete a task with reduced cost. The adoption of the learning curve tool in the South African construction industry offers a solution to a lasting problem of productivity in the industry. This study will enlighten construction professionals on the concept of the learning curve and the benefits of the learning curve.

Keywords: learning curve, productivity, South African construction industry (SACI), cost

1. Introduction

The South African construction industry (SACI) is a vast sector that contributes to the economy of the country, infrastructure and adequate housing [1]. This sector plays a monumental part in the development of the South African economy [2]. Declining labor productivity has been a major issue in the last decade and this has a serious adverse effect on the project's completion and cost [3]. The SACI has its own difficulties that are both internal and external which also impact labour productivity negatively thus the decision-makers in the industry still face the challenge of forecasting and improving productivity [4]. Lack of labour abilities and inexperience of employees lead to poor productivity therefore construction employees and employers need to work together to ensure that the workers become familiar with job processes, instruments and equipment and the working conditions of the construction site to achieve efficient productivity outcomes[3].The basic concept of the learning curve is that the more a particular task is repeated the less time it takes to complete it, furthermore, the learning curve is a practically proven increase in the volume of production based on the prior experience of the worker [5]. The learning curve has been applied over the years in different industries to help companies predict cost implications of the time spent while learning a skill and how it affects productivity and the caliber of outcomes [6]. Hence, this study seeks to the adoption of the learning curve tool into the SACI to improve productivity by investigating the circumstances under which the learning curve tool may be adopted into the SACI and the benefits that may be expected should the learning curve be adopted into the SACI.

2. The construction industry

The construction industry one of the biggest sectors in the world in which a building project includes beginning with nothing but an idea and establishing a continuous and durable facility that meets the demands of aesthetics, quality, security and function [7]. This is an industry that operates under the mandate to build and improve the infrastructure of the country thus the progress and success of this industry can be seen in the rate at which the country's projections of development are reached, specifically relating to the development of infrastructure in the country [8]. One of the prominent functions of the construction industry is that it plays a monumental role in the development of a country's asset base because the outputs of construction work are classified as capital or investment goods to the country [1] hence the SACI, much like the construction industries of other countries, has a crucial effect on the economy of the country [9]. The SACI is, by nature, a labor-intensive industry and as such it deploys a significant amount of manpower including semi-skilled and unskilled labor which will, inevitably, impact the level of productivity on construction sites [10]. The variety of labour within the SACI results in productivity being a continuous struggle that the construction industry faces throughout the sector as a whole [11]. This study seeks to expose the possibility of improvement in productivity in the SACI through the adoption of the learning curve.

3. Declining productivity

Productivity is the measure of the speed of execution of the job, in whatever field it may be and in building, the production is typically expressed in weight, length or quantity, and the input resource is generally in labor or man-hours costs [12]. Labour productivity is a useful starting point for productivity assessment as it is the single most significant manufacturing factor and represents how effectively labour is combined with other production factors, how many of these other inputs are accessible per employee, and how quickly technically embodied and disembodied change is taking place [13]. Thus labour productivity, by basic definition, is the quantity of goods and services a worker produces in a given amount of time and as such poor labour productivity greatly causes overruns of cost and time in construction projects thus any increase in labour productivity will therefore lead significantly to improving general productivity and improving general output in the industry in terms of quality, cost and time[14]. In many nations, declining labour productivity has been a major issue in the last decade [3] hence the relevance of a study of the learning curve in the construction industry as a declining productivity remedy.

4. The learning curve

The learning curve concept was first studied and used in the discipline of psychology by Hermann Ebbinghaus in 1885 and his purpose was to establish the form of the patterns of the people's ability to learn and retain information in his study of memory with the assistance of learning and forgetting curves [15]. Subsequently, T. P. Wright made the first mathematical expression of the learning curve in 1936 when he noted that in the aircraft industry the costs per unit are likely to lessen in a foreseeable way as the employees become more acquainted with the job [16]. Fogliatto & Anzanello [17] recorded that for production, a formula was deduced by Wright in 1936 to look into the reasons for a decline in the assembly cost of airplanes after repetitions of the task. The learning curve is a mechanism used in the process of projecting future performance in terms of work done by a person or a company and it further links the projected performance to repetitive efforts applied to a task [18]. Jarkas and Horner [19] added that all learning curve models, as many and as seemingly different as they may be, deduce the same fact that an increase in the number of outputs decreases each unit's production inputs such as time, cost and man-hours. Furthermore, a decrease in the time or cost necessary to accomplish a task is expected as an individual or a group repeatedly does the task, thus with increasing experience comes somewhat of expertise in the task, making it quicker to execute [5]. The learning curve is presented in a graph format that represents the relationship the effectiveness of the subject and the practice, with relation to productivity thus a concave graph may be expected which is an indication that improvement in productivity is as a result of repetitive work when the practice is plotted on the x-axis [20].

5. Circumstances under which the learning curve may be adopted

According to Malyusz & Varga [21], forecasting the cost and time it takes to complete repetitive tasks can be done by the adoption of the learning curve theory to the scheduling of activities on-site by using either the unit time method or the cumulative average method which are both effective in the measurement and calculation of activity time for repetitive works. Son, Lee & Lee [6] documented that the most commonly used model of the learning curve is also recorded to be the first one ever to be used in production and the source of all other models that followed – the Wright model because of its simplicity and accuracy, adding that this learning curve is widely applied in many industries and is not confined to just one. Furthermore, Lee et al [22] observed that the learning curve would be put to its best use in the construction industry because of the repetitive nature of the activities in the construction industry and its use would further improve construction productivity. The learning curve further plays an integral role in contractor claims and a proper examination of this theory should be observed in construction[20]. Wong, Cheung & Hardcastle [23] examined the adoption of the learning curve theory on the performance of construction contractors to predict productivity and eventually improve it. Brockmann & Brenziski [24] evaluated the adoption of the learning curve in bridge construction with focus on four specific large freeways in Bangkok, Thailand and in the eventual interpretation of the study the conclusion was made that learning curves may be used in the construction industry as a management tool and that through the activities of construction, firms may get to experience the learning curve effects that contribute to the savings in cost of construction projects. Yap & Shavarebi [25] explored the ideas of learning in construction to determine ways in which the delivery of construction contracts can be improved especially linked to cost overruns and schedule delays. This study further examines the benefits of adopting the learning curve into the SACI.

6. Benefits of adopting the learning curve in the construction industry

Applying the learning curve is most advantageous with planning a budget as the cost of producing the outputs can be calculated, offers the ability to forecast labor hours that may be needed for any kind of work and further plays a monumental role in the decision to distribute the resources of the company effectively [5]. According to Glock et al. [15], the application of the learning curve in industry work may yield benefits that include a more accurate establishment of labor standards, observation of realistic objectives and goals of production, prediction of working time for a task, and forecasting productivity in a specific job. The learning curve, when used effectively, may help to decrease the gross cost of operations associated with the business and the repetition encouraged by the learning curve theory further improves the quality of the services rendered and/or the quality of the outputs produced by those who repeatedly do the task to sharpen skills [5]. The following benefits were outlined in another study of the significance of the learning curve effect [26]:

- Workers become more familiar with the job
- Better team and plant synchronization
- Advanced task planning
- Improved engineering support
- Refined daily management and supervision
- Development of more effective techniques and strategies
- Development of more effective material supply systems
- Definite designs resulting in fewer changes and rework

Gong & Wang [5] further documented that the experience acquired from spending time applying the principles and technique of a task and the continuation of the process of learning enable the employee to improve in the skill until the time that was required to carry out a task is decreased thus causing a decline in the cost of operations that was initially in place hence in a case where a contractor recruits new staff, determining the candidate's ability to adapt to new work is critical to the appointment process because the candidate's prior experience in similar work leads to a greater chance that the new work will be learned quicker and easier and results in a reduction in training time and cost of training. In a construction site, the application of the learning curve results in the project manager surely having a cost-saving because there is a reduction in the labor force needed for work that has been repetitively done over time [21]. The planning of construction projects, monitoring of progress, improvement of productivity and more which lead to further cost savings and control during the administering of construction contracts are the rewards that can be expected as the learning curve theory is applied in the construction industry [27]. The reduction in cost that is attributed to the learning curve effect is a result of a repetitive work in which fewer labor-hours are necessary to produce a unit of work as the production of units continues to increase [16].

7. Methodology

7.1 Research area

The study was executed in the Eastern Cape Province, South Africa. This province was chosen because of its proximity to the researcher and as part of the nine provinces of South Africa with the same regulations and statutory bodies that govern the rest of the SACI then it meets the ideals of this study. It was also an accessible area for the researcher and did not pose distance problems for data collection. Figure 1 shows a map of the Eastern Cape Province.

Figure 1 Map of the Eastern Cape Province
Source: http://www.amsterdamcg.nl/map-cape-province-south-africa/

7.2. Research approach and design

The Quantitative Methodology was adopted for this study, using the descriptive statistical method to analyze the data received from the respondents. The targeted respondents comprised of construction professionals such as Project Managers, Quantity Surveyors, Engineers, Architects, Health & Safety Officers, Construction Managers and Contracts Managers who practice the respective professions in the South African construction industry. The random sampling approach was adopted and further, the simple random sampling method was utilized. The research area for this study was the Eastern Cape, South Africa. This was chosen for its easy access and familiarity with the researcher for ease in the collection of data. A structured questionnaire was adopted for data collection. The Likert Scale was used to determine the level of awareness and the degree of agreement of the respondents to the information entailed in the research questionnaire. A total of 106 questionnaires were sent out and 62 were received back representing a response rate of 58.5%.

7.3. Statistical package for social science

The MIS was computed electronically with the Statistical Package for the Social Sciences (SPSS) software Version 25 and the items were then further ranked by the researcher with the MIS computed and the Standard Deviation of each item in depreciating order respectively.

7.4. Point likert scale

The five-point Likert scale of the agreement was used to determine to what extent the respondents agreed or disagreed with the factors that influence productivity in the SACI, the circumstances under which the learning curve may best be adopted in the SACI and the benefits of adopting the learning curve tool in the SACI. The Likert Scale of the agreement includes the ranges: 1. = Strongly disagree (SD); 2. = Disagree (D); 3. = Neutral (N); 4. = Agree (A); 5. = Strongly agree (SA)

7.5. Computation of the mean item score (MIS)

The computation of the relative mean item score (MIS) was calculated from the total of all weighted responses and then relating it to the total responses. This was based on the principle that respondents' scores on all the selected criteria, considered together, are the empirically determined indices of relative importance. The index of MIS of a factor is the sum of the respondents' actual scores (on the 5-point scale) given by all the respondents as a proportion of the sum of all maximum possible scores on the 5-point scale that all the respondents could give to that criterion. A weighting was assigned to each response ranging from one to five for the responses of 'strongly disagree' to 'strongly agree' and the same was assigned to the other responses. This is expressed mathematically below. The mean item score (MIS) was calculated for each item as follows;

$$MIS = \frac{1n1 + 2n2 + 3n3 + 4n4 + 5n5}{\sum N} \tag{1}$$

Where;

n1 = Number of respondents for extremely unlikely or strongly disagree;

n2 = Number of respondents for unlikely or disagree;

n3 = Number of respondents for neutral;

n4 = Number of respondents for likely or agree;

n5 = Number of respondents for extremely likely or strongly agree;

N = Total number of respondents

After mathematical computations, the criteria are then ranked in descending order of their mean item score (from the highest to the lowest). A mean value of 3.50 or more was deemed to be significant to the study.

8. Findings

8.1. Findings – The circumstances under which the learning curve tool may best be adopted in the SACI

Table 1 reveals the responses of the respondents to the circumstances under which the learning curve tool may best be adopted in the SACI, calculated together using the MIS method and thus assigned a ranking of the concepts in descending order. The findings showed that out of the circumstances listed, when 'scheduling and planning for construction activities' ranked first, with a mean score of 4.10 and a standard deviation of 0.900; when 'erecting High-rise multiple story buildings' ranked second, with a mean score of 4.05 and a standard deviation of 1.015; when 'forecasting the cost of operations on-site' ranked third, with a mean score of 4.00 and a standard deviation of 0.789; when 'construction designs have repetitive measurements for different floors' ranked fourth, with a mean score of 3.98 and a standard deviation of 0.983; and when 'an unchanged construction crew works on foundations of identical measurements' ranked fifth, with a mean score of 3.97 and a standard deviation of 0.829, which comprised the top-ranked circumstances under which the learning curve tool may best be adopted in the SACI. Furthermore, the least ranked circumstances under which the learning curve tool may best be adopted in the SACI include: when 'there's an estimated period of one week between similar projects' which ranked twelve, with a mean score of 3.65 and a standard deviation of 0.960; when ‘mechanization is highly incorporated in the task’ which ranked thirteen, with a mean score of 3.60 and a standard deviation of 0.896; when ‘workers are aware of the learning curve theory’ which ranked fourteen, with a mean score of 3.58 and a standard deviation of 1.033; when ‘the work proceeds from harder to easier tasks’ which ranked fifteen, with a mean score of 3.48 and a standard deviation of 0.987; and when ‘there’s an estimated period of one month between similar projects’ which was least ranked sixteen, with a mean score of 3.45 and a standard deviation of 1.066.

Table 1: The circumstances under which the learning curve tool may best be adopted in the SACI

The learning curve tool is best adopted in the construction industry when…	**$\bar{x}$**	**σX**	**R**
…scheduling and planning for construction activities.	4,1	0,9	1
…erecting High-rise multiple story buildings.	4,05	1,015	2
…forecasting the cost of operations on site.	4	0,789	3
…construction designs have repetitive measurements on different floors.	3,98	0,983	4
…an unchanged construction crew works on foundations of identical measurements.	3,97	0,829	5
…the drawings and specifications are crucial to the execution of the task.	3,89	0,994	6
…the same project manager for different jobs with similar specifications.	3,84	0,961	7
…similar projects are constructed in the same geographical location.	3,81	1,006	8
…an unchanged construction crew works on identical structures of the same size.	3,77	0,965	9
…the working space is not overcrowded.	3,74	0,867	10
…the task is not a one-man job.	3,74	1,07	10
…the repetitive task is complex and difficult.	3,66	0,867	11
…there are no interruptions and delays in the work.	3,66	0,991	11
…there’s an estimated period of one week between similar projects.	3,65	0,96	12
…mechanization is highly incorporated in the task.	3,6	0,896	13
…workers are aware of the learning curve theory.	3,58	1,033	14
…the work proceeds from harder to easier tasks.	3,48	0,987	15
…there’s an estimated period of one month between similar projects.	3,45	1,066	16

($\bar{x}$ = MIS; σX = Standard deviation; R = Rank)

8.2. Findings - The benefits of adopting the learning curve tool

Table 2 reveals the responses of the respondents to the benefits of adopting the learning curve tool in the SACI, calculated together using the MIS method and thus assigned a ranking of the concepts in descending order. The findings revealed that ‘Development of more effective techniques and strategies’ ranked first, with a mean score of 4.24 and a standard deviation of 0.740; ‘Workers become more familiar with the job’ ranked second, with a mean score of 4.19 and a standard deviation of 0.827; ‘Sharpening the skills/craft of employees’ ranked third, with a mean score of 4.19 and a standard deviation of 0.865; ‘Higher quality construction work, structures and buildings’ and ‘Reduction of time taken to complete repetitive task’ both ranked fourth, with a mean score of 4.13 and a standard deviation of 0.839 respectively; and ‘Better team and plant synchronization’ ranked fifth, with a mean score of 4.13 and a standard deviation of 0.859. Moreover, the least ranked benefits of adopting the learning curve in the SACI included: ‘Reduction in training time and cost for new staff’ which ranked twelfth, with a mean score of 3.95 and a standard deviation of 0.798; ‘Cost saving due to decrease in no. of laborers' which ranked thirteenth, with a mean score of 3.94 and a standard deviation of 1.006; ‘Easier recruitment process for new staff, tenderers and subcontractors’ which ranked fourteenth, with a mean score of 3.87 and a standard deviation of 0.932; ‘Definite designs resulting in less changes and rework’ which ranked fifteenth, with a mean score of 3.84 and a standard deviation of 0.961; and ‘Improved engineering support’ which ranked the least as sixteenth, with a mean score of 3.69 and a standard deviation of 1.049.

Table 2: The benefits of adopting the learning curve tool in the SACI

Benefits of the Learning Curve Tool	x̅	σX	R
Development of more effective techniques and strategies.	4,24	0,74	1
Workers become more familiar with the job.	4,19	0,827	2
Sharpening the skills/craft of employees.	4,19	0,865	2
Higher quality construction work, structures and buildings.	4,13	0,839	3
Reduction of time taken to complete a repetitive task.	4,13	0,832	3
Better team and plant synchronization.	4,13	0,859	3
More accurate scheduling for construction activities.	4,1	0,824	4
Advanced task planning.	4,08	0,836	5
Better monitoring of progress.	4,06	0,866	6
Refined daily management and supervision.	4,06	0,862	6
Less number of laborers required for repetitive tasks.	4,03	0,809	7
More accurate estimates for the construction budget (monetary and labor hours).	4,03	0,829	7
Development of more effective material supply systems.	4,02	0,896	8
Reduction in training time and cost for new staff.	3,95	0,798	9
Cost-saving due to a decrease in no. of laborers.	3,94	1,006	10
The easier recruitment process for new staff, tenderers and subcontractors.	3,87	0,932	11
Definite designs resulting in fewer changes and rework.	3,84	0,961	12
Improved engineering support.	3,69	1,049	13

(x̅ = MIS; σX = Standard deviation; R = Rank)

9. Conclusion

The reviewed literature revealed that there is a vast well of knowledge that has been discovered about the learning curve tool ever since the investigation into the concept commenced. That knowledge has not yet spread into the SACI thus rendering the industry at a loss of the benefits that could be utilized in it from the learning curve tool. The practices of the SACI are recognized to be conducive to the adoption of the learning curve tool to improve productivity. Though there are measures in place that are designed to help improve productivity in the SACI, here is a tool that has been examined for its productivity-improving benefits and aligned to the activities and operations in the SACI with the sampled construction professionals supporting the ideas around it. The study results showed that when scheduling and planning for construction activities, when erecting high-rise multiple story buildings, when forecasting the cost of operations on site, when construction designs have repetitive measurements on different floors and when an unchanged construction crew works on foundations of identical measurements were considered the most viable conditions under which the learning curve could be adopted into the South African construction industry while the most esteemed benefits of adopting the learning curve tool, as revealed in this study, were the development of more effective techniques and strategies, workers become more familiar with the job, sharpening the skills/craft of employees, higher quality construction work, structures and buildings and reduction of time taken to complete a repetitive task. In agreement with the data collected, it is safe to conclude that the study has enlightened the construction professionals who participated in the study of the learning curve tool and may successfully be adopted into the SACI for the improvement of productivity. The study has met all its objectives and answered all the research questions that were set out for this investigation.

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Real Estate MSc Curriculum in the New Era of Artificial Intelligence

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Abstract

In Real Estate industry a new era is approaching: Artificial Intelligence (AI) will re-design the map of the whole industry. As the real estate agency processes were moved to electronic platforms, and AI has significant role in brokerage and valuation, other Real Estate disciplines also will change dramatically, as Facility Management, Real Estate Development, Project Management and other related subjects. In this new upcoming era the academic education should accommodate the new approach and the AI-driven processes. In the paper, the Author overview those up-to-date changes and suggest a comprehensive curriculum for a Real Estate master-course which incorporates necessary skills and knowledge for the new generation of Real Estate professionals.

Keywords: real estate, education, artificial Intelligence

Introduction

Artificial Intelligence (AI) will transform the property business in the near future. Recently, this statement has been formulated by numerous people (see the current article of the Forbes magazine [1], the report of the Oxford Future of Real Estate Initiative [2] or the relatively older publication [3]); however, the expected impact of the COVID-19 pandemic will undoubtedly further accelerate this process. For that matter, some changes are well underway: residential property agencies have already shifted to electronic platforms and retail sales are increasingly supported — and in fact, replaced — by statistical hedonic models. In the field of facility management, however, smart buildings with intelligent building control at their heart are already commonplace. In the construction industry, increasingly more efforts are being invested in artificial process optimisation and robotics. These changes and others are transforming the real estate industry almost from one day to the next. Higher education must teach these changes to future professionals; moreover, prepare them, the new generation, for controlling such changes and overcoming new challenges. This paper attempts to introduce new paradigms in the context of the standard framework of real estate education.

Its first chapter reviews the literature on real estate education and analyzes the curricula of leading real estate courses. The second chapter details the AI-dominated market changes mentioned in the introduction. Finally, the author uses the last chapter to recommend modifications to the traditional framework curriculum.

2. Review of the relevant literature

The modernisation of education in general, including university education, the introduction of new technologies and the establishment of opportunities for self-study training and mastering varied skills [4] have been objectives for a long time. Although the education technology and methodology have been widely available, all over the world, university-level real estate education has only partly followed these general objectives. The scope of university-level real-estate education is defined by three fundamental schools: the “surveying” approach of the United Kingdom and the Commonwealth countries, the “investment and financing” approach of the USA and finally, the European school, which approaches the discipline of real estate in an interdisciplinary context [5]. Real estate education must adhere to the international trend of globalisation of the real property market, meaning that the methods, procedures, and process participants are the same on said market [6]. The education trends have a notable, decade-long past, just as the programmes of educational institutes. These programmes are quite inert as they were incapable of renewal even after the major real estate crisis of 2008 [7,8,9]. Another issue is that the educational institutes fail to adjust the learning content to industry requirements and a single common corpus, rather choosing to develop it on the available knowledge of teachers [10]. Although the courses have set the goal of meeting industry requirements and training competent professionals, employer feedback shows that this goal is only partly achieved [11]. According to the survey of the courses accredited by the RICS (Royal Institution of Chartered Surveyors), employers expectations focus on knowledge in the following 5 fields:

- Property valuation,
- Property law,
- Landlord and tenant law,
- Internship and ethics,
- Client management.

Although employers do not necessarily look to the future when defining required knowledge, a 2013 survey showed that IT skills were regarded as least necessary among the content taught to real estate professionals [12].

In their 2004 article [10], Galluppo and Worzolla specify the common learning content of real estate higher education (MSc programmes) based on a widespread survey. They divide this learning content into the following three groups.

- Basic courses: Housing financing and housing policies; Real estate law; Ethics and public politics; Commercial real estate financing and investments; Urban and rural real estate development; Real estate valuation.
- Special courses: Urban land economics; Commercial real estate markets; Strategic real estate asset management.
- Cornerstone courses: Negotiation and ethics in the real estate industry; Feasibility study.

Inviting industry speakers, discussing case studies, on-site and company presentations are integral parts of educational programmes [13]. Course content is, of course, also greatly determined by the regulatory environments of countries as well as the authorisation standards of the property industry [14].

Currently, no aggregate data is publicly available on the number of open real estate higher education courses; given that the current RICS list of accredited courses has 394 items[3], however, the number of courses could be over 1,000 globally. We have checked the content of some outstanding courses (based on the ranking of the “best-masters” website[4]) to measure the extent of the paradigm shift related to artificial intelligence. Only one of the top 10 real estate higher education courses with publicly accessible programmes had a relevant course unit: “Real Estate Technology and Innovation”, an elective course unit, of the Cornell Baker Program in Real Estate[5].

We have also reviewed the offer of European higher education programmes in 2020 based on the list of “KEYSTONE Academic Solutions”[6], which lists a total of 50 courses in English language, including MSc, MBA,

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[3] http://www.ricscourses.org/Course/#Level=Postgraduate/, accessed on 09.04.2020
[4] https://www.best-masters.com/ranking-master-real-estate-management-construction.html, accessed on 09.04.2020.
[5] https://baker.realestate.cornell.edu/programs/concentrations/
[6] https://www.masterstudies.com/Real-Estate/

and MA courses. Among the fifty courses, we have found only one, at the ESCP Business School[7], in which "Real Estate Technology and Innovation" is a complete unit (including modules on Proptech, BigData, SmartCities and real estate software development). The other 49 courses do not include AI or any of its aspects in its programme at all.

The analysis of available courses outlined above also demonstrates that leading real estate courses in higher education still barely touch upon the relationship between AI and the real estate industry.

3. Fields that will be driven by Artificial Intelligence

As mentioned in the Introduction, AI is already present in many fields of the real estate industry. The following non-exhaustive list looks at the key fields in which artificial intelligence is already part of everyday business. We relied on the RICS "The World Built Environment Forum" online professional forum in identifying the topics (available at: https://www.rics.org/ssa/wbef/).

Property valuation The most highly-regulated and well-defined real estate discipline. The spread of so-called non-traditional methods has been characteristic of the development of property valuation in the past decade. These methods include hedonic valuation, the use of nervous system networks, contingent valuation or the introduction of fuzzy logic in appraisal [15]. The methodologies, which are often collectively referred to as "mass appraisal", are based on the systematic and automatic analysis of large databases, supported with self-learning models.

Real estate brokerage The residential real estate market is the field that shows the most spectacular breakthrough of AI. This segment of the real estate market has essentially moved to the virtual reality, and the different sites increasingly replace the job of real estate agents by organising, filtering, and presenting the supply in various ways. With the help of artificial intelligence, real estate sites can also provide counselling: they prioritise buyer criteria as required, analyse the relation between an individual offer and the market and give advice on the purchase price based on the varied methods of mass appraisal. The pioneer in this field was the ZILLOW company [16], but a growing number of local sites are also catching up with this trend.

Building operation New commercial buildings are designed almost exclusively with BIM models. BIM is a three-dimensional design tool; during operation, however, the building changes with time—in terms of layouts as well as individual built-in elements. Some authors refer to this change in time as the fourth dimension of BIM, while the "5th dimension" includes operational parameters (e.g. maintenance data or financial aspects) [17]. Building operation systems based on such models, known as CAFM systems, use enormous datasets as well as integrated "smart technologies" and the input data of automated building management systems (BMS). This enormous and continuously changing database underlies the operation-optimisation of intelligent subsystems such as the energy management function or the smart parking-lot allocation function. Smart buildings — which are not futuristic anymore and automatically ensure an optimum balance between sustainability parameters and user needs — are the next step in this process.

Urbanism "Smart cities" with their autonomous, intelligent, and closely connected systems such as sustainability, public utilities networks, public transport, energy management, and community communication are just a step away from smart buildings. Although there is no single definition for "smart cities" [18] and the entire theoretical concept still does not function in practice, there are some examples and subsystems that show the unavoidable development trend (see, for example, the results of Aspern, an experimental neighbourhood in Austria[8]).

In a broader sense, the real estate business (or real estate industry) also includes the construction industry. Although lagging considerably behind other industries, the appearance of robots at construction sites and in building operations is only a matter of time. Moreover, intelligent decision-support systems, including

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[7] https://www.escpeurope.eu/programmes/specialised-masters-MScs/MSc-in-real-estate?utm_source=keystone%20masterstudies &utm_campaign=Megapriority
[8] https://www.aspern-seestadt.at/en/business_hub/innovation__quality/urban_lab

construction process-optimisation solutions and self-learning project management algorithms are already unavoidable in the construction industry. This transformation of the construction industry is one of the main topics of the Creative Construction Conference series and the keynote speech of Prof. Wen-der Yu at the 2019 conference provides an up-to-date summary of this process [19].

In our opinion, AI will shortly appear in further fields of the real estate business and the real estate industry. Architectural design is one of them. Human creativity is still indispensable in this field; a host of design subtasks — area allocation optimisation according to the function mix or the preparation of detail drawings, product designs — could, however be algorithmised and automated. Layout design is, for example, a process that works with a lot of variables and conditions at the same time. Why not code these variables and rules and use existing examples to teach artificial intelligence to optimally consider usage and cost parameters?

We've seen that AI is already reshaping the everyday work of real-estate valuators and agencies. The artificial transformation of the real estate market, pricing and timing purchases and sales are just a step away from this. Stock exchange software applications are used on stock markets and real estate investment funds (REITs) are already traded automatically. In itself, this is a market-shaping factor that could be followed by the automated sale and purchase of individual real estates, based on broker firms' databases.

Optimising real estate use is another opportunity for AI. The shared economy has long reached the real estate business, as demonstrated by AirBnB and similar short-term rental services as well as coworking spaces. Apartments and offices, however, are not the only spaces available for short-term use, but partial functions as well. For example, mortgage loan repayment can also be divided between the owner and the lodger. Another example is letting garages in detached houses for temporary or medium-term storage purposes; moreover, some restaurants also rely on private households to extend their kitchen capacities. This also includes the shared economy related to mobility; scooters, bicycles and cars that can be rented even for a couple of minutes have become a part of our everyday lives. The spread of these vehicles will fundamentally affect not only urban transport but also the use of parking places in buildings.

The rapid transformation of the retail sector is also remarkable. 22% of household purchases have shifted from the streets and malls to e-marketplaces[9], and this shift is accelerating all over the world. E-commerce in retail transforms not only the background real estate portfolio (logistics centres instead of shop floors, showrooms instead of supermarkets and department stores, etc.) but also the AI systems behind sales by integrating user parameters into the real estate utilisation process.

We mustn't fail to mention the dire and direct consequences of the protective measures against the Covid-19 pandemic. Working from home is now a reality in the broadest sense all over the world; in most cases, remote employees are only connected by electronics and logistics (home deliveries and courier services). This experience is expected to transform, expand or end entire industries.

Naturally, AI is based on continuously expanding electronic databases as well as data and metadata that are available on the world wide web. The above-listed fields of the real estate industry are typical examples of applying BIG DATA. In fields with existing or possible large databases, the growing mathematical and increasingly available calculation toolset of data analysis will transform previous practices in a matter of minutes.

It is indisputable that the emergence of AI in the real estate industry will transform professional rules and activities; this, however, is only possible with a redesigned knowledge base. Therefore, our opinion is that the content of real estate education must be renewed.

[9] https://www.shopify.com/enterprise/the-future-of-ecommerce

4. Proposal for a new framework for real estate education

Azuso and Gibler attempted to renew the framework of real estate education with the CIDO method in 2015 [20]. We feel that the above-detailed major changes in the real estate business require that training contents be rebuilt from scratch. The following is an attempt to do so.

We propose two fundamental methods for organising the relevant knowledge. The first method is the real estate life cycle, an organising principle of all real estate-related activities. Main cycle elements include analysis, planning, execution, marketing and operation (the last two can be listed concurrently as well). The other classification method is according to related disciplines. The real estate discipline is commonly considered a combination of engineering, economic, and legal disciplines; management disciplines must, however, undoubtedly be added to this trio [21]. This review has also clarified that IT is another relevant discipline; the original trio is, therefore, to be transformed into a quintet. The matrix of Figure 1 below shows the combination of the two organising principles.

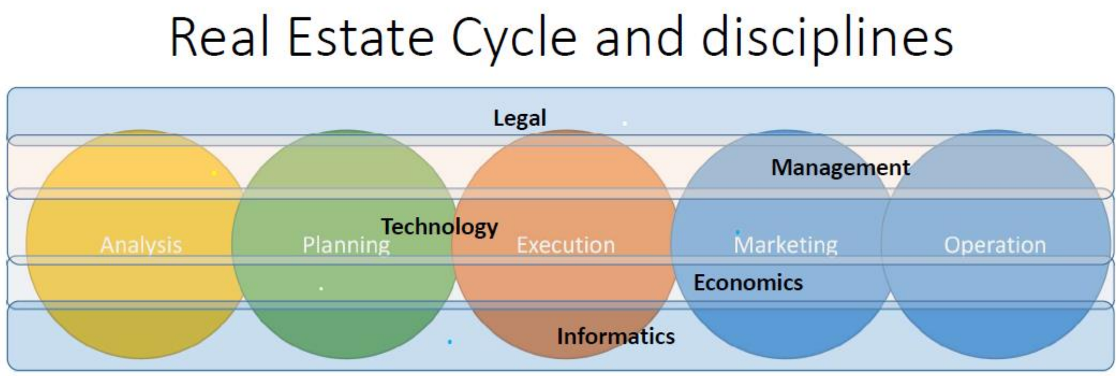

Figure 1: A combined matrix of the real estate market cycle and related disciplines

The main courses could be based on this system. Based on the 5-by-5 table, we propose the following 25 courses and topics as main knowledge units for higher education courses in real estate. (Table 1).

Table 1: Proposed education topics

		RE Cycle process				
		Analysis	Planning	Execution	Marketing	Operation
Discipline	Legal	RE Law	Building Law	Civil Law	Economic Law	Urbanism
	Management	Negotiation	Human Resource Management	Project Management	RE Marketing	Organisational Behavior
	Technology	Valuation	Development	Building technologies and structures	Building Diagnostics	Energetics
	Economics	RE Market	Finance	Controlling	Business Economics	Accounting
	Informatics	Statistics	BIM	Low voltage systems & BIS	BIG DATA	AI

Courses could be scheduled either according to the real estate cycle or deviating from it; the conceptual structure of Figure 1 should, however, be explained to the students when introducing each module. The topics summarised in Table 1 are based on one another and are related both horizontally and vertically. We also wish to note that urbanism, which is another related discipline, could have been included in any of the rows or columns of the table; it is, therefore, highlighted with a different background colour. Obviously, it is not possible to present, teach and assess the understanding of the entire knowledge base of each and every related discipline in a real estate course, yet this is not the goal. Moreover, the topics of Table 1 do not necessarily have an identical weight or credit scores.

The present study only focuses on a handful of knowledge units that are significant in terms of our topic, AI. As for the legal aspects, we must note that the new virtual world now taking shape raises a host of legal issues (personality rights, prompt contracts, intellectual property rights) that real estate lawyers are not prepared for. The knowledge of this field is also continuously taking shape and expanding. In management, the development of human resources and enhancing creative energies are becoming increasingly important. The traditional real estate market approach rather prefers regulated processes and hierarchy; however, in the age of AI, when background processes are performed by computers, educational courses must prepare students for creative management as well as giving them thorough insights into the background processes and intermediary organisations. The technical knowledge base is infinite—just like that of the other disciplines. For real estate market players, the most important new requirement is sustainability, which appears in and interlaces all activities; therefore, it does not require a separate block. At the same time, building energy plays a special role in sustainable operations; a separate course should, therefore, deal with this field, despite the fact that it was previously neglected in real estate courses. Understanding financial and controlling processes and the ability to make creative decisions based on the information provided by artificial intelligence are more important for students than ever before. Teaching mathematical statistics in the IT block is also to ensure that students understand the functions, capabilities and limits of the "machine". As shown above, BIM and the various building model dimensions appear in the entire real estate lifecycle and future real estate professionals should be able to interpret and manage these models. The weak current network is the "nervous system" and the building management system (BMS) is the "brain" of our buildings. Professionals should understand these complex systems just as traditional building structures. The storage and organising of large datasets (BIG DATA) and obtaining meaningful and efficient information from data are further knowledge and skills that take real estate professionals closer to understanding and perhaps coding AI. We must know how artificial intelligence can best serve human and, more specifically, real estate needs, when set free.

5. Summary

The changing and reshaping real estate industry requires new skills and knowledge. Previous course literature and current practices have not yet adapted to these new requirements. The learning content that has been developed over decades and which is now the backbone of professional knowledge cannot and should not be discarded. It should be further developed and extended to prepare real estate market players for the direct challenges of co-existing with artificial intelligence.

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The Integration of Newly Graduated Construction Managers into the South African Construction Industry

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Abstract

Anecdotal evidence indicates that newly graduated Construction Managers experience difficulty in terms of integrating into the construction industry.

Construction Managers (CMs) and Construction Project Managers (CPMs) registered with the South African Council for the Project and Construction Management Professions (SACPCMP) were surveyed by means of an online survey to determine the status quo with respect to newly graduated construction managers.

In terms of findings, graduates were rated: average to good / good in terms of overall performance, however, marginally so; marginally below average in terms of their performance relative to the functions of management work; highest relative to computer literacy, numeracy, and trust and honesty in terms of attributes / skills during probation; highest relative to computer literacy, numeracy, and written communication after probation; highest relative to construction technology, construction science, and research methodology in terms of knowledge areas, and highest relative to personal integrity in terms of ten core competencies.

Conclusions include: graduates are employable; challenges exist in terms of newly graduated Construction Managers, and tertiary built environment education must enhance graduates' attributes, knowledge, skills, core competencies, and emotional intelligence (EI).

Recommendations include: tertiary institutions should ensure that graduates are well versed and developed during their four-year study period; emphasis should be placed on developing core competencies and EI; employers should subject graduates to graduate training programmes; the interface between industry and tertiary education should be optimised through forums, and students should undertake construction-related vacation work and generic part-time work.

Keywords: construction management, graduates, integration, performance

1. Introduction

In any country, education and skills levels are contributory to economic growth because highly skilled individuals such as entrepreneurs create jobs and adequately skilled people can be absorbed into employment when jobs are generated [1].

The concern emerges from the stature of young people completing high school, and continues with a vulnerable tertiary education and training system, which manifests itself in the low figures of knowledgeable people emerging from either the formal education system, or from skills development programmes, and finally in the non-alignment of the skills of those qualifying and the skills needs of employers [1].

The nature of the construction industry in South Africa, combined with the uncertainty of worldwide competitiveness and evolving regulatory necessities, has developed the need for well taught and trained construction management graduates who can excel [2]. Similarly, firms are consistently challenged to appoint people who will increase the value of their businesses and contribute to organisational success [3]. This challenge is amplified in South Africa where there is an increasing shortage of skilled people [3]. An implication of this reality is that it is no longer sufficient for graduates to merely possess a degree or good grades, as it is imperative that they possess a range of aptitudes that promote employability, and integrate into new methods of production [4].

According to Jonck [5], research indicates that there was no measurable relationship between skills advancement in higher education institutions and the expanded likelihood of employment. This observation serves as one of the reasons why graduate employability has surfaced as a profoundly topical and challenging topic because employers are of the sentiment that construction management graduates are not appropriately groomed for the world of work. Therefore, it has become imperative that built environment-related academia deliver qualitative education that develops the requisite skills necessary for graduates to respond to the needs of their employers [2].

Given the aforementioned, a study was conducted to determine the status quo with respect to newly graduated construction managers in terms of their:

- attributes, skills, core competencies, and emotional intelligence at various stages, and
- performance relative to knowledge areas and the functions of management work.

2. Review of the literature

2.1. Attributes and skills

Love, Haynes & Irani [2] state that intelligence, flexibility, adaptiveness, and the ability to deal with uncertainty and rapid change are the essential personal attributes sought by potential employers.

Ogunsanmi [6] categorises the essential skill requirements for Construction Managers as: personal; managerial; industry and business; professional; technical; legal and contractual, and people. Furthermore, Ogunsanmi [6] states that it is imperative that construction managers possess the required skills that will enable them to function efficiently and profitably in high pressure situations. However, Love et al. [2] contend that construction management graduates are often unjustifiably criticised by their employers due to the fact that they are new to the workforce and subsequently have constrained, if any, viable experience. Therefore, it is imperative that construction management programmes produce graduates who have the fundamental skills and abilities to satisfy the needs of their function, and are able to work and cooperate and collaborate in an agreeable way.

2.2. Core competencies

A core competence is an organisational capability to perform some aspect of a production function in a manner consistently superior to its competition that in turn leads to above-average organisational performance [7]. According to Clardy [7], core competencies lead to persistent superior performance in several ways as they generate more efficient and effective performance that allow firms to adapt better changing conditions by providing a platform for continuous innovation in products and services.

Sanghi [8] and Vazirani [9] suggest that competencies are divided into two categories: the surface, which are required to be at least effective, and core, which distinguishes superior performance from average performance. The surface competencies are:

- Knowledge: information regarding content, and
- Skills: ability to perform a task.

The core competencies are:

- Self-concept: values, aptitude, attitude, and self-image;
- Traits: self-confidence, team player, and handles ambiguity, and
- Motives: focus on client success, and preserves organisation / personal integrity.

2.3. Emotional intelligence

Songer & Walker [10] describe Emotional Intelligence (EI) as an "individual's ability to identify emotions in oneself and others and to exhibit appropriate responses to environmental stimuli." Complex projects place additional emphasis on project managers' (PMs) needs for EI, because of the unique characteristics such as complexity of personnel, multiplicity of goals, strong uncertainty of activities, and difficulty in coordinating stakeholders, which means there is a 'strong positive correlation between PMs' EI and project performance [11].

2.4. Functions and activities of management work

Allen identifies two classes of work – mechanical and human. He then subdivides the class of human work into the orders of management work and technical work, and then subdivides the order of management work into functions – planning, organising, leading, and controlling, and suggests a fifth in the form of coordination [12]. The functions of management work are then subdivided into activities - Planning: forecasting; developing objectives; programming; scheduling; budgeting; developing procedures, and developing policies; Organising: developing organization structure; delegating, and developing relationships; Leading: decision making; communicating; motivating; selecting people, and developing people, and Controlling: developing performance standards; measuring performance; evaluating performance, and correcting performance.

3. Review of the literature

3.1. Research method and sample stratum

The study adopted a quantitative approach and the sample strata included Professional Construction Project Managers (Pr. CPMs), Professional Construction Managers (Pr. CMs), Candidate Construction Project Managers (Can. CPMs), and Candidate Construction Managers (Can. CMs) registered with the South African Council for the Project and Construction Management Professions (SACPCMP).

The questionnaire consisted of twenty-four questions, six of which were demographic, seventeen were closed-ended, of which fifteen were five-point Likert scale type questions, and a further open-ended question. Given that it was a web-based questionnaire survey, the link to the questionnaire and the cover letter, which explained the purpose of the study and instructions regarding how the questionnaire should be completed, were e-mailed to the sample stratum.

Forty-seven responses were received and included in the analysis of the data. The analysis of the data entailed the computation of descriptive statistics in the form of frequencies and a measure of central tendency in the form of a mean score (MS).

3.2. Research findings

8.5% of the respondents were Pr. CPMs, 19.1% were Pr. CMs, 17.0% were Can. CPMs, and 34% were Can. CMs. 70.2% are employed in the public sector, and 29.8% are employed in the private sector. 12.8% were females, and 87.2% were male. The youngest respondent was 24 years of age and the oldest was 73 years of age. The mean age was 41.7 years. 53.2% of respondents were 40 years of age or younger, and 46.8% were older than 40 years of age. Per definition relative to workers, people > 40 years of age are 'older workers'.

In terms of qualifications, 38.3% of the respondents have a Bachelors degree, 23.4% have a National Diploma, 14.9% have a Honours degree, 8.5% a Masters degree, 8.5% a Grade 12 Certificate, and 6.4% have other qualifications.

61.7% of respondents are mentoring, and 38.3% are not.

Respondents were required to rate the overall performance of graduates on a scale of 1 (very poor) to 5 (excellent). The resultant MS of 3.47 falls within the range of > 3.40 to ≤ 4.20, which indicates that the respondents rate the overall performance of CM graduates as average to good / good.

Table 1 indicates the respondents' rating of graduates' skills prior to employment in terms of percentage responses to a scale of 1 (very poor) to 5 (excellent), and MSs ranging between 1.00 to 5.00. It is notable that all the MSs > 3.00, which indicates the respondents rate graduates' skills above average as opposed to below average as in the case of a MS ≤ 3.00.

Only 1 / 4 (25.0%) MSs is > 3.40 ≤ 4.20, which indicates the respondents rate graduates average to good / good relative to first ranked academic achievement.

The three (75.0%) MSs of written communication, oral communication, and interpersonal skills are > 2.60 to ≤ 3.40, which indicates the respondents rate the graduates' poor to average / average relative thereto.

Table 1. Respondents' rating of graduates' skills prior to employment.

Skill	Response (%)						MS	Rank
	Un-sure	Very poor……………………..Excellent						
		1	2	3	4	5		
Academic achievement	0.0	4.3	4.3	27.7	46.8	17.0	3.68	1
Written communication	0.0	2.1	19.1	38.3	25.5	14.9	3.32	2
Oral communication	0.0	2.1	19.1	40.4	27.7	10.6	3.26	3
Interpersonal	0.0	2.1	8.5	63.8	21.3	4.3	3.17	4

Table 2 presents a comparison of respondents' rating of graduates' attributes / skills during and after their probationary period in terms of MSs based upon percentage responses to a scale of 1 (very poor) to 5 (excellent), after-MSs expressed as a multiplier of the before-MSs, and the percentage after-MSs are greater than before-MSs. The attributes / skills are courtesy of Love et al. [2].

It is notable that 14 / 17 (82.4%) during-MSs as opposed to all (100.0%) after-MSs are > 3.00, which indicates the respondents rate the graduates' attributes / skills above average as opposed to below average, as in the case of 3 / 17 (17.6%) during-MSs and no (0.0%) MS, which are less than ≤ 3.00.

It is notable that whereas only 3 / 17 (17.6%) during-MSs are > 3.40 ≤ 4.20, which indicates the respondents rate graduates average to good / good, 16 / 17 (94.1%) after-MSs are.

Then, whereas 14 / 17 (82.4%) during-MSs are > 2.60 to ≤ 3.40, which indicates the respondents rate the graduates' poor to average / average, only 1 / 17 (5.9%) after-MS is.

In terms of the difference between the after and during MSs, it is notable that all after-MSs are higher than during-MSs. The greatest difference is relative to leadership capability (34.2%), followed by practical building knowledge, adaptable to changing environment, environmental awareness, and problem solving. The least difference is relative to computer literacy (2.4%), followed by trust and honesty, and numeracy.

Table 2. Comparison of respondents' rating of graduates' attributes / skills during and after their probationary period.

Attribute / Skill	During		After		After/ Dur	% After > Dur
	MS	Rank	MS	Rank		
Computer literacy	3.89	1	3.96	1	102.4	2.4
Numeracy	3.60	2	3.85	2	109.6	9.6
Written communication	3.40	4	3.77	3	115.4	15.4
Teamwork	3.26	6	3.70	4	119.5	19.5
Update professional knowledge	3.36	5	3.68	5	113.6	13.6
Trust and honesty	3.51	3	3.66	6	106.0	6.0
Oral communication	3.17	7	3.60	7	119.8	19.8

Interpersonal	3.17	8	3.60	8	119.8	19.8
Adaptable to changing environment	3.13	10	3.60	9	122.1	22.1
Environmental awareness	3.06	13	3.51	10	121.8	21.8
Leadership capability	2.87	16	3.51	11	134.2	34.2
Accept responsibility	3.17	9	3.47	12	113.8	13.8
Work autonomously	3.09	12	3.46	13	117.7	17.7
Exercise professional judgement	3.09	11	3.45	14	117.2	17.2
Practical building knowledge	2.83	17	3.43	15	132.8	32.8
Time management	3.06	14	3.43	16	118.0	18.0
Problem solving	2.98	15	3.38	17	120.2	20.2

Table 4 indicates the respondents' rating of graduate's attributes / states prior to employment in terms of percentage responses to a scale of 1 (very poor) to 5 (excellent), and MSs ranging between 1.00 and 5.00. It is notable that 6 / 7 (85.7%) MSs > 3.00, which indicates that respondents rate graduate's attributes / states prior to employment as above average as opposed to below average.

Optimism is ranked first based upon a MS of 3.34, indicating that optimism is perceived to impact the performance of graduate's attributes/states prior to employment more than other attributes/states.

The MSs of self-regard, emotional self-awareness, assertiveness, empathy, self-actualisation and impulse control are > 2.60 to ≤ 3.40, which indicates that the extent to which respondents perceive the performance of graduate prior to employment in the related attributes/states is poor to average / average.

Table 3. Respondents' rating of graduates' attributes / states prior to employment.

Attribute / State	Response (%)						MS	Rank
	Un-sure	Very poor…………………..Excellent						
		1	2	3	4	5		
Optimism	0.0	0.0	17.0	42.6	29.8	10.6	3.34	1
Self-regard	0.0	0.0	14.9	53.2	25.5	6.4	3.23	2
Emotional self-awareness	0.0	0.0	19.1	48.9	25.5	6.4	3.19	3
Assertiveness	0.0	2.1	19.1	46.8	23.4	8.5	3.17	4
Empathy	0.0	2.1	17.0	53.2	23.4	4.3	3.11	5
Self-actualisation	0.0	2.1	21.3	51.1	19.1	6.4	3.06	6
Impulse control	0.0	4.3	23.4	53.2	14.9	4.3	2.91	7

Table 4 presents a comparison of respondents' rating of graduates' attributes / states (EI) during and after their probationary period in terms of MSs based upon percentage responses to a scale of 1 (very poor) to 5 (excellent), after-MSs expressed as a multiplier of the before-MSs, and the percentage after-MSs are greater than before-MSs. The fifteen attributes / states are courtesy of Butler and Chinowsky [13].

It is notable that 14 / 15 (93.3%) during-MSs as opposed to all (100.0%) after-MSs are > 3.00, which indicates the respondents rate the graduates' attributes / states (EQ) above average as opposed to below average, as in the case of 1 / 15 (6.7%) during-MSs and no (0.0%) afrer-MS, which are less than ≤ 3.00.

It is notable that whereas only 3 / 15 (20.0%) during-MSs are > 3.40 ≤ 4.20, which indicates the respondents rate graduates average to good / good, all (100.0%) after-MSs are.

Then, whereas 12 / 15 (80.0%) during-MSs are > 2.60 to ≤ 3.40, which indicates the respondents rate the graduates' poor to average / average, no (0.0%) after-MS is.

In terms of the difference between the after- and during-MSs, it is notable that all after-MSs are higher than during-MSs. The greatest difference is relative to stress tolerance (29.6%), followed jointly by interpersonal relationships and problem solving, and self-actualisation. The least difference is relative to happiness (1.2%), followed by flexibility, and independence.

Table 4. Comparison of respondents' rating of graduates' attributes / states (EQ) during and after their probationary period.

Attribute / State	During		After		After / Dur	% After > Dur
	MS	Rank	MS	Rank		
Interpersonal relationships	3.28	10	3.68	1	117.5	17.5
Optimism	3.43	3	3.66	2	109.5	9.5
Self-regard	3.32	8	3.63	3	113.4	13.4
Independence	3.45	2	3.62	4	106.9	6.9
Self-actualisation	3.30	9	3.62	5	113.9	13.9
Happiness	3.57	1	3.60	6	101.2	1.2
Emotional self-awareness	3.39	5	3.57	7	107.5	7.5
Problem solving	3.17	14	3.55	8	117.5	17.5
Assertiveness	3.33	7	3.55	9	109.4	9.4
Flexibility	3.40	4	3.51	10	104.6	4.6
Social responsibility	3.34	6	3.51	11	107.3	7.3
Reality testing	3.28	11	3.51	12	110.1	10.1
Impulse control	3.19	13	3.49	13	113.7	13.7
Stress tolerance	2.89	15	3.45	14	129.6	29.6
Empathy	3.22	12	3.45	15	110.4	10.4

Table 5 indicates the respondents' rating of graduates' core competencies in terms of percentage responses to a scale of 1 (very poor) to 5 (excellent), and MSs ranging between 1.00 and 5.00. It is notable that all the MSs > 3.00, which indicates that respondents rate graduate's core competencies as above average as opposed to below average.

5 / 10 (50.0%) MSs are > 3.40 ≤ 4.20, which indicates the respondents rate graduates average to good / good relative to personal integrity, self-image, self-confidence, attitude, and team player.

The remaining 5 / 10 (50.0%) MSs of focus on client success, aptitude, adaptability, values, and handling ambiguity are > 2.60 to ≤ 3.40, which indicates the respondents rate the graduates' poor to average / average relative thereto. It should be noted that the MS of focus on client success is 3.40, the upper limit of the range.

Table 5. Respondents' rating of graduates' core competencies.

Competency	Response (%)						MS	Rank
	Un-	Very poor…………………….Excellent						
	sure	1	2	3	4	5		
Personal integrity	0.0	0.0	14.9	36.2	27.7	21.3	3.55	1
Self-image	0.0	0.0	8.5	48.9	27.7	14.9	3.49	2
Self-confidence	0.0	0.0	17.0	38.3	25.5	19.2	3.47	3
Attitude	0.0	0.0	17.0	36.2	31.9	14.9	3.45	4
Team player	0.0	0.0	19.2	34.0	29.8	17.0	3.45	5
Focus on client success	0.0	2.1	17.0	36.2	27.7	17.0	3.40	6
Aptitude	0.0	0.0	12.8	46.8	29.8	10.6	3.38	7
Adaptability	0.0	0.0	14.9	55.3	19.2	10.6	3.26	8
Values	0.0	2.1	12.8	55.3	19.2	10.6	3.23	9
Handling ambiguity	0.0	2.1	23.4	51.1	12.8	10.6	3.06	10

Table 6 indicates the respondents' rating of graduate's performance relative to knowledge areas in terms of percentage responses to a scale of 1 (very poor) to 5 (excellent), and MSs ranging between 1.00 and 5.00. It is notable that 6 / 8 (75.0%) MSs > 3.00, which indicates that respondents rate graduate's performance relative to knowledge areas as above average as opposed to below average. However, 5 / 6 (83.3%) MSs are within 0.13 of 3.00.

7 / 8 (87.5%) MSs are > 2.60 to ≤ 3.40, which indicates that the extent to which respondents perceive the performance relative to knowledge areas is poor to average / average. Construction technology predominates, followed by construction science, research methodology, construction business environment, construction economics, project management, and management principles and practices. The rank of the latter is notable as it is a 'major' subject in construction management programmes.

The MS of construction law is > 1.80 to ≤ 2.60, which indicates that respondents perceive the performance relative thereto is very poor to poor / poor.

Table 6. Respondents' rating of graduates' performance relative to knowledge areas.

Knowledge area	Response (%)						MS	Rank
	Un-sure	Very poor……………………..Excellent						
		1	2	3	4	5		
Construction technology	0.0	2.1	19.2	34.0	36.2	8.5	3.30	1
Construction science	0.0	2.1	23.4	42.6	23.4	8.5	3.13	2
Research methodology	0.0	4.3	23.4	38.3	27.7	6.4	3.09	3
Construction business environment	0.0	0.0	29.8	42.6	21.3	6.4	3.04	4
Construction economics	0.0	2.1	34.0	29.8	27.7	6.4	3.02	5
Project management	2.1	6.4	25.5	34.0	23.4	8.5	3.02	6
Management principles and practices	0.0	2.1	31.9	42.6	17.0	6.4	2.94	7
Construction law	0.0	4.3	40.4	29.8	17.0	8.5	2.49	8

Table 7 indicates the respondents' rating of graduates' performance relative to the functions of management work in terms of percentage responses to a scale of 1 (very poor) to 5 (excellent), and MSs ranging between 1.00 to 5.00. It is notable that only 1 / 5 (20.0%) MS is marginally > 3.00, which indicates the respondents rate the performance of graduates relative to organising as above average as opposed to below average as in the case of a MS ≤ 3.00.

All the MSs are > 2.60 to ≤ 3.40, which indicates the respondents rate the graduates' poor to average / average in terms of performance relative to the five functions of management work.

Table 7. Respondents' rating of graduates' performance relative to the functions of management work.

Function	Response (%)						MS	Rank
	Un-sure	Very poor……………………..Excellent						
		1	2	3	4	5		
Organising	0.0	6.4	21.3	44.7	19.1	8.5	3.02	1
Planning	0.0	4.3	29.8	42.6	10.6	12.8	2.98	2
Coordinating	0.0	8.5	25.5	36.2	21.3	8.5	2.96	3
Controlling	0.0	6.4	29.8	42.6	12.8	8.5	2.87	4
Leading	2.1	6.4	46.8	25.5	12.8	6.4	2.65	5

4. Conclusions

Given the respondents' rating of graduates in terms of four skills prior to employment, it can be concluded, that graduates are to a degree prepared for employment. This is underscored by the respondents' rating of graduates in terms of seventeen attributes / skills during their probationary period.

Given the percentage difference between the after- and during-MSs relative to the rating of graduates in terms of seventeen attributes / skills, it can be concluded that the probationary period and related mentoring had an impact. However, the notable difference between the respective MSs relative to leadership capability, practical building knowledge, adaptable to changing environment, environmental awareness, and problem solving, indicates a need for tertiary education interventions.

Given the respondents' rating of graduates in terms of seven of fifteen attributes / states (EI) prior to employment, it can be concluded that graduates are to a degree emotionally intelligent. This is underscored by the respondents' rating of graduates in terms of seventeen attributes / skills during their probationary period.

Given the percentage difference between the after- and during-MSs relative to the rating of graduates in terms of fifteen attributes / skills (EI) it can be concluded that, to a degree, the probationary period and related mentoring had an impact. However, the notable difference between the respective MSs relative to stress tolerance, interpersonal relationships, problem solving, and self-actualisation indicates a need for tertiary education interventions. Although stress is a perennial challenge in the construction industry, graduates must be prepared to 'manage' it.

Given the respondents' rating of graduates' core competencies, it can be concluded that graduates are relatively well 'prepared' in terms of core competencies. However, there is a need for attention, particularly with respect to handling ambiguity.

Given the respondents' poor to average / average rating of graduates' performance relative to eight knowledge areas, it can be concluded that there is a need for tertiary education interventions, particularly with respect to construction law.

Given the respondents' poor to average / average rating of graduates' performance relative to the functions of management work, it can be concluded that there is a need for tertiary education interventions. An understanding and appreciation of the functions and their related activities, and the ability to plan, organise, lead, control, and coordinate are critical in industry, and the essence of construction management.

Given the respondents' average to good / good rating of the overall performance of graduates, it can be concluded that the tertiary education process is producing employable graduates.

5. Recommendations

Tertiary institutions should ensure that graduates are well versed and developed during their four-year study period. They must be knowledgeable with respect to the 'basics', which includes construction science, technology, management including the management of the business of construction, and construction law. They must be subjected to integrative projects and projects that simulate the construction process, and the practicing of the functions and activities of management work. Emphasis should also be placed on developing core competencies and emotional intelligence through, inter alia, team building activities. Employability and performance must be promoted through nurturing the requisite attributes during tertiary education.

Employers should subject graduates to graduate training programmes to facilitate their integration into the construction industry courtesy of a structured developmental process. Registration as candidates, which requires mentoring by a Pr CM, will further facilitate such integration.

The interface between industry and tertiary education should be optimised through forums, and the focus should be on promoting and providing vacation work, 'work shadowing', and structured visits to construction businesses and sites, and the delivery of guest lectures by industry practitioners.

Students should consider extracurricular activities such as generic part-time work to compensate for limited vacation or similar work, if the case, thereby developing work-related skills, their core competencies, and EI.

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Women in U.S. Construction Management Positions: A Qualitative Look at Motivations, Challenges and Considerations

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Abstract

This research study considered why there are relatively so few women working in the United States construction management industry. The qualitative study examined the social and economic factors that influence women's career opportunities and choices, identified ways to interest girls and women in construction management, and determined how employers can better support women already working as construction managers. Five women who either are currently working in U.S. construction management positions, or who have worked in construction management, were interviewed using a qualitative research design. These structured-interviews focused on the women's motivations to join the construction industry, what barriers they encountered both in their education and on the job, and what suggestions they have for ways to support women either interested in or already participating in the U.S. construction industry.

Keywords: construction management, human resources, personnel management, women

1. Introduction

America's persistent urban sprawl and rapidly aging infrastructure will continue to necessitate a competent construction industry to meet the nation's needs. For those that appreciate managing a project from the planning phase, through construction, and into building commissioning, construction management can be an excellent line of work. Due to the high median salary and low unemployment rate, the position of construction manager is ranked as the best construction job available, according to U.S. News & World Report's Best Jobs Rankings (2017). Additionally, the career field of construction management is projected to grow 5% from the years of 2014-2024 (BLS, 2015). Considering that women comprise 47% of the working population (DOL, 2011), it is shocking that women account for only 3% of construction managers (Stephenson, 2017). Why are there relatively so few women working in construction management? The research for this paper will identify social and economic factors that influence women's career opportunities and choices, identify ways to interest girls and women in construction management, and determine how employers can better support women already working as construction managers.

2. Background

2.1. Social and economic factors influencing women's career decisions

One of the major factors influencing many women's career decisions is the fact that women are often responsible for a greater share of the family and household responsibilities than men. Occupations that require odd or extended hours, like construction management, can be particularly challenging to women (Schieder and Gould, 2016). Work-life balance must be considered as 70% of women with minor children living at home participate in the labor force (BLS, 2017). Economic considerations also influence women's career path. In 2016, the median annual salary for construction managers was $89,300 (BLS, 2015). Since women tend to hold lower paying positions (Schieder and Gould, 2016), this relatively high salary could better support many working women and their families.

Girls and boys are often influenced by family members, teachers, and society in general to select toys that are gender normative. This results in girls often being steered towards dolls and people-oriented toys while boys are often encouraged to create structures with blocks, use power tools to build bird houses and other small projects, and help with household maintenance. This early experience working with their hands can contribute to boys' increased confidence which can affect their chosen fields of study in the future (Buschor, Berweger, Frei, Kappler, 2014). Traditional ideas of gender roles and norms influence women's career decisions and contribute to women being overrepresented in people-oriented careers such as healthcare, teaching, and sales (Lippa, Preston, Penner, 2014). Men are much more likely to be interested in and pursue things-oriented occupations, such as construction management (Lippa, Preston, Penner, 2014). Once these gender norms are imposed, often by the age of four, they are difficult to overcome and are even reinforced often by society (Islam, 2013).

2.2. Creating interest in construction management among girls and women

Educators and industry alike are placing a greater emphasis on exploring STEM (science, technology, engineering, and mathematics) subjects and promoting STEM careers than in the past. This should benefit recruitment in the field of construction management, as it involves working with new technologies and problem solving with engineering principles on every project. However, the STEM related areas are not emphasized and opportunities are squandered to introduce construction management to a new generation. Girls are particularly disadvantaged in this scenario as they are less likely to have hands-on experience with construction or building design than their male counterparts (Stephenson, 2017). It may seem obvious that girls benefit from being encouraged to pursue STEM interests in school. However, the timing of this encouragement is significant. Girls and female adolescents were much more likely to lose interest in STEM-related academic pursuits during the grades of K-12, than they were in the transition between high school and higher education or during their time in college (Buschor, Berweger, Frei, Kappler, 2014), illustrating the need to promote STEM and construction management as early and often as possible to girls of school age.

The kind of STEM instruction girls receive is also critical. It is imperative to encourage hands-on, experiential learning environments including practical STEM-related experiments (Buschor, Berweger, Frei, Kappler, 2014). These experiments can contribute to an increased sense of excitement for STEM as well as greater confidence for the subjects. BASE (Broadening Access to Science Education) Camp is a summer camp in Fairfield, Connecticut for less privileged high school girls. The camp promotes STEM and incorporates an immersive learning experience, identification and discussion of STEM careers, and a guidance for college admission and applications (Phelan, Harding, Harper-Leatherman, 2017). The camp is for female students and run by female career women and graduate students currently in STEM fields. The BASE Camp has experienced great success and influenced 84% of the girls attending the camp to pursue STEM careers (Phelan, Harding, Harper-Leatherman, 2017). The camp's administrators attribute the participants' greater awareness and understanding of STEM subjects with increasing their confidence and excitement for STEM related occupations.

Finally, girls often expect to encounter negative experiences and feelings in STEM careers and expect to have lower positive experiences. Interestingly, the anticipation of negative experiences does not discourage girls from pursuing STEM careers as much as their anticipation of having fewer positive experiences (Schuster, Martiny, 2016). Therefore, it is crucial to introduce girls to role models in construction management who are willing to share their positive experiences in construction in order to inspire and excite girls about the field.

2.3. Supporting women in construction management

Employees of either gender want to feel physically safe on the construction site, as well as appreciated and respected (Barlow, 2016). This can be particularly elusive for women in construction management and there are steps the construction industry can take to better support women in construction. Isolation on the construction site can invite conflict and provide an opportunity for women to be harassed or assaulted. In an interview with National Women's Law Center (NWLC), Patricia Valoy, a civil engineering student working in construction management, described her experience with harassment on site as follows, "I worked on the site for a year until I decided the stress of constantly being harassed, belittled, and intimidated was not worth the effort. We need more women in the construction industry so we're no longer a rarity" (NWLC, 2014). In the spring 2017 issue of BuildingEnergy Magazine, Kate Stephenson has developed some "Tips for Retention" for construction companies looking for specific ways to better support women in construction. One such tip is to "End isolation on worksites by assigning women, trans and gender non-conforming people, especially those new to the trades, in pairs or more" (Stephenson, 2017).

Women, like men, want to feel that their work is appreciated and that they are respected by their peers. In fact, feeling underappreciated is a significant stressor for women in construction management (Bowen, Edwards, Lingard, Cattell, 2014). In the construction industry, women also tend to report higher stress levels than men (Bowen, Edwards, Lingard, Cattell, 2014).

One barrier that faces women in construction may arise from their own family or support system. Construction management is considered by some people to be a lower status occupation (Lippa, Preston, Penner, 2014). There is a culture around construction that tends be interpreted as "masculine" and often requires working long hours in physically challenging conditions (Ness, 2012). This can make it particularly challenging for women to find support from their families and friends when they express an interest in construction. It is critical to have women role models from construction management that can present a positive point of view for the industry and help improve the image and connotations associated with construction (Barlow, 2016). Respecting a work-life balance is also critically important to support women in construction management. Long term job satisfaction and commitment is greatly impacted by a company's understanding of and support for their employees' desire for work-life balance (Malone, Issa, 2013). Additionally, policies that allow flex time, working from home, or other family-friendly leave practices positively impacted an employee's level of job satisfaction (Malone, Issa, 2013).

3. Research methodology

Interviews were conducted with five (5) women, all of whom are either currently working in or have previously worked in construction management, to provide qualitative research to explore and understand the interviewees' experiences as women in construction management and to understand how these experiences may influence other women's interest in the construction industry.

A standardized, open-ended interview method will allow the interviewer to ask the same questions of all interviewees, but provide the interviewer flexibility to follow up with questions or ask for more information as necessary. Through personal telephone or in-person interviews, this paper will seek to illuminate why women who either are working or have worked as construction managers were motivated to join the construction industry, what barriers they have encountered both in their education and on the job, and identify methods to support women either interested in or already participating in the construction industry.

Interview questions:

1. Please describe your education and work experience in construction management.
2. Please describe when and how you became interested in construction management.
3. Were you encouraged, with the help of a family member, teacher, or mentor, to build things when you were a child (i.e. bird houses, anything with hand tools, etc)?
4. As applicable, when you were in school or early in your career, were you overtly encouraged or discouraged from interest in construction management, either from your family members, friends, professors, classmates, coworkers, management, etc? If so, please provide example(s).
5. In which geographic regions have you worked in construction management? Describe the difference in experiences and attitudes towards you in those areas, if any.

6. How often have you taken positions with a different company? Did you feel that you had to transition to another company in order to get a raise and/or promotion?
7. How often are you aware of seeing women in construction management represented in training materials (i.e. videos, manuals, etc.), promotional materials (for university construction management programs, construction company advertising posters, brochures, etc.), and construction company websites? Please describe the impact this has on you, if any.
8. Please describe any steps your employer (or previous employers) could take to support women in the workplace (i.e. training, benefits, etc)?
9. Have you personally experienced harassment or assault (sexual or otherwise) while on the job? If so, please explain, to the extent you are comfortable sharing. How did you and your employer address the situation?
10. Do you participate in mentoring relationships, professional organizations for women in construction (i.e. National Association of Women in Construction (NAWIC), Professional Women in Construction (PWC), etc.), or apprenticeship programs? If so, how does this benefit you and/or other women in construction?
11. What advice would you offer to a woman interested in entering the field of construction management?

4. Data analysis

4.1. Interviewee information

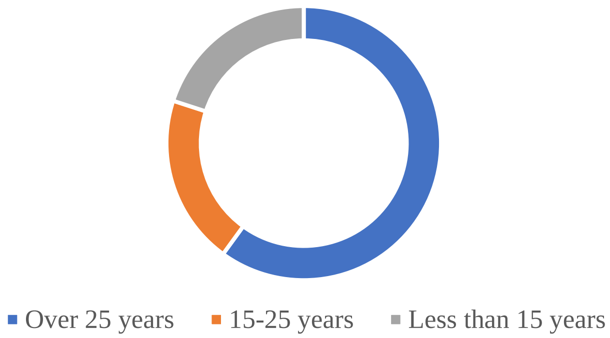

Figure 3: Interviewees' Years of Experience Working in Construction Management

The interviewees were carefully selected to represent a diverse set of experiences, with career length varying from thirteen to over thirty years of experience in the construction industry. Interestingly, none of the women interviewed for this paper were originally trained specifically in construction management. Two women have degrees in civil engineering, two women either are or were licensed interior designers, and one woman was trained as an architect. Most of their collective construction experience has been in the southeastern United States, though two women interviewed have managed construction overseas. A summary of each interviewee's educational and professional experience is listed below for context.

Ms. Catron-Cox graduated with a Bachelor's degree in Interior Design from the University of Tennessee in Knoxville, TN. She successfully completed the National Council for Interior Design Qualification (NCIDQ) exam, a professional exam which is required for registration and licensing. Her professional experience includes over 20 years of professional experience, with all but three of those years being in construction management positions. After college, she worked at an architectural and design firm in Knoxville, Tennessee for three years. She then became a consultant for a large medical imaging company, where she worked in construction management on site. She worked for Siemens doing consultant work as a full-time facility planner and designer. The first project she was primarily responsible for was a $5-8 million addition. She was the "Internal Gatekeeper" for that project. Her career progressed with Siemens and she enjoyed the highly technical requirements and challenges of working with facilities which manufactured specialized medical equipment. At Siemens, she began as a facility planner, then facility manager, and eventually rose to Director of Facilities when Siemens was still a privately held facility. All told, she worked for Siemens for 13 years. After leaving Siemens, she worked for a church-related nonprofit in construction management, but after five and half years there, she became frustrated with the lack of training and opportunities in that position. She decided to pursue other opportunities. She currently works for CBRE real estate property management and is responsible for eighty to ninety BBT banks. She is ultimately responsible for the construction of these buildings.

Ms. Stanley has a B.S. in civil engineering from Georgia Southern University. She has worked for the U.S. Army Corps of Engineers for over 30 years, and most of that time was spent managing construction projects. She has worked on heavy civil projects, such as airport runways, as well as vertical construction. During her career, she has worked at Headquarters, with the Savannah and Mobile district offices, and now is working at the Huntsville Engineering and Support Center.

Ms. McDowell has a dual Bachelor of Science degree in mathematics and civil engineering from Georgia Tech. She has worked in construction management for 13 years. Ms. McDowell worked at a private construction consultant company for five years managing the construction on state government contracts. Afterwards, she began working for the federal government for eight years. She has worked for the Environmental Protection Agency and the U.S. Army Corps of Engineers.

Ms. Baldwin has a degree in interior design from the University of Alabama. She worked for nineteen years with an architectural and design firm in Huntsville, Alabama where she was responsible for many design-build projects. After that, she spent eight years working as a Subject Matter Expert for design-build projects with a government contractor for projects on the Redstone Arsenal before finally taking an interior design position for the U.S. Army Corps of Engineers Huntsville Engineering and Support Center. Altogether, she has more than thirty years of experience, with most of that being in managing design-build construction projects.

Finally, the last interviewee is **Ms. Beverly Gilliand-Parkes**. Ms. Gilliand-Parkes earned a Bachelor of Architecture from Mississippi State University and worked in architecture for seven years after graduation. The architects she worked with recommended her for design-build construction projects. She soon left architecture and worked for Turner Universal Construction for ten years, first as an estimator and then she worked in their preconstruction department. She then went to work for Jessie Stutts, Inc., an electrical contractor in Huntsville, Alabama for approximately one year. After that, she worked at JH Partners Architecture-Interiors, a former architectural and design firm in Huntsville, Alabama. She worked there for approximately five years in the Construction Administration department where she was responsible for quality control on the firm's projects and acted as a liaison between the construction contractors and the architectural firm on design-build projects. She then worked for Dyson Construction for approximately two years and she currently works in government contracting for the federal government. Ms. Gilliand-Parkes has over twenty-five years of experience in architecture and construction management.

4.2. Influences in childhood or school

Many of the women interviewed for this research were interested in construction and building as children. While two of the women interviewed became interested only after their careers began. Three of the women, Sara Catron-Cox, Tamika McDowell, and Beverly Gilliand-Parkes, became interested in construction and building in their early childhood. Out of those three women, Ms. Gilliand-Parkes was actively discouraged from an interest in construction, because her father felt that it was inappropriate for his daughter. Her father supported her interest in architecture and drew a distinction between architecture and construction. She states that, to her father, "architecture was considered respectable." Out of the interviewed group, only Vicky Stanley was actively encouraged to help with maintenance and repairs around the house that would require the use of hand tools. As the oldest child in the family, Ms. Stanley was often included in work around the house and in the yard with her Dad. This is important because it may have contributed to a sense of confidence around this kind of equipment that she would not have had otherwise. She was not intimidated by work that required tools and equipment and that experience was unique of the women interviewed for this study. In fact, Ms. Catron-Cox was not allowed to use hand tools as a child. In college, she was the only female student in her surveying course. She got a chance to use hand tools for the first time in the class and expressed excitement for the opportunity.

Two of the women interviewed, Ms. Catron-Cox and Ms. Baldwin, studied interior design in college. This was encouraged by their family, although it is a more gender normative field of study. Ms. Stanley, Ms. McDowell, and Ms. Gilliand-Parkes, chose to pursue engineering, a dual mathematics and engineering degree, and architecture, respectively. Ms. McDowell shared her intentions to go into construction management upon graduation, and she had an aunt that would routinely discourage her from going into the construction industry. She states that, while she was in her third or fourth year of college, her aunt would tell her, "You will never be able to prosper in the construction industry." Ms. McDowell says that she believes her aunt meant that, as a female in the industry, it would always be an uphill struggle for her. If recruiting more women into the field of construction is the goal, these experiences are important to understand. Other women may face similar obstacles and challenges and respond by abandoning their interest in construction. Parents, other family members, and mentors can choose to support girls and young women when they show interest in construction, hand tools, and building.

4.3. Experience with peers' attitudes while working in construction management

Three of the five women interviewed described experiencing harassment on the construction site, while none of the women interviewed indicated that they were ever assaulted. Ms. Stanley describes whistling and cat calls being directed at her from men on site earlier in her career. Ms. Catron-Cox describes working with a man at the same position level as her who was "incredulous" towards her and she believes that was due in large part to her gender.

Ms. Gilliand-Parkes has worked on sites where men made crude comments about her body and began false rumors of her having affairs with other people on the site. She felt that some of the men on the team felt compelled to invent other reasons about why she would have her job, failing to believe that she was there because she was qualified and a valuable team member. Ms. Gilliand-Parkes also states that when it comes to personality on the jobsite, "You can't be 'the girl' and you can't be one of the guys. In a way, you just have to neuter yourself." She says that she feels that she must only be concerned with the work. She went on to state that her first job at a major construction company was "horrific" and that "Men didn't know how to handle it." In fact, the superintendent told her she "wouldn't get to prop (her) feet on the desk and eat bon-bons" while she worked for him. She clarifies that this was never her intention. Ms. Gilliand-Parkes goes on to say that she often feels the need to prove that she "isn't the secretary on the jobsite."

4.4. Seeing other women working in construction management

When asked if they were aware of seeing women in construction management represented in training materials (i.e. videos, manuals, etc.), promotional materials (for university construction management programs, construction company advertising posters, brochures, etc.), and construction company websites, the women all responded that they had noticed that, in recent years, women were being represented in these training and promotional materials more often. However, none of the women interviewed indicated this had any personal impact on them.

Ms. Stanley even appeared in a U.S. Army Corps of Engineers training video and printed training materials for Construction Quality Management for the Redstone Arsenal. She says, "At HQ, they were doing a diversity recruitment initiative which included a photo shoot with a professional photographer." The effort resulted in a fully produced video and a full-page color advertisement in the 1990s. Many of the women indicated that they were determined and did not require this form of modeling to be encouraged. Ms. McDowell says, "I am strong willed. I don't have to see that represented for me to do it." Ms. Baldwin and Ms. Gilliand-Parkes indicated that they believed this increased visibility of women in construction management was due, at least in part, to an "EEO" initiative and not as a reliable reflection of the changing workforce in construction management.

Additionally, none of the five women interviewed participate, or have ever participated, in professional organizations specifically for women in construction management such as the National Association of Women in Construction (NAWIC) or Professional Women in Construction (PWC). One of the women had even been encouraged by a colleague to participate in meetings at a similar organization and declined the invitation. Although none of the interviewees had attended any meetings, it was not a priority for them and they did not see enough benefit in these organizations to attend. However, organizations like this could provide some desired support and networking that could positively influence their careers.

4.5. Steps employers could take to better support women in construction management

Ms. Gilliand-Parkes believes that employers could make a better effort to build a more inclusive, respectful environment for women. She refers to the difficult superintendent that she worked for and notes that he never included her as part of their team. She says, "He never introduced me as Project Engineer over Quality Control." Instead, he would introduce her only by her name and omit her title. She believes it took a lot longer for her to build the trust and respect of the other team members because the superintendent signaled to them that he did not see her as respectable or part of the team.

Ms. McDowell also believes that it is imperative to have management that supports women in construction management. She says that laborers would often question her direction, until her management made it clear that they stood behind her. She was treated very differently from her male counterparts on site. She remembers that, on a jobsite in Florida, the men in the field would take direction from a male in Quality Assurance, who was not a degreed engineer, before they would take direction from her. She believes that was due to her gender. Ms. McDowell says that, in meetings on site for her work in North Carolina, she would typically be the only woman in the room. She says that she could "sit in a meeting, offer a suggestion, be ignored by everyone at the table, and then, fifteen minutes later, someone else at the table would have the same idea and everyone would get on board."

Ms. Baldwin speaks of "one good ol' boy experience" she had after she ended her employment with a government contractor. "It was a very male environment," she says. She felt that she could not fit in with the culture of the company. She said, "They could have given me the chance to manage projects, but they didn't want to let go of anything." She worked for the company for less than a year and described it as a "devastating experience" and one which she believes was gender-driven. Adequate and appropriate training opportunities were particularly important to two of the women interviewed. Ms. Catron-Cox states that the support for training was not there earlier in her career when she worked for a large healthcare corporation in the facilities division, but that she "didn't push it" with management. She then left the corporate world to work for a nonprofit for the value of the experience and to give back to her community. However, she eventually wanted more support for professional development and again found work in a for profit corporation. Ms. McDowell states, "In the majority of places I've worked, the management was really over supportive of training for me personally," Ms. McDowell says. When she worked in the private sector, her company encouraged her to take management training and it made her feel valued as an employee. Employers could either provide more opportunities for advancement within the company, or better communicate the existing opportunities for advancement to their female employees. Ms. Stanley says, "Women should be exposed to opportunities available to them (when they have) a civil engineering degree."

Ms. McDowell has typically felt that she needed to take a different position to get a promotion and/or earn a higher salary. She states that she has "only been promoted through movement, regardless of performance, workload, or responsibilities."

4.6. Interviewees' advice for women interested in construction management

The women interviewed for this research were asked what advice they would give to a woman interested in entering the field of construction management. Their advice was illuminating and it is a clear indication that there is more that could be done to support women in construction management. Their advice has been included below.

Ms. Catron-Cox suggests that, early in their construction management career, women should "stand up boldly for what they need in salary requirements." She also states, "Go full steam ahead and don't look back. Don't let anything stop you. You can make a difference. Building those structures says a lot about our world. It's important to have knowledgeable people in construction management that care." She also stated that she recommends women in construction management stand up for themselves. She says to "Express yourself calmly but boldly." She also says, "Talk through things. Learn from each other. Remember that you're always learning. Work together as a team. What do you have to lose?" Ms. Stanley would encourage a woman interested in construction management to dress professionally and project a professional image. Ms. Stanley says, "You have to be smarter, as a woman, to get noticed and promoted. Be a strong personality. Be confident." She also cautioned, "Sometimes they're testing you because you're new, not because you're a woman."

Ms. McDowell offers the following advice, "Be ready to fight. It's an uphill struggle. You have to work twice as hard to be taken seriously. If that is where your passion lies, seek out support and guidance." Ms. McDowell states that women in construction management "have to be twice as smart and knowledgeable" as men in the industry. MS. Baldwin offers the following advice to women who are interested in the field of construction management: "Take no bull. Work with experienced contractors to build a wealth of knowledge. Get hands on." Ms. Gilliand-Parkes: "Go for it. There's no magic advice other than you got to jump in with both feet. Learn the job, do the job, and you'll eventually get the respect."

5. Conclusions

Construction management positions pay well, often offer opportunities to travel and work in different areas of the world, and can be greatly satisfying to someone that enjoys seeing a project literally rise from the ground. However, many of these benefits are not being adequately communicated to girls and young women that may have an interest in construction. The interest in construction and building is worthy of being encouraged, regardless of the gender of the person expressing the interest. Parents, teachers, mentors, and other people in position of influence in young people’s lives should embrace and support this interest.

To attain gender parity in construction management, employers should focus on requiring a respectful, inclusive workplace culture with zero tolerance for harassment or assault for all employees. People in management positions have great influence in setting expectations for the rest of the team. When these people signal to the team that they respect each team member, regardless of gender, and expect others to as well, women directly benefit and they tend to notice and appreciate the effort.

Employers should also focus on providing quality training opportunities for continued professional development for women in construction management. Training ranked highly among the interviewees as important to their career. One interviewee even left a position in part because that employer was not supportive of adequate training. Employers could also better support and encourage participation in professional organizations specifically for women in construction management. Women not involved with such an organization could be missing valuable networking and resources for support. If women feel more supported, even outside of their employment, they may be more likely to remain in place and continue to contribute to that employer. Although the women interviewed tended to feel unaffected by seeing women in construction management modeled for them in training and promotional materials, the women interviewed acknowledged that they are seeing more women portrayed this way than ever before. The women interviewed may not be as susceptible to this type of modeling, but it may be beneficial to recruit more women in to the construction industry, specifically women who may not be as self-assured as the women interviewed.

Finally, the interviewees’ advice for women considering a career in construction management clearly indicates that there are opportunities for improvement in the construction industry. The advice underscores that there are still challenges that women experience in construction. The cautionary advice is important for women to know, but it is also noteworthy that the women interviewed found construction management rewarding and fulfilling. They were all encouraging of other women to enter the construction industry. It is possible to create greater gender parity in construction management and an aging infrastructure is going to continue to require experienced, knowledgeable construction managers. Greater exposure to construction, building, and tools and equipment can increase confidence in girls and young women that may make them more inclined to consider construction management as a career. Once in the field, female construction managers may require specific support from employers to overcome gender-specific challenges. With a relatively high median salary and forecasted job availability, the field of construction management offers excellent opportunities to women interested in construction.

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Women's Representation in Federal Transportation Agencies: A Descriptive Analysis

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Abstract

Gender inequality in engineering career fields has been a source of social and economic disturbances for many years. In several cases, women are underrepresented, and disparities persist despite policies that have focused on initiatives to promote gender equality in the industry, and the inadequacy of tools for measuring and analyzing the imbalance confounds the problem. This study investigates women's underrepresentation in engineering careers from 2011-2017, by aggregating data from 17,889 demographic profiles of the U.S. Department of Transportation (USDOT) workforce. The objective of the study was to perform a descriptive analysis to (1) explore women's representation in the USDOT, and (2) discover the factors that can reduce or eliminate the low representation of female engineers and if there is any wage gap that exists between the genders. This includes the impact of factors such as job location, education level, type of appointment, job position and its importance, level of experience, and supervisory role of the employee. According to the outputs, women hold fewer high-level positions than men in the USDOT, but no significant gender-related wage inequality exists. The findings can help public and private organizations design legislative initiatives to achieve greater gender equality and assist employers of engineering organizations in moving toward a more gender-diverse working environment to reduce or eliminate gender inequality and its consequent challenges.

Keywords: women, underrepresentation, USDOT, transportation agencies, workforce, wage rate

1. Introduction

Today's worldwide economy is driven to a large degree by advancing technology and provides opportunities for women to pursue education and careers in fields, including engineering, that have been historically dominated by men. Women were much more limited in their choice of a career in the past, but for the last several decades, they have assumed important roles in most socioeconomic activities [1,2]. Women are now hired for many of the positions previously filled exclusively by men [3,4]; however, underrepresentation of women in engineering fields still remains an issue that leads to adverse socioeconomic consequences [5] and discourages women from pursuing engineering careers [4]. Education level, experience, efficiency, gender discrimination, etc. are also factors that contribute to women's underrepresentation in engineering.

Several scholars have conducted studies on gender inequalities in engineering fields. Beaton et al. [6] indicated that there is a direct relationship between the underrepresentation of women and their unwillingness to pursue an engineering career. Hunt [7] identified discrimination by male peers as an important reason why women engineers exit engineering fields. Infante-Perea et al. [8] revealed that while pursuing an engineering career, women often face gender-related barriers and discrimination that prevent them from actually entering the field. They also identified lack of confidence and self-esteem as obstacles for women in occupying higher level engineering positions.

Despite research into women's underrepresentation in engineering fields, disparities still exist between women and men [9]. To resolve this issue, it is important to measure and analyze the factors that contribute to the problem. The goal of this research was to (1) explore the current status of women's representation in transportation related engineering careers, and (2) discover the factors that can reduce or eliminate this challenge. This research will assist employers of engineering agencies in creating more gender-diverse working environments that will result in reducing and/or eliminating gender inequality and the consequent challenges in their organizations.

2. Literature review

Rapid changes in technology in the past several decades have made engineering occupations more attainable for individuals of any gender [10,11] even though traditionally, the inherent activities such as design, field work, etc., have been perceived as masculine occupations [12]. Despite the claim by some that gender inequalities and women's underrepresentation in engineering fields have declined, there is still a gap [13]. In the US, for instance, only 15% of those in the engineering sector are women [14]. Since more women are pursuing an engineering career today than they did decades ago, an accurate analysis of the factors that lead to women being underrepresented is needed [15,16].

Various efforts have been attempted to decrease women's underrepresentation in the engineering fields. Women have been encouraged to pursue an education that would equip them for the engineering professions [9], and initiatives such as the Packard Scholars Program have been offered to motivate them [17,18] and to improve the public's perception of women in what has been a male-dominated field [9,16]. Research and activities have been conducted to determine the factors that have led to female underrepresentation, and one of the earlier ones concluded that it is a result of social beliefs about gender-related roles that are established in childhood and continue into adulthood [19]. However, Galy-Badenas [20] showed that the recent technological advancements have led women to achieve higher education levels and consequently have changed the general social beliefs and behaviors about women's social roles and abilities. Burke [21] identified several factors, including diverting high school girls from math courses because they were perceived as being too difficult for them. Wang et al. [22] investigated the relationship between women's educational pathways and their success in engineering fields and revealed that self-efficiency was a significant motivating factor for better representation in engineering. In addition, race and marital status were identified as potential barriers for women that resulted in their not pursuing engineering professions [22]. Karimian et al. [23] developed a framework identifying the employees at risk of wage inequality and demonstrated that women working in engineering sectors are at risk of wage inequality.

Notwithstanding the efforts that were made to decrease the gender inequalities, women still encounter obstacles and challenges to becoming engineers and surviving in the workforce [24,25]. Balamuralithara et al. [26] indicated that many engineering companies/organizations and their male workforce do not consider women capable of performing difficult engineering tasks, especially in higher level positions. Mahajan and Golahit [27,28] also revealed that the competitive and objective qualities required for obtaining higher wages and positions in engineering organizations are perceived as being masculine, which leads women engineers to underestimate their capabilities in competing with men. Myers [29] says that it is this stereotypical behavior that prevents women from climbing the proverbial career ladder. Foust-Cummings et al. [30] showed that the lack of role models, mentors, and sponsors for women employed in engineering fields impedes their progress.

In summary, there is an increasing demand in engineering fields that makes the involvement of women important and the elimination of the underrepresentation necessary. The inequalities between men and women have decreased during the past few decades, but they are still male-dominated. An accurate analysis of the impeding factors should be performed to resolve this issue [30,31].

3. Methodology

This study aimed to investigate the representation of women employees in USDOT, using descriptive analysis. Demographic data of the skilled labor in the USDOT from 2011-2017 was used, which included 17,889 USDOT employees. The following variables were used:

(1) The gender variable is a categorical variable based on two values: male and female.
(2) The salary range variable is a categorical nominal variable based on six values: under $30K, $30K to $49K, $50K to $69K, $70K to $89K, $90K to $109K, and over $109K per year.
(3) The age range variable is a categorical nominal variable based on nine values: under 25, 25-29, 30-34, 35-39, 40-44, 45-49, 50-54, 55-59, and 60 or higher.
(4) The education level variable is a categorical nominal variable based on four values: high school degree or less, college with no bachelor's degree, bachelor's or post-bachelor's degree, and graduate or professional degree.
(5) The years of service variable is a categorical nominal variable based on eight values: under 4 years, 5 to 9 years, 10 to 14 years, 15 to 19 years, 20 to 24 years, 25 to 29 years, 30 to 34 years, and over 35 years.
(6) The job position variable is a categorical variable based on nine values: community planning, contracting, engineering, financial management, human resources professional, information technology, Non-MCO, transportation safety, and transportation specialist.
(7) The fiscal year variable, which represents the year that the employee is hired, is a categorical nominal variable based on seven values: from 2011 to 2017.

Two primary indexes were used in this study to investigate women's representation, including (i) the total number of female employees, and (ii) the ratio of female to male employees. The impact of factors such as salary range, education level, job position, and the level of experience on gender representation was investigated. Six null hypotheses are shown in Table 1. A statistical analysis, called the likelihood-ratio test (LRT), was used to test the goodness-of-fit between the ratio of female to male employees and other factors, based on each null hypothesis. The likelihood-ratio test rejects the null hypothesis if the P-value is smaller than 0.01 (significance level of 1%). A statistical software called JMP was used to perform LRT (JMP 2019). JMP software is partly focused on exploratory data analysis and visualization. It was designed for users to investigate data to learn the unexpected, as opposed to confirming a hypothesis.

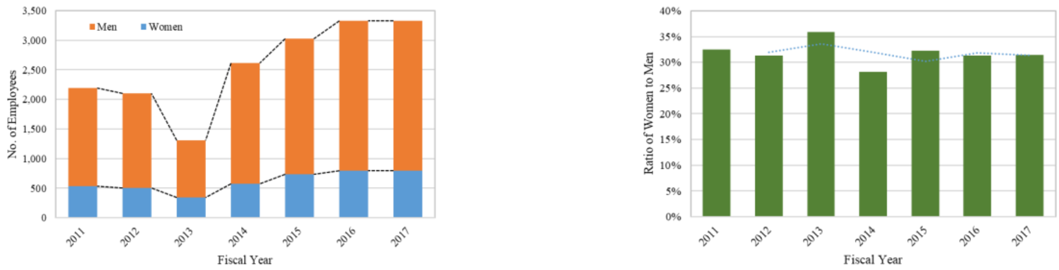
Table 1. The null hypotheses tested in this study

No	Null Hypothesis
1	There is no significant correlation between female to male employees ratio and the year of employment
2	There is no significant correlation between female to male employees ratio and the age of employees
3	There is no significant correlation between female to male employees ratio and the salary range
4	There is no significant correlation between female to male employees ratio and the job positions
5	There is no significant correlation between female to male employees ratio and the education level
6	There is no significant correlation between female to male employees ratio and the experience level

4. Results and discussion

4.1. Women's representation

The trend of female employee numbers and their proportion to male employees was explored for different years at USDOT. Among the 17,889 employees studied, only 4,286 were females (24%); the ratio of female to male employees was 32%. Fig. 1.a shows the trend of employment for each year, based on the gender of the employees, and illustrates that except in 2013, when there was a decrease, the number of employees at USDOT (both male and female) increased every year. Fig. 1.b shows the ratio of female to male employees each year and illustrates that although there was a decrease in the total number of employments and accordingly a decrease in the number of female employments in 2013, the ratio of female to male employees was at the highest (36%). A year later, however, in 2014, this ratio was at the lowest (28%). A likelihood-ratio test was used to test whether there was a statistically significant correlation between the female to male employee ratio and the year of employment (null hypothesis #1). It resulted in a P-value of 0.0965, which cannot reject the null hypothesis; therefore, no statistical evidence was found that women's representation changed.

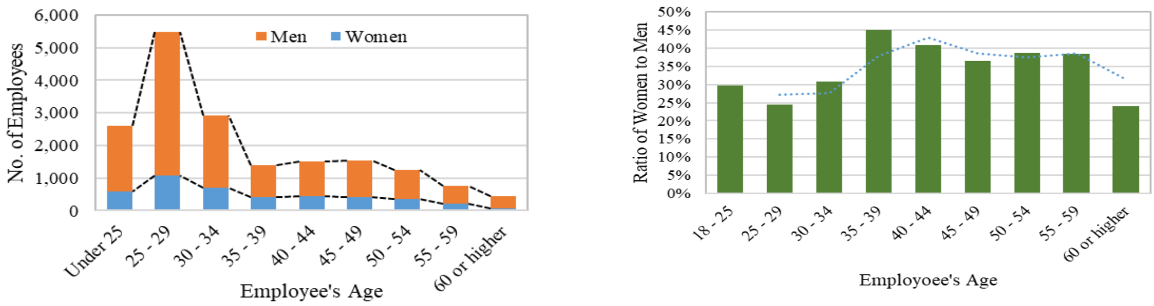


a. Number of employees in different years

b. Female to male employees ratio in different years

Fig. 1. Female representation in different years at USDOT

Fig. 2.a shows the number of employees based on gender for each age range and illustrates that except for the age group under 25, there were more jobs at USDOT for younger employees of both genders. Fig. 2.b shows that the ratio of female to male employees was higher than average from ages 35 to 59, with the highest (42%) for the age range of 35 to 39 years old. This ratio was smaller than average for those under 34 years old and 6o years old and higher. A likelihood-ratio test was used to test whether there was a statistically significant correlation between the female to male employee ratio and the year of employment (null hypothesis #2). It resulted in a P-value of <0.0001, which rejects the null hypothesis. Therefore, there is statistical evidence to prove that women's representation has changed regarding the age of employees. In general, it can be concluded that there is greater representation of women in older employees.



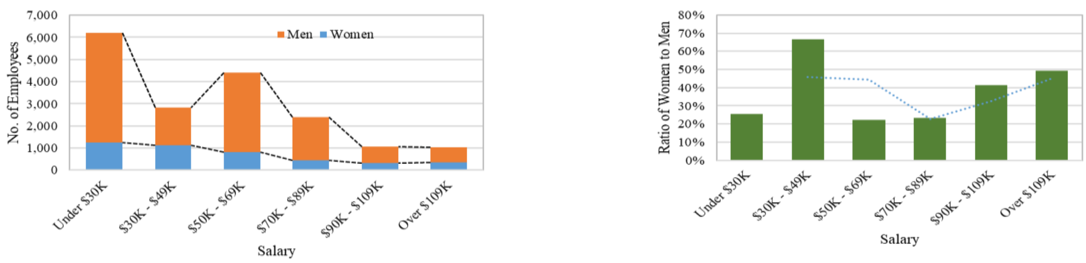
a. Number of employees in different ages

b. Female to male employees ratio in different ages

Fig. 2. Female representation in different age range at USDOT

4.2. Women's salary

The salaries of the female employees at USDOT were explored. Fig. 3.a shows the number of employees based on their salary range, and illustrates that the number of female employees with higher salaries was smaller than the number of female employees with lower salaries. It was almost the same for male employees, except for the $30K to $49K salary range. Fig. 3.b shows the ratio of female to male employees in each salary range and illustrates that except for the salary range of $30K to $49K, which unexpectedly had a lower number of male employees and so a higher ratio of female to male employees, this ratio usually increased with an increase in the salary range.

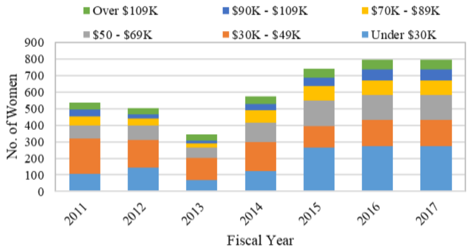


a. Number of employees with different salary

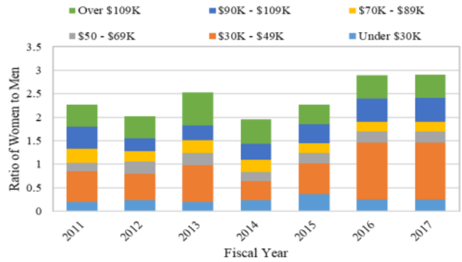
b. Female to male employees ratio in different salary

Fig. 3. Female representation in different salary range at USDOT

For the salary range of over \$109K, this ratio was as high as 50%. A likelihood-ratio test was used to test whether there is a statistically significant correlation between the female to male employee ratio and the salary range (null hypothesis #3). It resulted in a P-value of <0.0001, which rejects the null hypothesis. Therefore, there is statistical evidence to prove that women's representation has changed regarding the employee's salary range. In general, it can be concluded that there are more women in jobs with higher salaries. In addition, the trend of female employee numbers and their proportion to male employees was explored for different years and different salary ranges at USDOT.



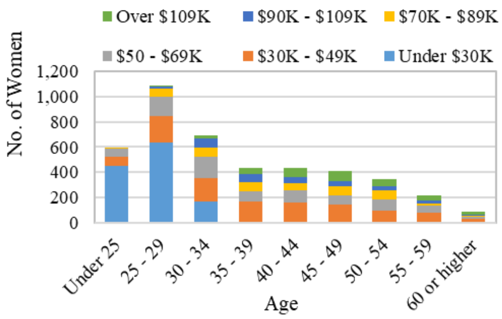
a. # of female employees in different years and in different salary range



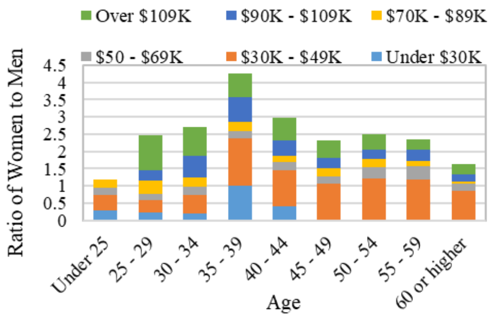
b. Female to male ratio in different years and different salary range

Fig. 4. Female representation in different years with different salary ranges at USDOT

Fig. 4.a shows the trend of female employees for each year and in each salary range. The figure illustrates that in recent years, more female employees with salaries under \$30K or over \$90K were hired at USDOT than with average salary ranges. Fig. 4.b shows the ratio of female to male employees for each year and each salary range, and illustrates that more women earned salaries of \$30K to \$49K almost every year. The trend of the USDOT number of female employees and their proportion to male employees was explored for the different age groups and years. Fig. 5.a shows the trend of female employees for each year and in each salary range, and illustrates that younger female employees usually have the lower-salaried positions. Fig. 5.b shows the ratio of female to male employees for each year and with different age ranges, and illustrates that the ratio of younger females to younger male employees was higher in jobs with higher salary ranges. As an example, although the salary range of \$30k to \$49K had the highest ratio of female to male employees, for the employees aged of 25 to 34 years old, this ratio approached 100% for employees with a salary over \$109K.



a. # of female employees in different years and with different ages

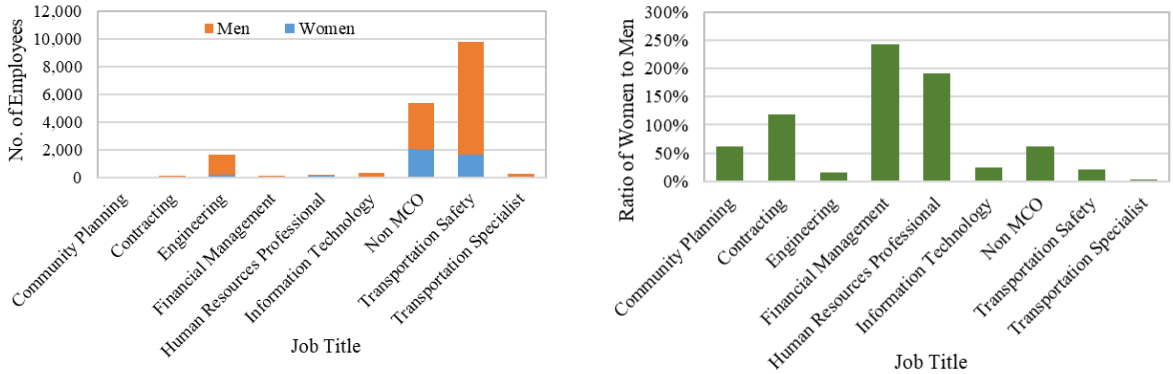


b. Female to male ratio in in different years and with different ages

Fig. 5. Female representation in different years with different ages at USDOT

4.3. Women's job positions

In this section, the job position of female employees at USDOT is explored. Fig. 6.a shows the number of employees based on their job positions and illustrates that 94% of the employees had one of three jobs: transportation safety, non-MCO (not related to mission-critical occupation engineering family), and engineering. The job position of non-MCO had the highest number of female employees (48%), while transportation safety had the highest number of male employees (60%). Fig. 6.b shows the ratio of female to male employees for each job position.

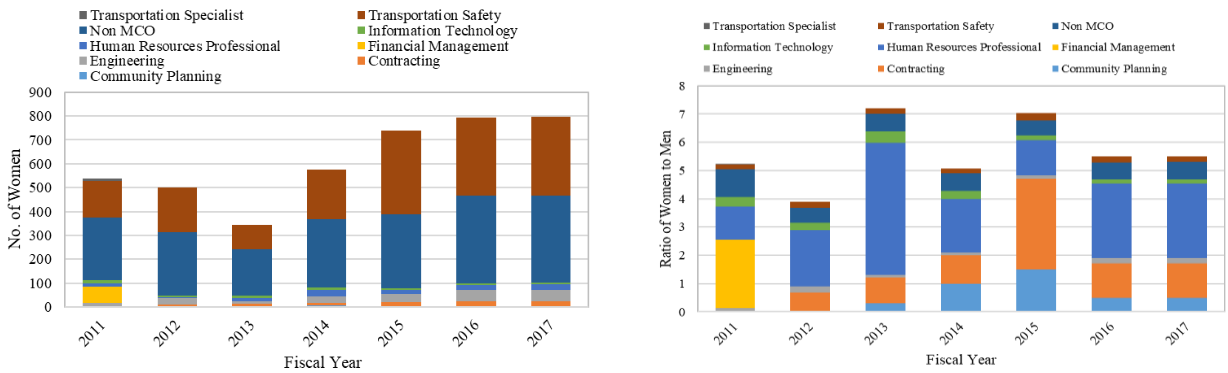


a. Number of employees in job positions

b. Female to male employees ratio in job positions

Fig. 6. Female representation in different job positions at USDOT

Although there were a large number of female employees in transportation safety, non-MCO, and engineering positions, the ratio of female to male employees was extremely low in these positions (0.20, 0.62, and 0.15, respectively) because of the high number of male employees. On the other hand, the very high ratio in financial management (2.43) and human resource professional (1.90) illustrates the large number of women in those job positions. A likelihood-ratio test was used to test whether there is a statistically significant correlation between female to male employee ratio and job positions (null hypothesis #4). It resulted in a P-value of <0.0001, which, as was expected, rejects the null hypothesis. Therefore, there is statistical evidence to prove that women's representation has changed in different job positions. In general, it can be concluded that more women hold positions in financial management, human resources, and contracting. Fig. 7.a shows the trend of female employees for each year and in each job position, and illustrates that in recent years, more female employees have been hired in transportation safety, non-MCO, and engineering positions. Fig. 7.b shows the ratio of female to male employees for each year and each job position, and illustrates that in recent years, the ratio of female to male employees was higher in human resource professional and contracting positions.

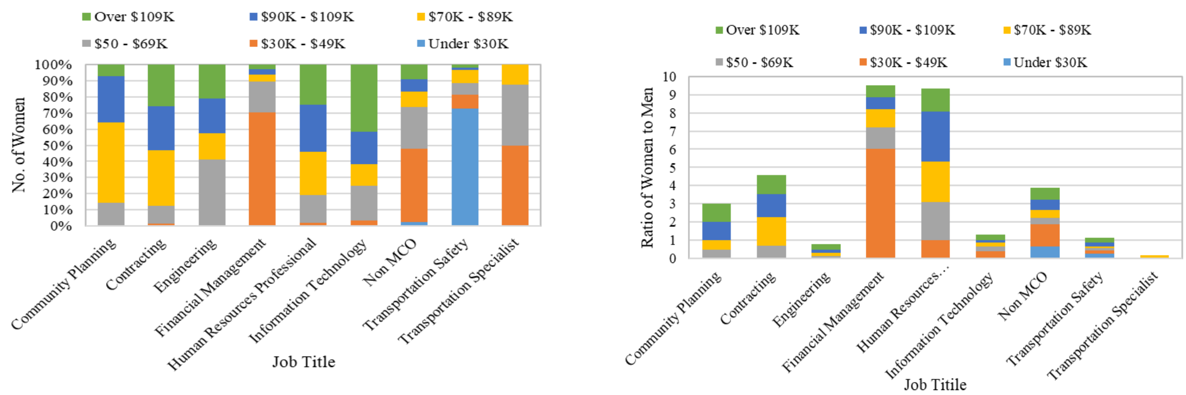


a. # of female employees in different years and in different job positions

b. Female to male ratio in different years and in different job positions

Fig. 7. Female representation in different job positions in different years at USDOT

The trend of the number of female employees and their proportion to male employees was explored for different job positions with different salary ranges at USDOT. Fig 8.a shows the trend of female employees in each job position and each salary range, and illustrates that most of the female employees working in transportation safety had a salary under $30K, most of the female employees working in financial management had a salary range of $30K to $49K, and the female employees with a salary range of over $109K usually worked in information technology, contracting, or human resource professional positions. Fig. 8.b shows the ratio of female to male employees for each year and each job position, and illustrates that human resource professionals in higher salary ranges have higher ratios, as do those in financial management positions in lower salary ranges.



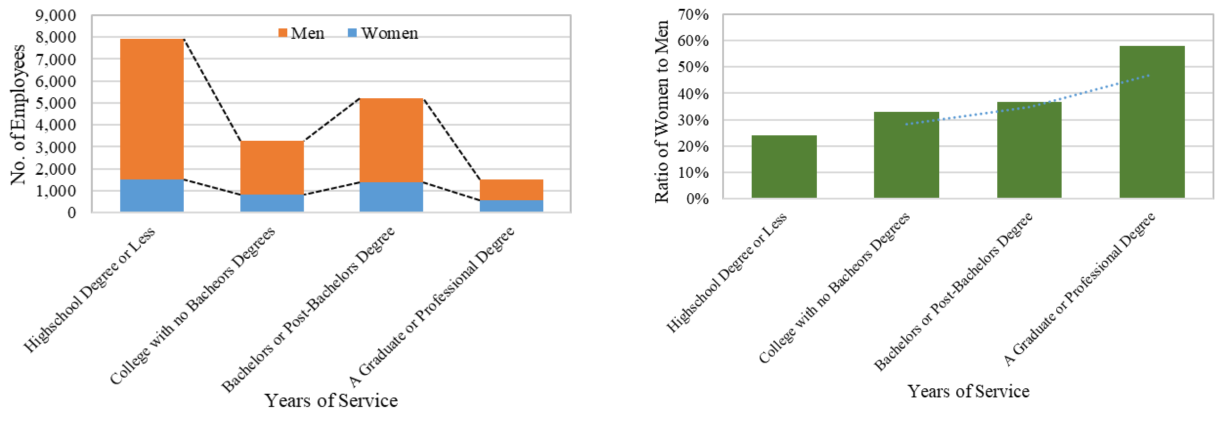
a. # of female employees with different salaries in different job positions

b. Female to male ratio with different salaries in different job positions

Fig. 8. Female representation with different salary ranges in different job positions at USDOT

4.4. Women's education levels

Fig. 9.a shows the number of employees based on their education level and shows that more employees, of both genders, had education levels of high school degree or less and bachelor's or post-bachelor's degree. Fig. 9.b shows the ratio of female to male employees in each education range and illustrates that the highest ratio was in the education level of graduate or professional degree (59%), while the lowest ratio was in the education level of a high school degree or less (22%). A likelihood-ratio test was used to test whether there is a statistically significant correlation between the female to male employee ratio and the education level (null hypothesis #5). It resulted in a P-value of <0.0001, which rejects the null hypothesis. Therefore, there is statistical evidence to prove that women's representation has changed regarding the employee's education level. In general, it can be concluded that there is more women representation with higher levels of education. In other words, higher education can reduce women's underrepresentation.



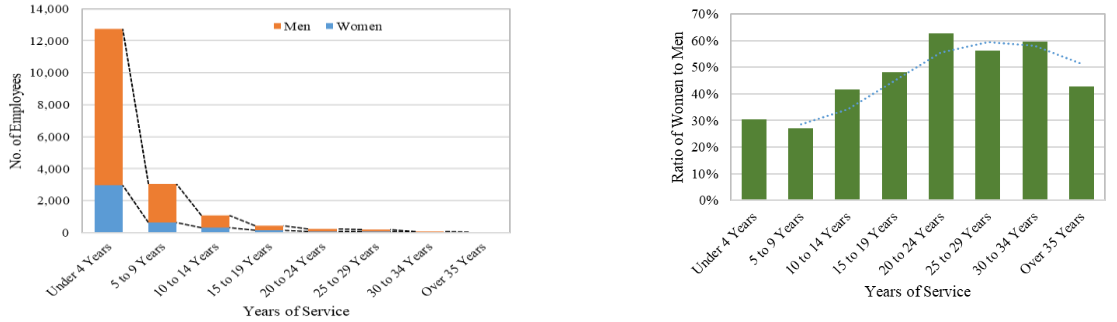
a. # of employees with education level

b. Female to male employees ratio with education

Fig. 9. Female representation in different education levels at USDOT

4.5. Women's experience levels

In this section, the experience level of female employees was explored at USDOT. Fig. 10.a shows the number of employees based on their experience range. The figure illustrates that, as was expected, there were more employees (both female and male) with a lower experience level. Fig. 10.b shows the ratio of female to male employees in each experience range. The highest ratio was in experience range of 20 to 24 years (61%), while the lowest ratio was in the experience range of 5 to 9 years (24%). A likelihood-ratio test was used to test whether there is a statistically significant correlation between the female to male employee ratio and the experience level (null hypothesis #6). It resulted in a P-value of <0.0001, which rejects the null hypothesis. Therefore, women's representation has changed regarding the employee's experience range, and it can be concluded that there is higher representation of women in employees with higher levels of experience.

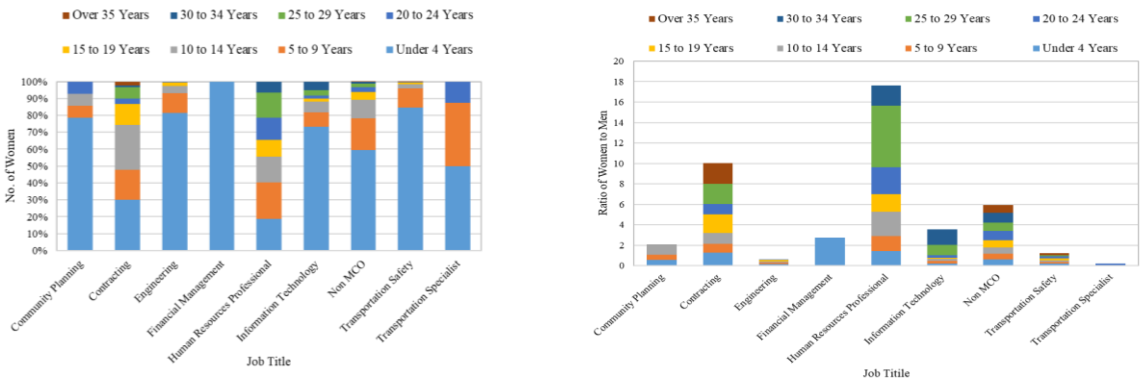


a. # of employees with experience ranges

b. Female to male employees ratio with experience

Fig. 10. Female representation in different experience ranges at USDOT

The trend of the number of female employees and their proportion to male employees was explored for different job positions with different experience ranges at USDOT. Fig. 11.a shows the trend of female employees in each job position and each salary range, and illustrates that for most of the job positions (except human resource professional and contracting), the major level of experience for female employees was under 4 years.

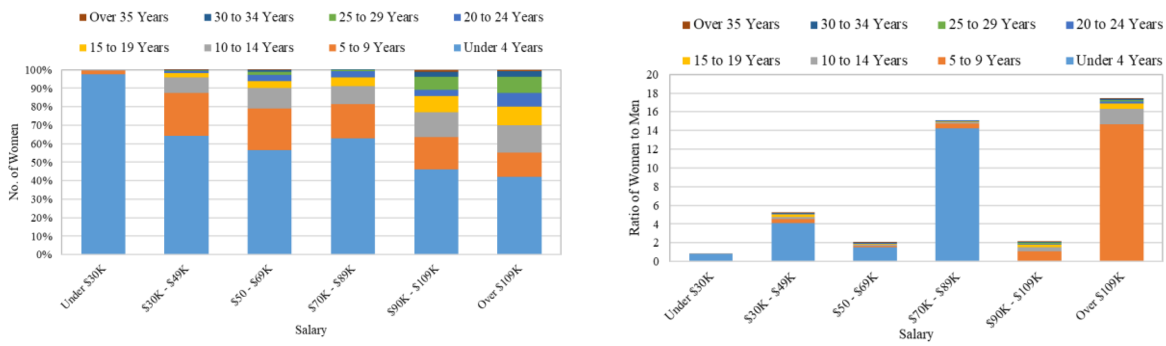


a. # of females with different experiences in different job positions

b. Female to male ratio with different experiences in different job positions

Fig. 11. Female representation with different experience levels in different job positions at USDOT

Fig. 11.b shows the ratio of female to male employees for each experience level and each job position. The trend of the number of female employees and their proportion to male employees was explored for different experience levels and salary ranges at USDOT. Fig. 12.a shows the trend of female employees for each experience level and in each salary range, and illustrates that more-experienced female employees usually had the higher-salaried jobs.



a. # of females with different experience levels and salary ranges

b. Female to male ratio with different experience levels and salary ranges

Fig. 12. Female representation with different experience levels and salary ranges at USDOT

Fig. 12.b shows the ratio of female to male employees with different experience ranges and with different salaries, and illustrates that in all of the salary ranges, the positions that require a lower level of experience (under 4 years or 5 to 9 years) had the highest ratio of female to male employees.

5. Conclusion

Women are less represented than men in engineering fields. Within the last decades, there has been an increase in the number of females going into engineering, but there is still a gap between the representation of men and women. This has led to several socioeconomic issues that make it necessary to analyze the corresponding causal factors. In this study, the current underrepresentation of women in engineering was explored, and the factors that can decrease and/or eliminate this issue were discovered. Demographic data of the USDOT workforce from 2011 – 2017 was used to perform a descriptive analysis. The factors that impact gender representation and a wage gap were investigated, including job location, education level, type of appointment, job position and its importance, level of experience, and the supervisory role of the employees. The outputs showed that even though the females were underrepresented among the USDOT employees, there was no considerable wage inequality. It was found that women were mostly underrepresented in the higher level positions, and the most significant factor in reducing the inequity was a higher level of education. The results of this study can help public and private organizations and agencies design legislative initiatives to reduce the gender gap and achieve more gender equality. Furthermore, the study will help the workforce of any engineering organization to move toward a more gender diverse working environment, which will result in the reduction and/or elimination of gender inequality and its consequent challenges in their agencies.

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A Deep Learning Algorithms to Generate Activity Sequences Using Historical As-built Schedule Data

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Abstract

Project schedule development requires having knowledge about the project's activities and the proper sequence of them. In traditional practice, arranging project activities in a feasible sequential order heavily relies on the project scheduler's practical experience. However, personal experience is limited and prone to include human errors. In this paper, a Deep Learning model is employed to be trained on historical project schedules to predict sequential activities. The proposed model uses a Bidirectional Long Short-Term Memory Recurrent Neural Networks that learns the activity predecessors in the forward direction and the activity successors in the backward direction. The model receives one or more activities and predicts subsequent and precedent activities in a sequential order that have the highest likelihood of occurrence in the historical data. The model is compared with a Sequential Pattern Mining technique that identifies the most probable sequential patterns of activities. The two methods are applied to as-built highway project schedules obtained from a highway agency in the U.S to compare the performance of the two methods. While the Sequential Pattern Mining model provides sequential patterns for certain activities, the Deep Learning model generates a back-tail and a front-tail of activities with any arbitrary length for to provide a more flexible support tool for project schedulers.

Keywords: Deep learning, LSTM, construction scheduling, sequence analysis, highway project schedules

1. Introduction

To develop a reliable project schedule, some of the major requirements are the knowledge about the project's activities, required and available resources, production rates, and the sequence logic of the activities. Project activities and quantities are typically identified in the estimated work item amounts in the contract. Production rate estimation of an activity can be can be determined with a reasonable level accuracy when the available resources are identified and historical performance data may provide likely ranges for different activities [1]. However, there are so many possible ways to arrange the order of activities in the project and not all of them result in an efficient plan which makes the activity sequence logic identification a challenging task. Inefficient activity sequence identification results in inaccurate critical path of the project and project duration and contract time determination. Inaccurate estimation of the contract time can lead to an increase in construction cost, inconvenience to the public, and a raise in the number of litigations [2, 3, 4].

In a typical department of transportation (DOT) in the U.S, schedulers use their own experience to determine the sequence logic of activities for a highway project, and may use guidelines in which a general sequence of activities are introduced [5, 6]. However, such guidelines are developed as a high-level guidance based on experts' experience and need frequent updating to reflect the recent requirements of standards. Moreover, human experience is limited to a few projects and thus, may cause some bias and is subject to human errors. Research studies tried to address this issue. Typical activity dependency rules have been identified based on physical and material constraints by analysing construction drawing and using experts' knowledge [7, 4]. A recent study developed a data mining model to analyse historical schedules to obtain common sequential patterns among activities [8]. The mining model explored the dataset of historical as-built schedules and identified the most common activity sequential pattern among schedules. Shrestha et al. [8] identified that historical as-built schedules are a valuable resource for identifying the realistic sequence of activities. Although identifying sequential patterns out of historical schedules can provide useful insights for schedulers, there is still a need for a more comprehensive model that can discover sequence insights of the schedules. There is a need that a model not only predict the next successor given one activity, but also the next successors and previous predecessors given one or a short series of activities. This paper developed a Bidirectional Long Short-Term Memory Recurrent Neural Networks (BLSTM) and compare it with a mining technique of Sequential Pattern Mining (SPM) to discuss advantages and disadvantages. The research implemented the two models on 34 real as-built schedule cases of highway project in Montana DOT to validate the results.

2. Background

Research studies have been conducted to identify activity dependency rules based on geometry and physical relationship between building components. Cherneff et al. [7] identified rules that determine precedence activities and extracted the geometry, material, and physical constraints information from the project's CAD drawing to help activity sequence identification. The information of geometry, quantity, and physical relationship of project components has also been extracted from BIM models [5]. Some researchers used expert knowledge to identify the common sequence of activities. Jeong et al. [4] obtained Oklahoma DOT schedulers' knowledge to develop fourteen highway scheduling templates. They illustrated activities using flow diagrams to show the sequence, concurrency, and time overlapping of activity implementation in fourteen highway project types. Similarly, Bruce et al. [9] consulted with project schedulers and analyzed historical projects to develop scheduling templates for twelve types of road and bridge projects for Illinois DOT. Montana DOT [6] identified typical sequences of activities for common highway projects. In this study, key controlling activities were described and the time of implementing each activity with regards to other activities was explained.

Some researchers used data-driven methods and analyzed real projects' schedules to obtain common sequential patterns. Shrestha et al. [8] used as-built schedules extracted from Daily Work Report (DWR) data of a State DOT and applied the Sequential Pattern Mining (SPM) technique to identify common activity sequential patterns. For example, they identified that in 78% of the projects in the dataset, the activity of "cold milling asphalt pavement" was implemented after the "maintenance of traffic". Since the probability of this event is relatively high among all probabilities in the dataset, this sequence pattern was considered as a common sequence. Advanced Artificial Intelligence (AI) tools have also been used for sequence analysis. Long Short-Term Memory (LSTM) [10] is a recurrent neural network architecture which has been applied for sequence analysis such as language models and text prediction to learn the sequence of tasks [11, 12, 13]. Amer and Golparvar-Fard [14] adopted a LSTM model to extract construction activity sequence knowledge using previous construction schedules. They used 12 actual construction project schedules and trained a LSTM model on historical construction schedules that learned the precedence relationships among schedule activities. Given a sequence of activities, the model predicted the next successor activities. Although AI tools have been adopted to extract sequence knowledge of schedules, there are more challenges ahead; schedulers want to know if they have one or multiple activities, what the most possible predecessors and successors of them are. This paper I) proposes a Deep learning model that is a Bi-directional Long Short-Term Memory (BLSTM), II) applies the model on 34 cases of real overlay project as-built schedules to extract sequence knowledge, III) compares the BLSTM results with a most recent activity sequence analysis model of Sequential Pattern Mining (SPM) technique that is applied to the same database to discuss the advantages of the proposed model.

3. Data

Historical as-built schedule data of 34 overlay projects from Montana DOT were used for this study. The data included 42 controlling activities and the projects were constructed is from 2008 to 2016. The as-built schedule of each project includes the project's controlling activities and the start and end dates of each activity.

4. Bi-directional LSTM model

LSTM has been applied in sequence analysis tasks as a sequence to sequence model with an encoder and a decoder. A sequence to sequence model takes a sequence of features as input in the encoder part, and outputs multiple next time steps as a target sequence that follows the input sequence in the decoder part [15, 16]. The encoder part takes time steps sequence values and passes through a hidden layer to create a final encoding vector that has the information of the input values and the hidden layer. The final encoding vector then is passed to the decoder to generate the next sequential values. If the hidden layer in the encoder part receives and passes the information in one forward direction, the encoder has memorized the information from the past time steps to predict the future, that is called a Unidirectional LSTM. If the hidden layer goes in a forward and a backward direction, the model has learned from the past and future for prediction, which is called a Bidirectional LSTM (BLSTM). Figure 1 shows the architecture of the proposed BLSTM model with an encoder part, input values, final encoding vector, and a decoder part. In the model, X_i is the input in the time step i and Y is the output element.

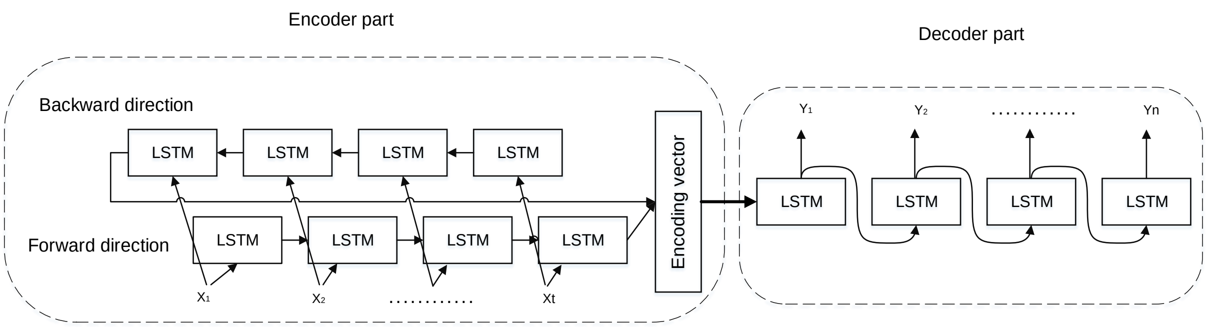

Fig. 1. The architecture of the proposed BLSTM model

The BLSTM model was developed and trained with the as-built schedule database. While training, the model learns the information of previous activities and previous relationships in forward direction and also learns the succeeding relationships via backward direction. The model receives one or many activities and predicts the most common successors and predecessor activities from the database.

Figure 2 illustrates four graphs of sample outputs of the BLSTM model. The model receives one or multiple input activities (green boxes with a bold font) and predicts successors (blue boxes) and predecessors (yellow boxes) with the highest likelihood of occurance in the database. In the first and second graph, one activity is given, and in the third and fourth, two and three sequential activities are given to the model. The numbers show the number of times that the sequence of activities, from the input activities until the specific activities, occurred in the database. For example, in the case #2, the input activity is "guard rail" that occured 21 times in the database. The model predicts the successors. For example, the sequence of "guard rail- rumble strip" occurred 6 times and the sequence of "guard rail- rumble strip – seal and cover" occurred 3 times and so on. For predecessors, the sequence of "plant mix surfacing – guardrail" occurred 5 times in the database and so on.

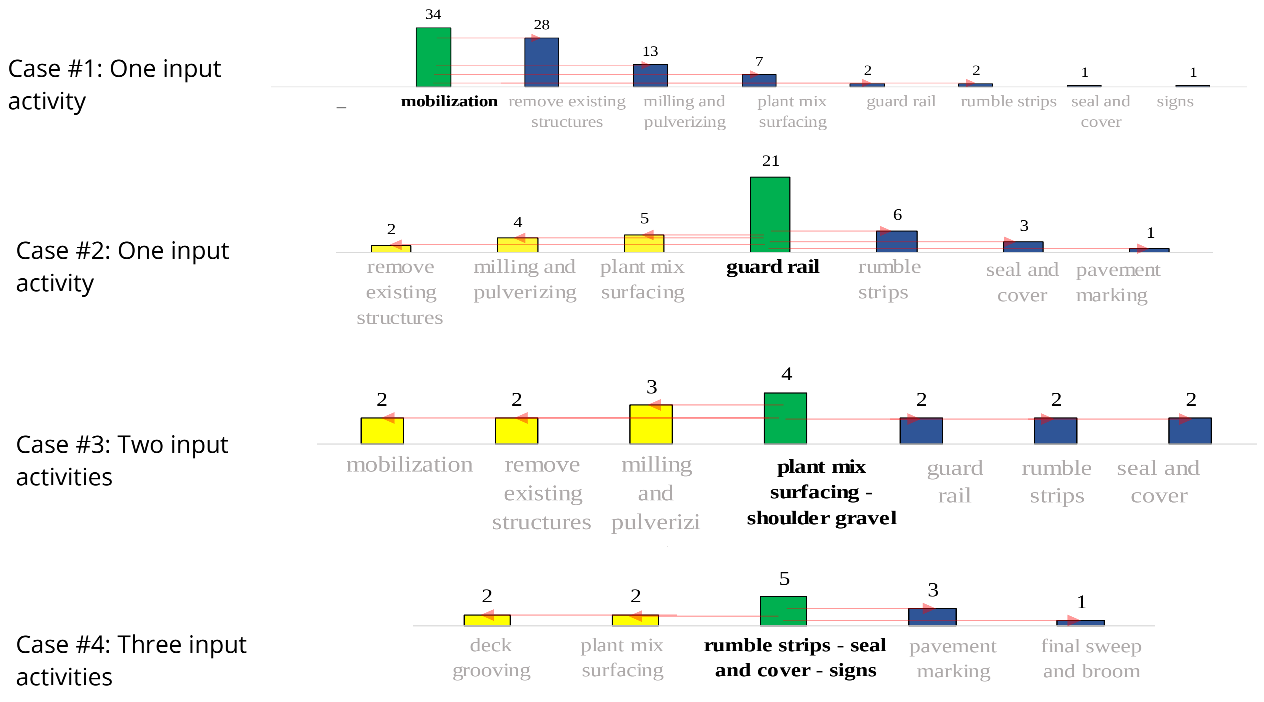

Fig. 1. Four samples of the results of the BLSTM model on the historical as-built schedule data

5. Sequential pattern mining (SPM) model

The method of SPM and the application on construction schedules is fully explained in Shrestha et al. [8]. Given a sequence of activities, the SPM discovers all sequential patterns with various lengths. The SPM is applied to the 34 cases of highway schedules and discovered the most common sequential patterns including eight-activities, seven-activities, and other lengths. The results for eight and seven activities are:

- The most common eight-activity pattern: “Mobilization -> Remove Existing Structures -> Milling and Pulverizing -> Plant Mix Surfacing -> Guard Rail -> Rumble Strips -> Seal and Cover -> Pavement Marking”.
- The most common seven-activity pattern: “Mobilization -> Remove Existing Structures -> Milling and Pulverizing -> Plant Mix Surfacing -> Guard Rail -> Seal and Cover -> Pavement Marking”

6. Comparison results

The results of the BLSTM and SPM models are compared in Table 1. Both models perform the same when it comes to identifying the common patterns. However, the advantage of BLSTM over SPM is the flexibility in receiving one or multiple specific activities and provide arbitrary number of next and previous activities. Although SPM can discover common patterns, it doesn’t provide successors of specific activities. The BLSTM can also predict the predecessors as well as successors, because of bidirectional training, while the SPM doesn’t predict predecessors. The results of the BLSTM model can be used by schedulers to identify proper activity sequences and relationships.

Table 1. Comparison of the results of the BLSTM and SPM models

Task	BLSTM	SPM	Description
Identifying the most common sequential patterns	✔	✔	Both models perform the same in this task.
Predicting successor activities, given specific activity/activities	✔	✖	The BLSTM receives spesific activities and predicts the related successors, while the SPM identifies the common patterns and cannot predict successors for spesific activities.
Predicting predecessor activities, given specific activity/activities	✔	✖	The BLSTM can predict successors and predecessors at the same time because of two-directional training. However, the SPM just work in forward direction and cannot predict predecessors.
Arbitraty number of inputs and outputs	✔	✖	The BLSTM is flexible in receiving one or multiple activities and predicting arbitrary number of successors and predecessors.

7. Conclusion

This paper introduced a Deep Learning Bidirectional LSTM (BLSTM) model to learn the sequence of activities in highway projects and trained on real cases of 34 as-built highway project schedules of Montana DOT. The model receives one or a chain of activities and predicts an arbitrary number of predecessor and successor activities. The model can help schedulers to identify the sequence of activities in highway schedules, in that the schedulers give one or multiple activities and the model provides the related activities and their sequential arrangement that are likely to have the highest probability of occurrence in the past projects. The results of the model were compared to a recent sequence analysis model, called SPM algorithm, that was applied on the same dataset. The comparison showed that the BLSTM model is able to predict the next and the past chain of activities at the same time. It is also more flexible in receiving any arbitrary number of input activities and provide the related predecessors and successors.

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A Project Crashing Strategy Considering Contract Clauses and Quality Considerations: An Illustrative Example

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Abstract

Project crashing, a.k.a. project compressing or time-cost trade-off, is an important aspect of managing construction projects. Project crashing can be defined as the time-cost optimization technique, which aims to compress the total project duration with the least incremental cost. In real life problems, the quality is affected when some activities are crashed. This effect may be in a positive or negative way. In addition, there may be strict contract clauses regarding the project duration in terms of early finish bonus and penalty. In this study, a mathematical integer linear programming optimization model is developed using Visual Basic Programming Language integrated with Excel Solver add-in, in order to evaluate different strategies for project execution considering time, cost and quality concerns. Moreover, the developed model takes into account the relationship between crashing cost, early finish bonus, and penalty cost. The proposed model enables project managers to select the most appropriate project crashing strategy at the beginning of the project. An illustrative example is also presented in order to show how the proposed approach can be implemented in real cases.

Keywords: contract clauses, illustrative example, integer linear programming, project crashing, quality considerations

1. Introduction

In the construction industry, all project parties, i.e., owners, design team, contractors, suppliers, etc., are obligated to fulfil their responsibilities specified in the contract clauses. A project's success mainly depends on how much these parties fulfil their responsibilities in order to meet the project objectives in terms of time, cost and quality requirements [1]. There is a relationship between these objectives. One way of shortening the project duration is the project crashing. Project crashing is a useful technique, which allocates additional resources, e.g., utilizing more efficient equipment or hiring more workers, for the critical activities to accelerate their durations with the possible lowest cost [2].

The large majority of the researchers deal with solving the relationship between time-cost [3-18], whereas the remainders deal with not only time-cost but also quality [19-28]. When reviewing the studies, which address time-cost-quality trade-off problem, it can be seen that quality is considered only as a threshold [20,23]. Few number of studies claim that project crashing may bring about an additional cost for the satisfaction of required quality level through corrective/preventive actions [5,21,22]. Moreover, only a few number of studies considered the contract clauses regarding the project duration in terms of delay penalty and early finish bonus [8,9,29]. However, these studies generally neglect the quality aspect.

Crashing activities has an impact on their quality level in a positive or negative way. If this impact is in a negative way, some corrective and/or preventive actions should be taken in order to satisfy the expected quality level, which may increase the overall project cost. On the other hand, if this impact is in a positive way, the exposition to the risk may decrease, which in turn may decrease the quality cost. Therefore, there is a need for a study, which considers time-cost trade-off problem as well as the effects of crashing on quality and the strict contract clauses regarding the project duration, e.g., penalty cost and early finish bonus.

This study aims to fulfil this gap through developing a tool, which automates project crashing considering not only time-cost trade-off but also its impact on quality and contract clauses in terms of penalty cost and early finish bonus. In order to demonstrate how the developed model can be used in real cases, an illustrative example consisting of 18 activities was used.

2. The proposed model

For the calculations of relationships of proposed model, Critical Path Method (CPM), which is firstly introduced to solve the "practical" business problems, is used [30]. The original CPM model aimed to finding the minimum cost of a project for all possible project durations [31], so it a useful method for the project crashing process. The proposed model mainly consists of four main steps, which are briefly explained below:

Step 1: In this step, the inputs of the developed model are specified. These inputs include definition of the activities, total number of activities, their normal durations, normal (direct) costs, predecessors and successors of activities, maximum allowable crash times, daily crashing costs of activities, daily indirect cost of the project, the impact of crashing the activity on quality (i.e., threat or opportunity), the quality cost of crashing of the activity for 1 day, the contract duration, penalty cost, and early finish bonus. The inputs of the proposed model are presented in Table 1.

Table 1. The inputs of the proposed model

Notation	Definition
i	Predecessor of activity j
j	Successor of activity i
N	Total number of activities in the project
T_{ndi}	Normal duration of activity i
C_{nci}	Normal (direct) cost of activity i
U_{aci}	Maximum allowable crash time of activity i
C_{cci}	Daily crashing cost of activity i
C_{ic}	Daily indirect cost of the project
$Q(TorO)_i$	Impact of crashing the activity i on quality (i.e., threat (T) or opportunity (O)) (+1 for T, -1 for O)
C_{qti}	Quality cost of crashing activity i for 1 day
T_d	Contract duration
C_p	Daily penalty cost due to the delay on the contract duration
C_{efb}	Daily early finish bonus due to early finish of the project

Step 2: In this step, two constraints are defined. The first constraint ensures that the crash time of an activity cannot excess the maximum allowable crash time assigned for this activity. The second constraint prevents violating the predecessor-successor relationships between activities.

Step 3: In this step, some transitional outputs are computed. The transitional outputs include actual project completion time, total normal (direct) cost (Eq. 1), total indirect cost (Eq. 2), the number of crashed days for each activity, total crashing cost (Eq. 3), total quality cost (Eq. 4), total penalty cost in the case of delay, if applicable (Eq. 5), and total early finish bonus that decreases the total project cost in the case of completing the project earlier than the contract duration (Eq. 6), if applicable. The transitional outputs of the proposed model are presented in Table 2.

Table 2. Transitional outputs of the proposed model

Notation	Definition
T_c	Actual project completion duration
C_{nct}	Total normal (direct) cost
C_{ict}	Total indirect cost
Z_i	The number of crashed days for activity *i*
C_{cct}	Total crashing cost
C_{Qt}	Total quality cost
C_{pt}	Total penalty cost
C_{efbt}	Total early finish bonus

The equations used to compute the transitional outputs are presented in Equations 1-6.

$$C_{nct} = \sum_{i=1}^{N} C_{nci} \quad (1)$$

$$C_{ict} = C_{ic} \times T_c \quad (2)$$

$$C_{cct} = \sum_{i=1}^{N} Z_i \times C_{cci} \quad (3)$$

$$C_{Qt} = \sum_{i=1}^{N} Z_i \times Q(TorO)_i \times C_{qti} \quad (4)$$

$$C_{pt} = \begin{cases} (T_c - T_d) \times C_p & \text{,if } \mathrm{T_c > T_d} \\ 0 & \text{,if } \mathrm{T_c \leq T_d} \end{cases} \quad (5)$$

$$C_{efbt} = \begin{cases} (T_d - T_c) \times C_{efb} & \text{,if } \mathrm{T_d > T_c} \\ 0 & \text{,if } \mathrm{T_d \leq T_c} \end{cases} \quad (6)$$

Step 4: In this step, the objective function is determined. For this purpose, first the total project cost (Eq. 7) is calculated, which is the sum of total direct cost, total indirect cost, total crashing cost, total quality cost, total penalty cost, and total early finish bonus.

$$C_{pc} = C_{nct} + C_{ict} + C_{cct} + C_{Qt} + C_{pt} - C_{efbt} \quad (7)$$

The objective function is the minimization of the total project cost (Eq. 8).

$$min(C_{pc}) \quad (8)$$

3. Illustrative example

The applicability of the proposed approach is demonstrated using a network consisting of 18 activities [32]. The network of the illustrative example is presented in Figure 1.

The inputs for the illustrative example is presented in Table 3. The activities A1, A2, A4, A5, A7, A8, A9, A11, A13, A14, A16, and A17 are considered to be threats, whereas the activities A3, A6, A10, A12, A15, and A18 are considered to be opportunities in terms of quality. The total project completion duration is found to be 105 days. The contract duration is accepted as 95 days. Daily penalty cost is considered to be \$300, whereas \$250 of daily early finish bonus will be paid to the contractor in the case that the project finishes earlier than the contract duration. Finally, the daily indirect cost is determined as \$400.

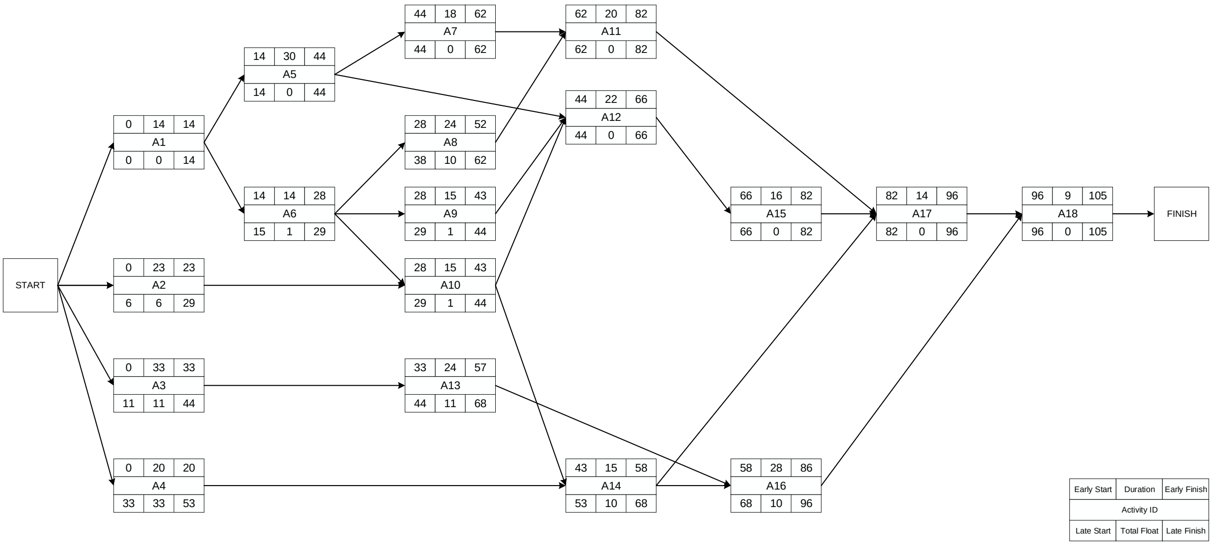

Fig. 1. Network for illustrative example.

The actual project completion duration is found to be 105 days.

Table 3. Inputs of the illustrative example.

Activity ID	Immediate Predecessor Activity	Duration (Day)	Max. Crash Times (Day)	Normal (Direct) Cost ($)	Daily Normal Cost ($/Day)	Daily Crashing Cost ($/day)	Quality Cost ($/day)	Threat or Opportunity (Binary)
A1	Start	14	4	20,000.00	1,428.57	285.71	114.29	T
A2	Start	23	5	19,000.00	826.09	165.22	66.09	T
A3	Start	33	8	23,000.00	696.97	139.39	27.88	O
A4	Start	20	4	24,000.00	1,200.00	240.00	96.00	T
A5	A1	30	6	11,000.00	366.67	73.33	29.33	T
A6	A1	14	3	20,000.00	1,428.57	285.71	57.14	O
A7	A5	18	6	22,000.00	1,222.22	244.44	97.78	T
A8	A6	24	7	25,000.00	1,041.67	208.33	83.33	T
A9	A6	15	3	35,000.00	2,333.33	466.67	186.67	T
A10	A2,A6	15	3	42,000.00	2,800.00	560.00	112.00	O
A11	A7,A8	20	4	41,000.00	2,050.00	410.00	164.00	T
A12	A5,A9,A10	22	5	35,000.00	1,590.91	318.18	63.64	O
A13	A3	24	8	42,000.00	1,750.00	350.00	140.00	T
A14	A4,A10	15	5	43,000.00	2,866.67	573.33	229.33	T
A15	A12	16	0	39,000.00	2,437.50	487.50	97.50	O
A16	A13,A14	28	8	24,000.00	857.14	171.43	68.57	T
A17	A11,A14,A15	14	3	15,000.00	1,071.43	214.29	85.71	T
A18	A16,A17	9	2	20,000.00	2,222.22	444.44	88.89	O

The proposed model was developed using Visual Basic Programming Language integrated with Excel Solver add-in. Having inputted the required information, the developed model automatically generates the schedule, determines the critical activities, and selects critical activity/activities for crashing. In the developed model, the project duration is shortened day by day. The process is repeated until a feasible solution cannot be found.

Two different scenarios were applied in the illustrative example. In the first scenario, it is assumed that crashing an activity does not have an impact on the quality level of the activity. The crashed activities and their crashing costs in the first scenario are presented in Table 4.

Table 4. Crashed activities and their crashing costs in the first scenario, where the impact on quality is not considered.

Project Duration (Day)	Sequence of Activities Crashed	Total Normal Cost ($) (1)	Total Indirect Cost ($) (2)	Cumulative Crashing Cost ($) (3)	Penalty Cost ($) (4)	Early Finish Bonus ($) (5)	Cumulative Total Project Cost ($) (1+2+3+4-5)
105	-	500,000.00	42,000.00	0.00	3,000.00	0.00	545,000.00
104	A5	500,000.00	41,600.00	73.33	2,700.00	0.00	544,373.33
103	A17	500,000.00	41,200.00	287.62	2,400.00	0.00	543,887.62
102	A17	500,000.00	40,800.00	501.90	2,100.00	0.00	543,401.90
101	A17	500,000.00	40,400.00	716.19	1,800.00	0.00	542,916.19
100	A1	500,000.00	40,000.00	1,001.90	1,500.00	0.00	542,501.90
99	A1	500,000.00	39,600.00	1,287.62	1,200.00	0.00	542,087.62
98	A1	500,000.00	39,200.00	1,573.33	900.00	0.00	541,673.33
97	A1	500,000.00	38,800.00	1,859.05	600.00	0.00	541,259.05
96	A5,A6	500,000.00	38,400.00	2,218.10	300.00	0.00	540,918.10
95	A5,A12	500,000.00	38,000.00	2,609.61	0.00	0.00	540,609.61
94	A5,A12	500,000.00	37,600.00	3,001.13	0.00	250.00	540,351.13
93	A18	500,000.00	37,200.00	3,445.57	0.00	500.00	540,145.57
92	A18	500,000.00	36,800.00	3,890.01	0.00	750.00	539,940.01
91	A3,A5,A12	500,000.00	36,400.00	4,420.92	0.00	1,000.00	539,820.92
90	A3,A5,A12	500,000.00	36,000.00	4,951.83	0.00	1,250.00	539,701.83
89	A3,A7,A12	500,000.00	35,600.00	5,653.85	0.00	1,500.00	539,753.85
88	A2,A3,A6,A7	500,000.00	35,200.00	6,488.62	0.00	1,750.00	539,938.62
87	A2,A3,A6,A7	500,000.00	34,800.00	7,323.39	0.00	2,000.00	540,123.39
86	A3,A7,A9,A10	500,000.00	34,400.00	8,733.90	0.00	2,250.00	540,883.90
85	A3,A7,A9,A10	500,000.00	34,000.00	10,144.40	0.00	2,500.00	541,644.40

In the second scenario, it is assumed that crashing an activity has an impact on the quality level of the activity. The crashed activities and their relevant costs in the second scenario are presented in Table 5.

Table 5. Crashed activities and their relevant costs in the second scenario, where the impact on quality is considered

Project Duration (Day)	Sequence of Activities Crashed	Total Normal Cost ($) (1)	Total Indirect Cost ($) (2)	Cumulative Crashing Cost ($) (3)	Cumulative Quality Cost ($) (4)	Penalty Cost ($) (5)	Early Finish Bonus ($) (6)	Cumulative Total Project Cost ($) (1+2+3+4+5-6)
105	-	500,000.00	42,000.00	0.00	0.00	3,000.00	0.00	545,000.00
104	A5	500,000.00	41,600.00	73.33	29.33	2,700.00	0.00	544,402.67
103	A17	500,000.00	41,200.00	287.62	115.05	2,400.00	0.00	544,002.67
102	A17	500,000.00	40,800.00	501.90	200.76	2,100.00	0.00	543,602.67
101	A17	500,000.00	40,400.00	716.19	286.48	1,800.00	0.00	543,202.67
100	A5,A6	500,000.00	40,000.00	1,075.24	258.67	1,500.00	0.00	542,833.90
99	A5,A6	500,000.00	39,600.00	1,434.29	230.86	1,200.00	0.00	542,465.14
98	A5,A6	500,000.00	39,200.00	1,793.33	203.05	900.00	0.00	542,096.38
97	A18	500,000.00	38,800.00	2,237.78	114.16	600.00	0.00	541,751.94
96	A18	500,000.00	38,400.00	2,682.22	25.27	300.00	0.00	541,407.49
95	A5,A12	500,000.00	38,000.00	3,073.74	-9.03	0.00	0.00	541,064.70
94	A5,A12	500,000.00	37,600.00	3,465.25	-43.34	0.00	250.00	540,771.92
93	A1	500,000.00	37,200.00	3,750.97	70.95	0.00	500.00	540,521.92
92	A1	500,000.00	36,800.00	4,036.68	185.24	0.00	750.00	540,271.92
91	A3,A7,A12	500,000.00	36,400.00	4,738.70	191.50	0.00	1,000.00	540,330.20
90	A3,A7,A12	500,000.00	36,000.00	5,440.72	197.76	0.00	1,250.00	540,388.48

Table 5 (continued). Crashed activities and their relevant costs in the second scenario, where the impact on quality is considered

Project Duration (Day)	Sequence of Activities Crashed	Total Normal Cost ($) (1)	Total Indirect Cost ($) (2)	Cumulative Crashing Cost ($) (3)	Cumulative Quality Cost ($) (4)	Penalty Cost ($) (5)	Early Finish Bonus ($) (6)	Cumulative Total Cost ($) (1+2+3+4+5-6)
89	A3,A7,A12	500,000.00	35,600.00	6,142.74	204.02	0.00	1,500.00	540,446.76
88	A1,A2,A3	500,000.00	35,200.00	6,733.07	356.52	0.00	1,750.00	540,539.58
87	A1,A2,A3	500,000.00	34,800.00	7,323.39	509.01	0.00	2,000.00	540,632.40
86	A3,A7,A9,A10	500,000.00	34,400.00	8,733.90	653.58	0.00	2,250.00	541,537.47
85	A3,A7,A9,A10	500,000.00	34,000.00	10,144.40	798.14	0.00	2,500.00	542,442.55

The total project cost is also affected by the contract clauses related to penalty cost and early finish bonus. Total project costs at different project completion durations based on the findings of different scenarios are compared in Table 6.

Table 6. Total costs at different project completion durations.

Project Duration (Days)	Contract Clauses and Quality are not Considered ($)	Contract Clauses are not Considered, but Quality Considered ($)	Contract Clauses are Considered, but Quality is not Considered ($) (Scenario 1)	Contract Clauses and Quality are Considered ($) (Scenario 2)
105	542,000.00	542,000.00	545,000.00	545,000.00
95	540,609.61	541,064.70	540,609.61	541,064.70
92	540,690.01	541,021.92	539,940.01	540,271.92
90	540,951.83	541,638.48	539,701.83	540,388.48
85	544,144.40	544,942.55	541,644.40	542,442.55

As it can be seen in Table 6, when the contract clauses related to penalty cost and early finish bonus are not considered (columns 2 and 3 in Table 6), the minimum total project cost attained in Days 95 and 92, respectively, since the daily crashing cost is lower than the sum of daily indirect cost and the quality cost (if applicable). On the other hand, when the contract clauses are considered (columns 4 and 5 in Table 6), the minimum total project cost is attained at Days 90 and 92, respectively, due to the contract clauses and decrease in indirect cost. Moreover, when the impact of crashing on the quality level of the activities is not considered (column 4 in Table 6), the total project cost is lower than the one when its impact is considered (column 5 in Table 6). This finding would be different in different cases. This finding also indicates that the impact of crashing on the quality level of the activities should be considered as it directly affects the total project cost and the sequence of the crashed activities.

4. Conclusion

Project crashing has been studied by numerous researchers for many years. In most of these studies, the contract clauses related to penalty cost and early finish bonus, and the impact of crashing on both the quality level of the crashed activities and the quality cost are neglected. This study proposes a crashing model, which considers both contract clauses and the impacts of crashing on quality. In order to demonstrate how the proposed model can be employed, an illustrative example was presented. For this purpose, the proposed model was developed using Visual Basic Programming Language integrated with Excel Solver add-in. The results indicated that both the contract clauses and quality considerations have significant influence on total project cost. This study is limited as the illustrative example consists of only eighteen activities. In future studies, the proposed model can be applied in a real-life project.

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Accelerating the Execution of Construction Projects by Relocating Resources

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Abstract

Project managers strive to reduce the capital project execution times. Project owners typically insists on quick delivery for financial benefits of early occupation of the built facility (commercial projects), or for reducing public dissatisfaction caused by the works (public projects like road repairs). Construction and civil projects are notorious for delays due to both external and internal factors. The delays require action to be taken to make the project "back on tracks" and finish on time. Given a limited budget and the need for efficient use of resources, the problem of scheduling projects with short completion times is being addressed by a variety of ideas, such as letting non-critical construction processes to be suspended to free resources to more crucial ones, switching to faster but costly construction methods, or allowing changes in the process sequence. This paper presents a new idea on how to accelerate a construction project by relocating some of the workers from non-critical processes to support crews performing critical ones, and possibly by employing additional resources. The authors describe their idea in the form of a mixed-integer linear problem. The model facilitates finding an optimal schedule of processes allowing the relocation of some non-critical or subcontractor resources to support critical crews and meet the baseline execution deadline. A numerical example illustrates the merits of the proposed approach. In practice, the method presented can constitute a valuable tool used in the management of construction projects.

Keywords: construction project management, construction project scheduling, resource allocation, resource-constrained project scheduling problem, schedule optimization

1. Introduction and literature review

Construction projects constitute a particular challenge for managers. The factors that contribute to their unpredictability include susceptibility of construction processes to weather, uniqueness of designs, late effects resulting from the construction process and long-term operation of the building objects, high employee turnover rates, various supply-related logistical problems, and high failure rate of the machines and equipment [1], [2]. On the one hand, these projects are commonly understood as exceptionally difficult to deliver on time. On the other hand, the project owners are rigorous about deadlines specified in the contract. The clients desire to benefit from the outcomes of the investment as quickly as possible. They also need to conform to the bank loan conditions. Thus, they tend to set short and fixed due dates with little understanding for the "unexpected obstacles" likely to be encountered by the contractor.

Managers of construction projects are faced with a challenging task: while meeting the quality and work safety requirements, they need to keep the schedules very tight. An even greater complication in the management process occurs in the event of some schedule risk materialising. The traditional tools and methods such as Critical Path Method (CPM), Precedence Diagramming Method (PDM), Linear Scheduling Method (LSM), Program Evaluation and Review Technique (PERT) prove inadequate for such challenges [3]–

[9]. The practical schedule crashing requires the planner to ensure efficient use of resources and to minimise costs. The time-cost trade-off belongs to the scheduling problems most frequently addressed in the literature. Even the first scientific paper on CPM focused on it [10]. PDM, the prevailing network technique of current construction practice, is being continuously developed. A catalogue of its potential enhancements, described by Haidu and Isaac [11], includes: maximal relations, splittable activities, logical switches on relations, point-to-point relations, continuous relations, bi-directional relations, and non-continuous activity time-production functions. Some of them have already been implemented in models presented in the literature on the subject. For instance, discontinuation of non-critical construction processes to make their resources available for the critical ones was adopted in [12] and [13]. Continuous precedence relations were used in [14]. Some authors consider the possibility of changing the manner the processes are executed in search of a trade-off between process cost and time, use extra resources [6], [15], or allow a change in process sequence (soft relationships) in the network model of a project [16], [17].

Tomczak and Jaśkowski developed models that improve the work continuity of the general contractor's in-house crews, both in non-repetitive [3], [18], and repetitive projects [19]. Their Mixed Integer Linear Problem (MILP) models assumed that subcontractors can be employed to help smooth the general contractor’s resources, which optimized the use of in-house labour and improved the harmonisation of work throughout the project.

The model presented by Altuwaim and El-Rayes [12] allowed interrupting secondary construction processes to reduce the overall project duration and to improve the continuity of works. The merits of the model were presented on the example of a repetitive project. García-Nieves et al. [15] developed a mathematical model minimizing the duration and tardiness of repeatable construction projects. The model helped select modes of process execution to accelerate their realisation. Additionally, it allowed the planner to define which tasks can be split if necessary, set fixed precedence relationships and optimum crew size. The authors applied their method to find optimal schedules in a project under seven scenarios of resource availability and continuity conditions.

Hajdu, Lucko, and Su [14] explore the potential of a new type of relationship between the processes, called the continuous precedence relation. It enables the planner to precisely model the processes’ overlapping, as it relates the whole processes, and not only their start and finish moments. In addition, this relationship allows the planner to use non-linear activity representations.

A model minimizing the overall cost of road projects, including the costs incurred by road users and surrounding businesses, was presented in the paper [20]. The modelling is done on two levels. The higher level of the system is formulated as a mixed integer problem and its aim is to set the optimum project start date in terms of the overall cost. The lower level of the system is intended to model the decision-making process of drivers in accordance with the project commencement times received from the higher level. The application of the approach can result in a reduction of business disruptions in the vicinity of the project with little increase in travel time.

To reduce work interruptions and improve the organization of work on a construction site, Rzepecki and Biruk [21] included the learning-forgetting effect in their scheduling model with constraints. A similar model [22] was used to minimize the time and cost of the project; the simulation analyses showed an improvement in the organisation of work in terms of the adopted criteria.

Despite the availability of construction management techniques and tools, it appears that the methods which already exist still fail to solve specific problems occurring in the management of construction projects. It is therefore necessary to develop further tools to support construction site managers in resolving emerging issues.

2. Methods used

The authors have developed a MILP, which accelerates a construction project by relocating some of the workers from non-critical processes to support crews performing critical ones, and possibly by employing additional resources. Due to the constrained length of the paper, the assumptions of the model are presented without the mathematical formulation.

The project needs to be described by an Activity-on-Node (AON) network diagram representing logical dependencies between the processes. In its current form, the model covers only the Finish-to-Start (FS) precedence relations, does not enable defining different calendars for the project and the resources, and operates only in working days. Therefore, the process durations are to be defined as numbers of working days. The planner needs to identify a list of crews capable of performing particular processes. The model assumes that at least some crews are composed of smaller operating units, further referred to as teams. As construction workers are usually trained in more than one trade, the crews are considered multi-skilled. This means that they are capable of delivering several types of processes. A team can be added to a crew to reinforce it. It can also be removed if some other crew needs urgent support. Thus, the planner is required to identify the processes and the crews from which teams are possible to be transferred out, as well as the processes and the crews that may need support in the form of extra teams.

Other assumptions are as follows: each process may be realised only in one execution mode. Subcontracting is possible but constrained: the cost of the subcontracted works may not exceed the cost of these works as if completed by in-house crews. Thus, the model helps take advantage of the general contractor's resources to the highest possible degree if economically justified.

The proposed model aims to reduce the project duration to meet the deadline by relocating selected working teams. The requirement to complete the project before the deadline is introduced as the model's constraint. However, the model's objective function is minimizing the number of instances of the teams' relocation. This is to obtain acceptable schedules while keeping modifications of crew composition to the minimum: changes in crew work routines are likely to generate disruption. The model respects the relationships between individual processes defined by the precedence network and prevents a crew from being assigned to more than one process at a time.

3. Example and results

Let us consider an example to illustrate the merits of the model: a project that consists in the erection of two buildings. The construction of each building comprises eight work packages. The general contractor has two crews (GC-1 and GC-2). The GC-2 crew is composed of two identical work teams, GC-2-1 and GC-2-2. If necessary, one of them may assist the GC-1 crew in executing selected work packages. There are also 5 subcontractor crews marked A to E. The network model of the project and the options of resource assignment are summarised in Figure 1. The process execution times according to resource options are presented in Table 1. Table 2 lists the costs of processes if entrusted to subcontractors. The total cost of subcontracted works must not exceed € 900,000.

A mathematical model of the problem concerning the sample construction project was developed and then solved using The Lingo14.0 software [23]. The calculations were performed on an Intel Core i5, 2 GHz CPU PC, with the solution delivered in 0.2 seconds.

The first analysis was devoted to a "baseline option" without the possibility of relocating the GC-2-2 work team to support the GC-1 crew and without subcontracting packages that physically could be entrusted to in-house crews. Its shortest duration was found to be 72 days with the cost of subcontracted works € 580,000.

Then the relocation of teams was enabled. The model prompted that the GC-2-2 should be relocated from processes 12 and 13 to processes 4 and 5. As a result, the duration of the project was reduced by 5 working days still using the same resources as the "baseline option".

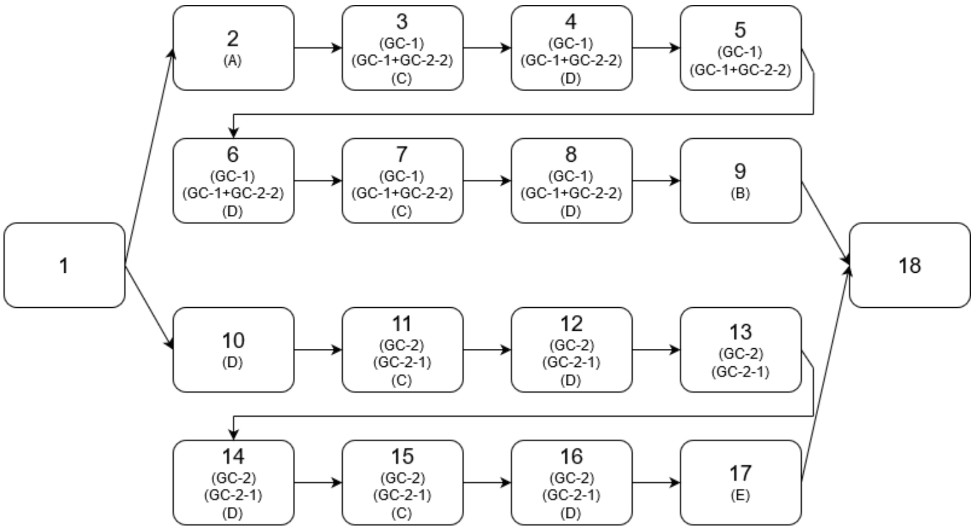

Fig. 1. The network model of the project with possible execution options

Table 1. Process execution times by resource variants

Building No.	Process No.	Process	Execution processes' durations [in working days]								
			GC-1	GC-1+GC-2-2	GC-2	GC-2-1	A	B	C	D	E
	1	Start									
Building A	2	Earthworks					3				
	3	Foundations	7	5					8		
	4	Foundation walls	14	11						16	
	5	Ground flooring	7	5							
	6	Walls	14	11						7	
	7	Floor	10	7					2		
	8	Walls of the attic	7	5						8	
	9	Roof						10			
Building B	10	Earthworks								1	
	11	Foundations			4	9			5		
	12	Foundation walls			7	14				9	
	13	Ground flooring			4	9					
	14	Walls			7	14				8	
	15	Floor			5	10			7		
	16	Walls of the attic			4	9				5	
	17	Roof									5
	18	Finish									

Further on, subcontracting was enabled. The employment of subcontractor crews for the execution of the processes 6 and 7 resulted in a reduction of 15 days in the construction duration. Eventually, the project duration was reduced to 52 days, with the cost of the subcontracted works of €850,000. A detailed Gantt chart for the optimal schedule of the sample construction project is presented in Fig. 2.

4. Conclusions

Managing construction projects is a challenge, and the consequences of wrong decisions are particularly costly. There is a need for reliable support for decision making. The method of reducing the project duration described in this paper may serve as one of such practical tools. It may be used for re-scheduling projects subject to serious disruption when one needs to find a way to speed up while relying on a fixed pool of resources. The method may also be used by contractors at the bidding stage to analyse how to make the best use of the resources at hand and how to subcontract economically while meeting the contractual deadlines.

Table 2. The execution costs of the individual processes realised by the subcontractor crews

Building No.	Process No.	Process	Execution processes' cost [in 1000 €]				
			A	B	C	D	E
	1	Start					
Building A	2	Earthworks	90				
	3	Foundations			100		
	4	Foundation walls				80	
	5	Ground flooring					
	6	Walls				150	
	7	Floor			120		
	8	Walls of the attic				50	
	9	Roof		250			
Building B	10	Earthworks				70	
	11	Foundations			70		
	12	Foundation walls				60	
	13	Ground flooring					
	14	Walls				120	
	15	Floor			90		
	16	Walls of the attic				30	
	17	Roof					170
	18	Finish					

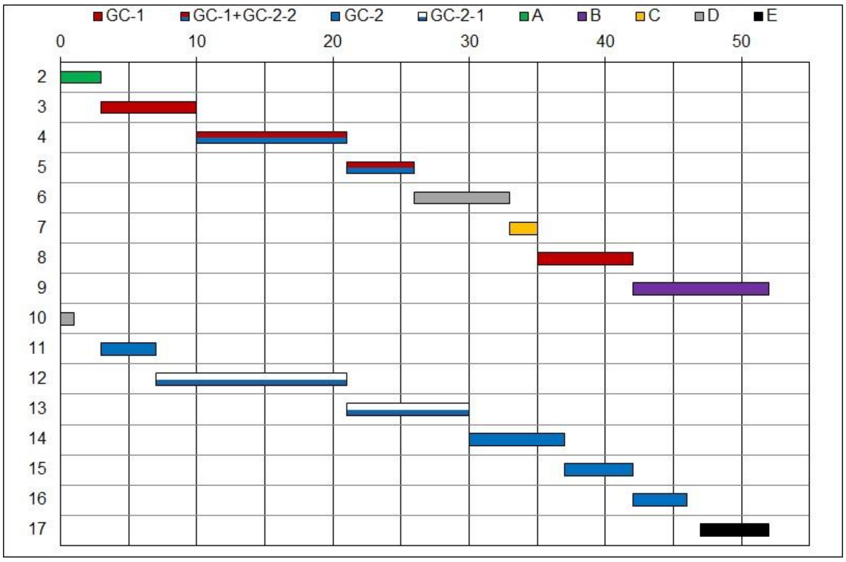

Fig. 2. A Gantt chart for the optimum schedule of the sample construction project

While the idea seems promising, the model is still crude. One of the future directions for its development is adapting it for repeatable projects. The model is going to be expanded to consider process relationships other than Finish-to-Start (FS). Moreover, as it is now purely deterministic, the next issue be addressed is adapting it for risk. Moreover, the model needs to be integrated with the existing scheduling tools for more user-friendly interface and useful options, such as calendars.

5. Acknowledgements

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An Enhanced Resource-Constrained Critical Path Method (eRCPM)

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Abstract

The Resource-Constrained Critical Path Method (RCPM) identifies resource-dependent activity relationships (links) when mitigating a resource-supply demand problem. These resource links allow the identification of a continuous critical path and the calculation of correct float values. This paper presents the application of an Enhanced RCPM (eRCPM) in a progressed resource-constrained schedule.

The Enhanced RCPM 1) performs three different serial-based resource-constrained scheduling heuristics (one of those was developed by the authors of this study), 2) keeps and removes specific resource links in a progressed schedule before re-running the algorithm, and 3) selects a default schedule after evaluating some schedule characteristics. Additionally, an Enhanced RCPM system was developed and integrated with Primavera P6.

This system imports and reads data from a P6 project; performs the Enhanced RCPM; updates the P6 file; and puts the project back into the Primavera P6 database. From this updated schedule, users can get: 1) correct early and late CPM dates; 2) correct float values; 3) a continuous critical path; 4) the resources links that were added into the schedule, and 4) the amount of phantom float (float that does not exist) each activity had before adding the resource links into the schedule. The development of the eRCPM computerized system allows the identification of a continuous critical path, practically, in P6 resource-constrained schedules.

Keywords: phantom float, Primavera P6, resource overallocation, resource-constrained scheduling, resource-depend activity relationships

1. Introduction

The baseline schedule is frequently used to track project performance [1]. Resources, as a key component of schedules, must be also monitored to prevent or mitigate any extension on the Project Completion Time (PCT) because of resource availability. When the resource demand exceeds the supply, activities must be delayed until resources become available.

Due to the projects' size and complexity, schedulers use scheduling software such as Primavera P6 or Microsoft Project to fix the resource conflicts of a schedule. Even though the software solves the overallocation problem applying Resource-Constrained Scheduling (RCS) methods, the results show incorrect total float values and a broken critical path. This happens because RCS calculations suggest that activities have float but much of this float does not exist – hence the named Phantom Float [2]; [3].

Even though the Resource-Constrained Critical Path Method (RCPM) correctly calculates the floats of activities and identifies a continuous critical path in resource-constrained schedules, some shortcomings must be addressed to enhance its capability and make it more practical for real construction projects [3], [4]. This study tackles some of the flaws of the RCPM and illustrates the application of the Enhanced RCPM (eRCPM) with a case study.

2. RCPM shortcomings

This section briefly describes some of the flaws of the RCPM. A detailed literature review identifying the shortcomings of RCS-related algorithms can be found in [4].

2.1. Priority rules

Heuristics are problem-dependent, so they are likely to be better in some situations than in others. Some priority rules may work well for a project but may not work well when applied to a different project [5]. Even if the PCT obtained by two or more heuristics is the same, the sequence of the activities may be different [6].

The RCPM applies the Late Start (LS) heuristic to mitigate a resource-supply demand problem. Since each heuristic works differently and produces different schedule outcomes, the eRCPM incorporates 1) two additional heuristics (ES and Enhanced LF) and 2) a criterion to evaluate the resulting schedules and to select one as a default.

2.2. Removal of resource links

The RCPM was developed to solve the issue of a broken critical path in a resource-constrained schedule. Hence, Kim and de la Garza (2003) did not explore the application of the RCPM for control purposes further i.e., the use of resource links in a progressed schedule.

The updates on a baseline/progressed schedule could change the priority order identified by a heuristic to schedule the activities when an over-allocation problem exists. When re-applying the RCPM, the resource links identified before updating the project may no longer be required and/or new resource links can be identified because of the changes in the schedule. Some of the existing resource links should be removed from the schedule because they were identified based on previous and different conditions. If these links are kept, they constrain the schedule.

The RCPM removes all existing resource links before re-running the algorithm in a progressed schedule [3]. The eRCPM removes only the resource links located right to the data date each time a project is updated, and the algorithm is re-applied. The eRCPM keeps the resource links located left to the data date because the project was already executed based on these activities' configurations.

2.3. Selecting resource-driving activities

One issue that arises when identifying activity resource relationships is having different possible links configurations between activities [7], [8]. This occurs when having many current activities with many predecessors (see Fig. 1). The difference between the different schedules that can be generated is not only the number of resource links created but also the number of critical activities.

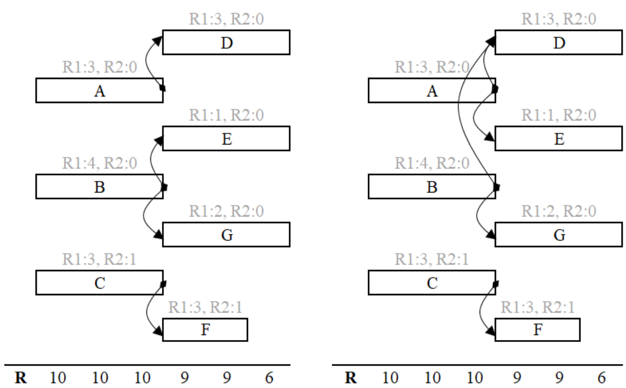


Fig. 1. Multiple Schedule Alternatives. Example taken from [8].

According to Nisar, Yamamoto, and Suzuki (2013), the resource dependences should be created in a way the total number of relationships is minimized without violating the resource constraints. The goal is to not increase the complexity of a network with a high number of resource relationships.

The RCPM does not incorporate any criteria to identify resource-driving activities. Instead, the RCPM creates all possible resource links configurations between the activities under consideration [3]. Given the influence on extending a PCT, the eRCPM considers the resources and duration of the activities as the main criteria to select a resource-driving activity.

2.4. RCPM prototype system

The RCPM prototype system developed by Kim and de la Garza in 2003 for Project Planner (P3) does not work for Primavera P6 because P6 is built on a different platform than P3. At present, there is a lack of practical mechanisms to identify resource relationships in P6 project schedules. Hence, the eRCPM was integrated with Primavera P6. The eRCPM system reads information from a P6 project, performs the necessary eRCPM procedures, and updates the P6 project with the corresponding resource relationships.

3. Enhanced Resource-Constrained Critical Method (eRCPM)

Figure 2 shows a comparison of the RCPM and eRCPM. This section explains each of the steps of the eRCPM (see Fig. 2b).

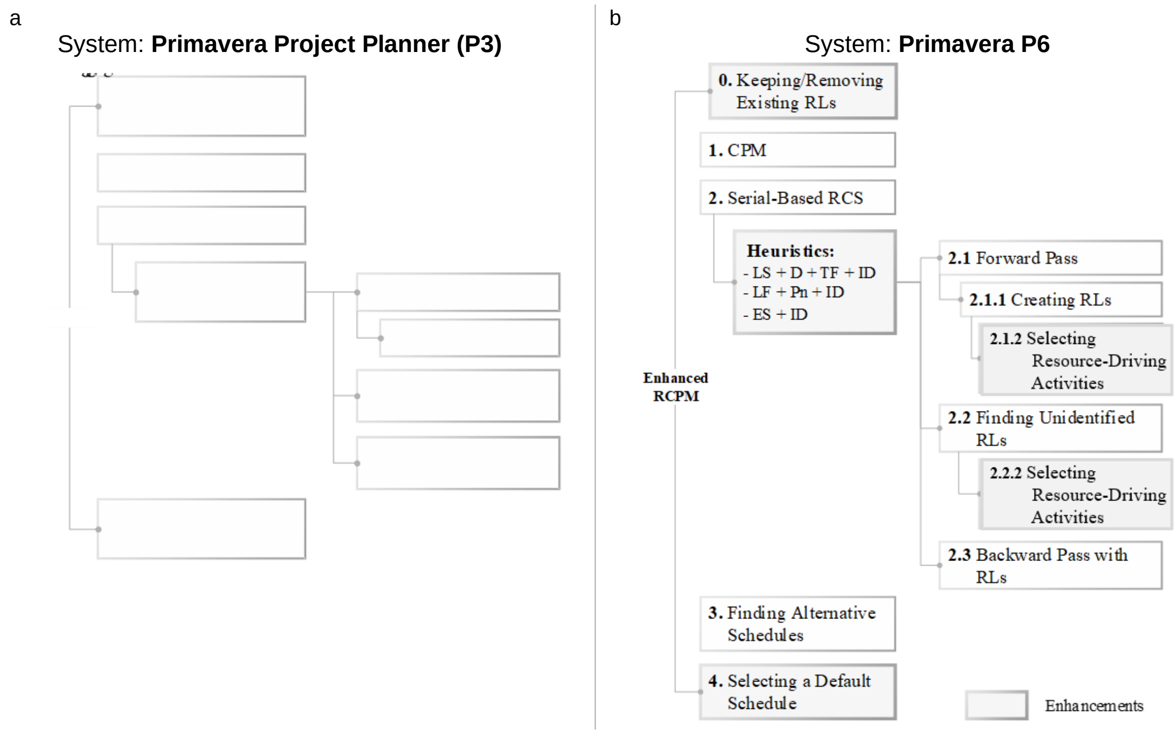


Fig. 2. Outline: (a) RCPM; (b) Fig. 2. Enhanced RCPM (eRCPM).

3.1. Step 0 - Keeping/removing resource links

In a progressed schedule with resource relationships, the eRCPM checks the status of each activity to determine whether a Resource Link (RL) should be removed from or kept on the schedule. The RLs are kept in the schedule if 1) both activities (predecessor and successor) are already complete and 2) the predecessor activity is complete, and the successor activity is in progress. Otherwise, the RLs are removed from the schedule if 1) the two activities (predecessor and successor) have not started yet and, 2) the predecessor activity is complete, but the successor activity has not started (see Fig. 3).

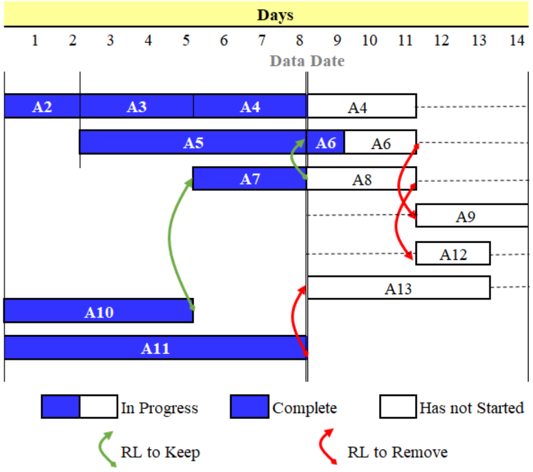


Fig. 3. Keeping and Removing Existing Resource Links before re-applying the eRCPM.

3.2. Step 1- Critical Path Method (CPM)

The eRCPM performs the CPM to find the early and late dates, and float values of each activity. If there is a resource overallocation problem, the eRCPM mitigates the resource-supply demand problem by applying resource-constrained heuristics.

3.3. Step 2 - Serial-based RCS heuristics with resource links

The eRCPM performs three different heuristics to mitigate a resource supply-demand problem: 1) Late Start (LS), 2) Enhanced Late Finish (LF), and 3) Early Start (ES). These three heuristics were incorporated into the algorithm because they produce better results in terms of extending the project duration than other existing priority rules [8]. The heuristics are performed under a serial approach, e.g., activities are sorted as a single group and then scheduled one at a time.

- In the Late Start heuristic, the priority is given to activities with the earliest values of Late Start (LS). If there is a tie with respect to the LS, the priority is given to the activity with the least duration (D). If the tie persists, the priority is given to the activity with the least total float (TF). If the tie persists, the priority is given to the activity with the smallest activity number (ID).
- In the Enhanced LF heuristic, the priority is given to activities with the earliest values of Late Finish (LF). If there is a tie with respect to the LF, the priority is given to the activity with the lowest Priority Number (Pn). The Priority Number, which is a tiebreaker that can be incorporated with any rule, is calculated based on the duration (Di) and total float (TFi) of each activity (see Equation 1). When an activity is critical ($TFi=0$), the TFi is assumed to be equal to 0.95. For an activity in progress, the remaining duration of the activity is used to calculate the Pn. If there is a tie with respect to the Pn, the tie is broken by the smallest activity number (ID). The formal definition of this new heuristic can be found in [9].

$$Pn = Di/TFi \qquad (1)$$

- In the Earliest Start heuristic, the priority is given to activities with the earliest values of Early Start (ES). If there is a tie with respect to the ES, the tie is broken by the smallest activity number (ID).

3.3.1. Step 2.1: Forward pass

Step 2.1.1 - Creating Resource Links: During the performance of any of the three RCS heuristics mentioned above, if there are not enough resources to execute an activity, the activity is delayed until resources become available. The resources causing the current activity delay are released from other activity completion [3]. Like the RCPM, the eRCPM creates a resource link (relationship) between the postponed activity (successor) and the preceding activity that shares the same resources (resource-driving activity).

Step 2.1.2 - Selecting resource-driving activities: The eRCPM considers three different cases to identify the "resource-driving activity" for the delayed task when having multiple alternatives.

Case I - One type of resource

When having one type of resource, the eRCPM selects as a resource-driving activity, the activity with the highest number of resources. If there is a tie with respect to the number of resources, the activity with the longest duration is selected. If the tie persists, the activity with the smallest activity ID is selected as a resource-driving.

For example, in Fig. 4, Activity A7 is delayed because of resource unavailability during days 1 to 8 (ten resources would be needed but only eight are available). Either A4 or A11 are the potential resource-driving activity of A7. For this scenario, the traditional RCPM creates two resource links, one between A4 and A7, and another between A11 and A7. The eRCPM creates only one link between A4 and A7 because A4 requires a higher number of resources than A7 (R = 2 vs R = 1).

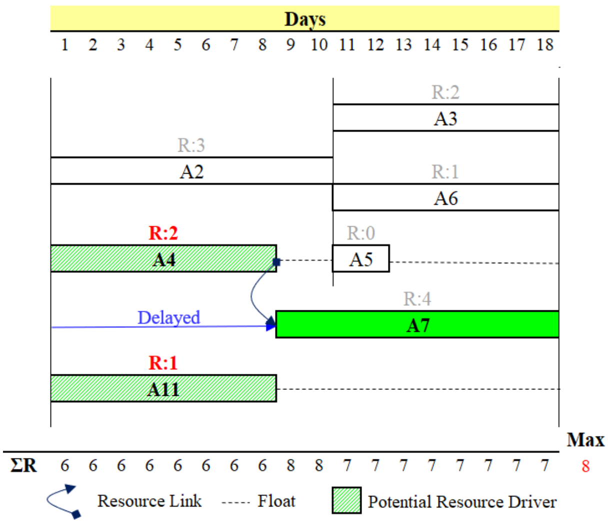


Fig. 4. Example of Case I: One Type of Resources.

Case II - Two types of resources and 1 conflicting resource

When having two types of resources and only one conflicting resource type, the eRCPM selects as a resource-driving activity, the activity with the highest number of conflicting resources. If there is a tie with respect to the higher number of resources, the activity with the longest duration is selected. If the tie persists, the activity with the highest number of the other type of resource is selected. If the tie persists, the activity with the smallest activity ID is selected.

In Fig. 5, Activity A11 was delayed because of the resource unavailability of R1. Activities A2, A4, and A10 are the potential resource-driving activities of A11. The traditional RCPM creates three RLs, one between A11 and A2; other between A11 and A4; and another between A11 and A10. The eRCPM creates only a link between A10 and A11. In this case, although A10 and A4 have the same higher number of the conflicting resource (R1 = 3) and the same duration (D = 7 Days), A10 requires more resources type two (R2 =2) than A4 (R2 =0).

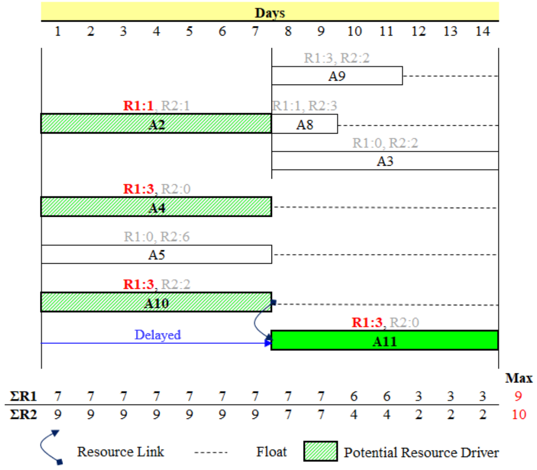


Fig. 5. Example Case II: Two Types of Resources and One Conflicting Resource.

Case III - Two or more conflict resources

When having two or more types of resources and several conflicting resource types, the eRCPM algorithm selects as a resource-driving activity, the activity with the highest average number of conflicting resources. If there is a tie with respect to the average number of conflicting resources, the activity with the longest duration is selected. If the tie persists, the activity with the smallest activity ID is selected as a resource-driving.

In Fig. 6, Activity A11 was delayed because of the resource unavailability of R2 and R3 (conflicting resource types). Activities A3, A7, and A8 are the potential resource-driving activities of A11. The traditional RCPM creates three RLs, one between A3 and A11, other between A7 and A11, and another between A8 and A11. The eRCPM creates only one link between A8 and A11. In this case, A8 has a higher average number of the two conflicting resources (Average A8= 3) than the other two activities (Average A3= 2.5; Average A7= 2).

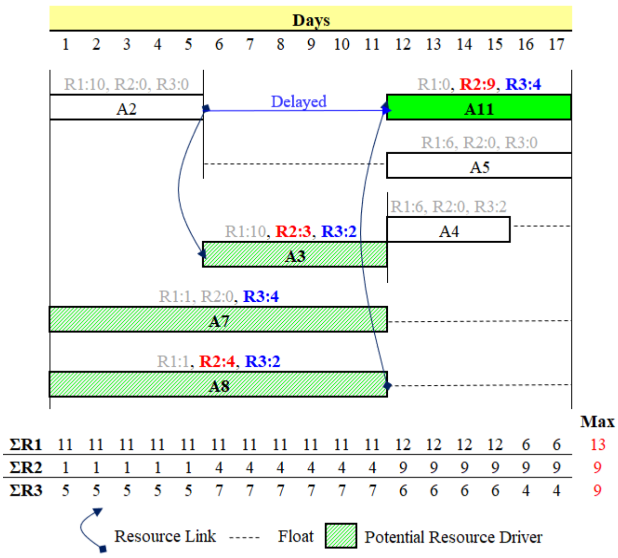


Fig. 6. Example Case III: Two or more Conflict Resources.

3.3.2. Step 2.2 Finding unidentified resource links

Like RCPM, before performing the backward pass, the eRCPM checks if non-critical activities (non-zero total float) can fully use the float (TF) or if there is any resource constraint for the float period [3]. If so, an additional resource link is created between the conflicting activities considering the three cases described above when having multiple possible resource-driving activities.

In Fig. 7, when checking for unidentified RLs, Activity A4, which has "apparently" seven days of float (Days 8 to 14), cannot be delayed because otherwise, an over-allocation arises with respect to R1 (11 resources will be needed and there are only nine available). Activities A8, A9, and A11 are the potential resource-driving activities of A4. The traditional RCPM creates three RLs, one between A4 and A8, other between A4 and A9, and another between A4 and A11. The eRCPM creates only a link between A4 and A11. In this case, although A11 and A9 have the same higher number of resources, the duration of A11 (D = 7 Days) is longer than A9 (D = 4 Days).

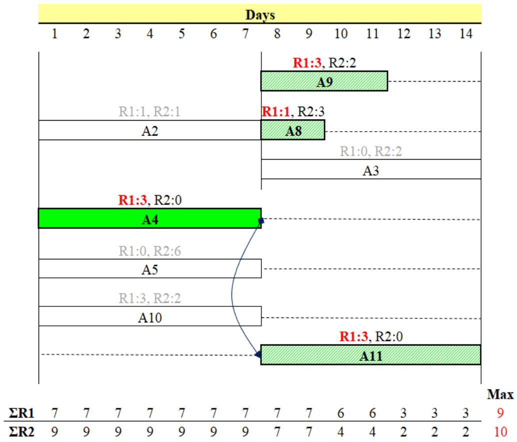


Fig. 7. Example: Identification of additional Resource Links.

3.3.3. Step 2.3 - Backward pass: Once all resource links are identified, the eRCPM performs the CPM backward pass considering both the technological and resource relationships. By considering both types of relationships, a continuous critical path can be identified in a resource-constrained schedule.

3.4. Step 3 - Alternate schedule

Like RCPM, the eRCPM finds alternative schedules by looking for activities that can be scheduled during a different period without breaching all the relationships.

3.5. Step 4 - Selecting a schedule

Since the eRCPM performs three different RCS heuristics (LS, Enhanced LF, and ES), the algorithm selects as a default schedule the one with the shortest duration. If there is a tie with respect to the Project Completion Time (PCT), the schedule with the smallest resource moment value (M_x) is selected.

The Minimum Moment (M_x) was chosen as a criterion to select a resulting resource-constrained schedule because it is a good measure of resource utilization. A lower value indicates a better resource allocation, e.g., a resource profile closer to a rectangular shape. The moment of the daily resource demands about the horizontal axis of a project's resource histogram (M_x) is calculated as shown in Equation 2 [10]. Where y_i represents the daily resource utilization. When having multiple types of resources in a schedule, M_x is calculated for each resource profile and then compared with the values of the other schedules. The schedule with the highest number of resource profiles with the lowest M_x is selected as a default schedule. The M_x is calculated after the data date for progressed schedules.

$$M_x = \frac{1}{2}\sum_{i=1}^{n} y_i^2 \qquad (2)$$

For example, the two schedules show in Fig. 8a and 8b (LS-based and ES-based respectively) have the same PCT (19 days) but different resource profiles. Since the M_x of the resource profile of the LS-based schedule is lower (197.0) than the that of the ES-based schedule (200), the eRCPM selects as default the LS-based schedule. The resource profile of this schedule is closer to a rectangular shape than that of the ES-based schedule and therefore, it has better resource allocation.

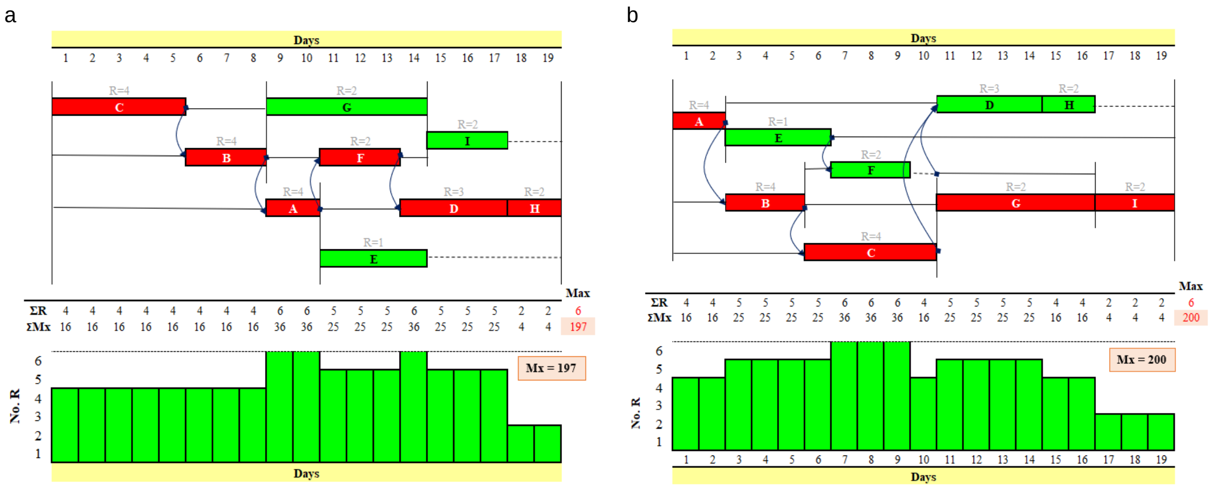


Fig. 8. Resource Profiles: Calculation of Mx: (a) LS-based Schedule; (b) ES-based Schedule.

If there is a tie with respect to the Mx, the schedule with the lowest number of critical activities (TF = 0) is selected as a default. If the tie persists, the schedule with the highest average of free float is selected as a default. The float values (TF and FF) were selected as parameters to select a resource-constrained schedule because 1) having a schedule with less critical activities decrease the probability of delaying the project completion time, and 2) having a schedule with a higher average time of free float gives more flexibility for delaying some activities without affecting the start time of the successor activities.

Finally, if there is still a tie between the three resulting schedules (LS, Enhanced LF, and ES based), the eRCPM selects the LS-based schedule as a default. If the tie is between the Enhanced LF and ES-based schedules, the eRCPM selects as the default the Enhanced LF-based schedule.

4. Enhanced RCPM (eRCPM) system

The eRCPM system was developed and integrated with Primavera P6 using the Primavera P6's Application Program Interface (API). The eRCPM prototype system handles smart relationships, multiple calendars, holydays and exceptions, multiple types of resources, and progressed schedules. The system 1) exports a P6 project in an XML format, 2) reads the project information from the XML file, 3) performs the Enhanced RCPM, 4) updates the XML file by adding the identified resource relationships, and 5) imports the XML file again into P6. Then, the updated schedule appears in the user's P6 database (see Fig. 9).

Since the updated P6 file has already the resource relationships (RLs) incorporated into the schedule, the user should only re-run CPM in P6 (schedule -F9) to obtain the early/late dates and float values. Primavera's users can identify the resources links that were added to the schedule adding a user-defined field created by the eRCPM system called "RL Successors". The user-defined fields are custom fields that P6 users can create to track specific project information. The eRCPM system also creates another user-defined field called "PF", which shows the phantom float (non-existent float) each activity had before adding the resource links into the schedule. Finally, if after comparing all three resulting schedules (LS, Enhanced LF, and ES based), the program selects as default the LF-based schedule, P6 users can add another user-defined field called "PN". This column shows the Priority Number used for each activity when applying the Enhanced LF heuristic.

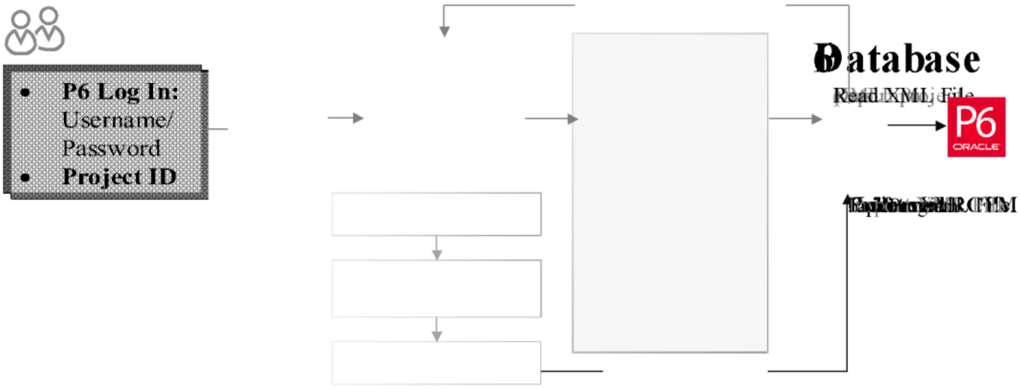


Fig. 9. Enhanced RCPM System.

5. eRCPM application

This section shows the application of the eRCPM to a progressed resource-constrained schedule. The eRCPM was performed by 1) hand and the resulting schedule was drawn in a fenced bar char and 2) using the eRCPM System.

This case study schedule consists of nine activities with two types of precedence relationships (FS and SS), two types of resources (R1 and R2), and two different calendars. Calendar 1 has seven workdays per week and Calendar 2 has five workdays per week. Both calendars have two days of exceptions (non-working days), October 23rd and November 1st. The maximum number of resources available per day for R1 is six and R2 is seven. Fig. 10 shows the network of the schedule.

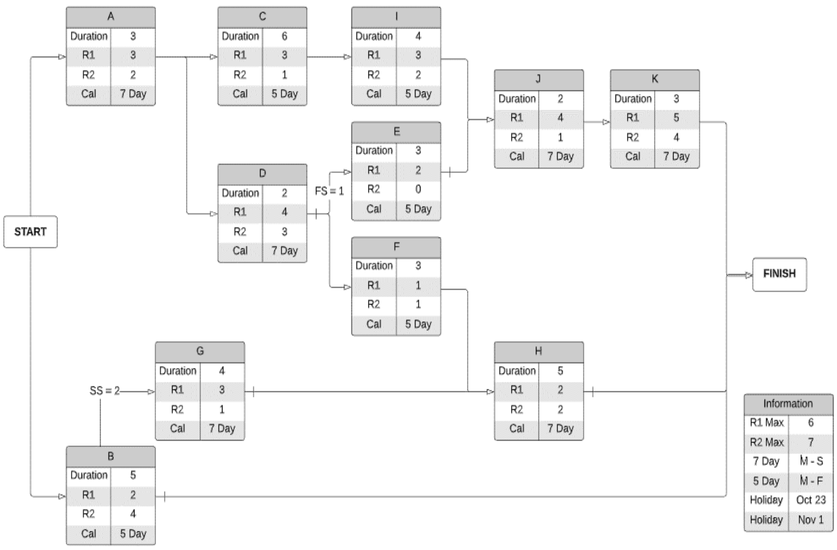


Fig. 10. Case Study: Network.

Fig. 11 shows the CPM fenced bar chart of the project. The CPM results indicated a Project Completion Time (PCT) of 23 days with activities A, C, I, J, and K as critical. As shown in Fig. 11, there is an over-allocation problem for R1 during days 9 to 11 and for R2 during days 10 to 11. The eRCPM was applied to mitigate this supply-demand problem.

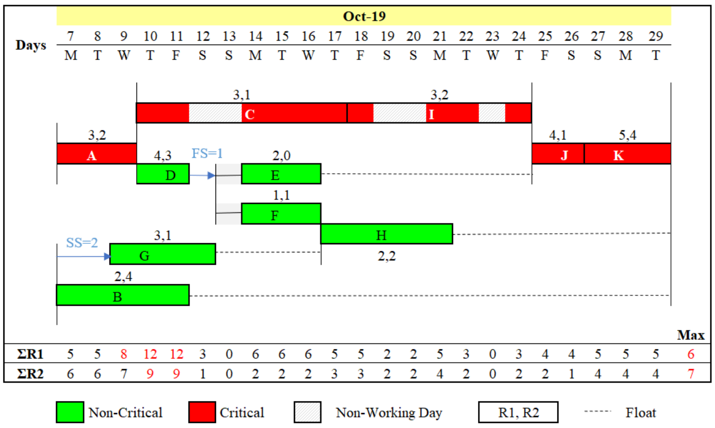


Fig. 11. CPM Fenced Bar Chart.

After applying the three heuristics, the eRCPM system selected the LF-based schedule as default. As shown in Fig. 12, after solving the resource overallocation problem, the PCT was extended by one day with activities B, D, E, G, H, and K as critical. Additionally, five resource links were incorporated in the schedule (B-D, C-G, E-G, F-G, and, H-K). This schedule (Fig. 12) was used as a baseline to update the project.

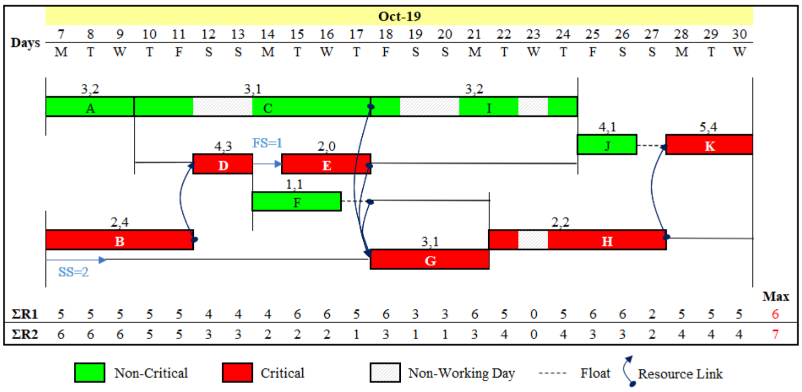


Fig. 12. eRCPM Fenced Bar Chart (LF-based).

The baseline schedule shown in Fig. 12 was updated at the end of week 1 (Oct 13, 2019). Activities A, B, and D have been complete and activity C is still in progress (see Fig. 13). Since this is a progressed schedule, the resource link located left to data date between activities B and D should be kept in the schedule because both activities are complete and the RLs between activities C – G, E – G, F – G, and H – K should be removed from the schedule because these activities have not started yet.

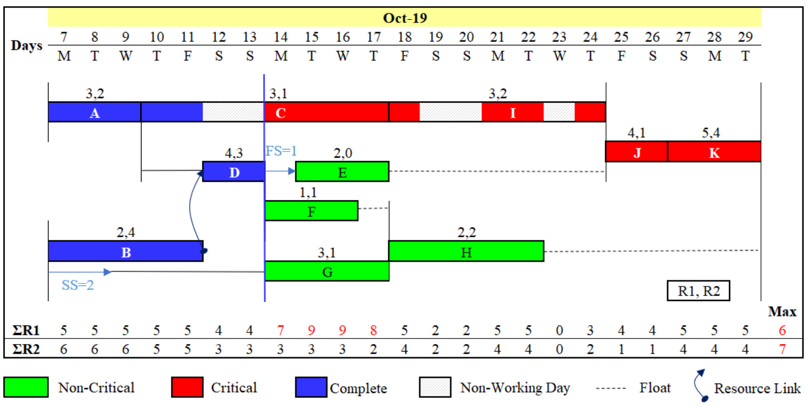
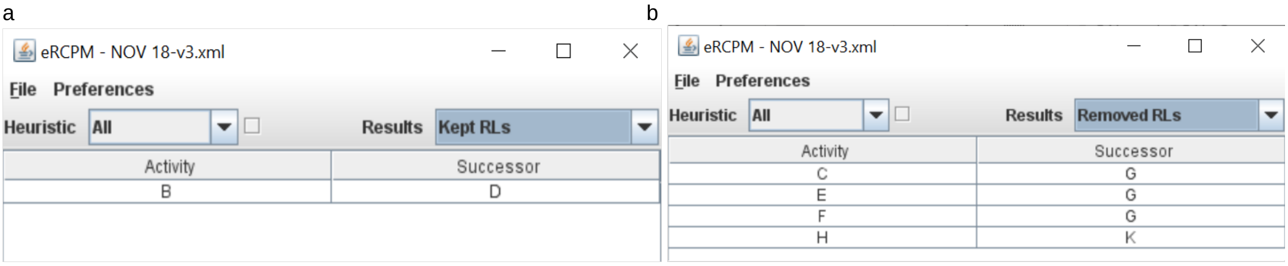


Fig. 13. Fenced Bar Chart: Schedule Updates.

Before re-running the eRCPM, the program identifies and displays the resource links that are kept in and removed from the schedule based on the data date of the project and the status of each activity. Fig. 14 shows the kept and removed RLs identified by the eRCPM system for the case study. With this activity configuration, the eRCPM was re-applied.



(a)

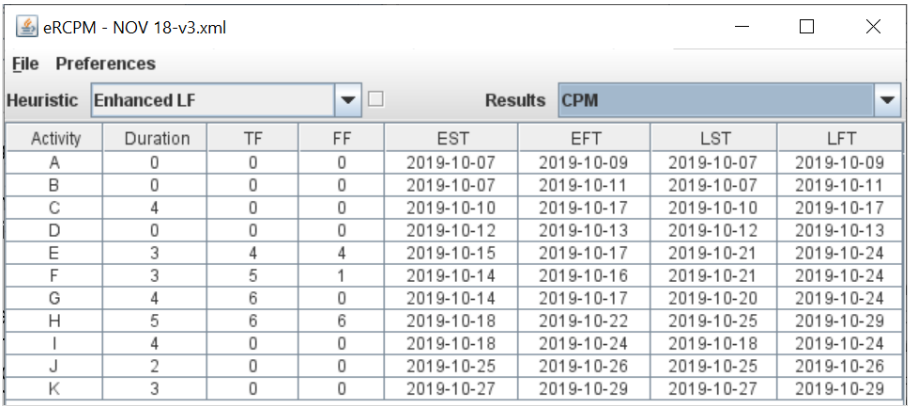
Activity	Successor
B	D

(b)

Activity	Successor
C	G
E	G
F	G
H	K

Fig. 14. Resource Links (RLs): (a) Kept (b) Removed, before re-running the eRCPM.

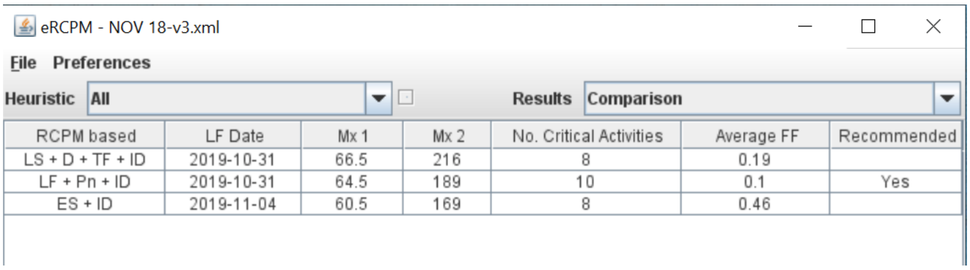
The CPM results indicate a project duration of 23 days (PCT: Oct 27, 2019) with activities C, I, J, and K as critical after the data date. For a progressed schedule, when an activity is complete, the program displays the activity duration as zero (see Fig 15). Additionally, there is an over-allocation problem during days 14 to 17 for R1 (see Fig. 13).



Activity	Duration	TF	FF	EST	EFT	LST	LFT
A	0	0	0	2019-10-07	2019-10-09	2019-10-07	2019-10-09
B	0	0	0	2019-10-07	2019-10-11	2019-10-07	2019-10-11
C	4	0	0	2019-10-10	2019-10-17	2019-10-10	2019-10-17
D	0	0	0	2019-10-12	2019-10-13	2019-10-12	2019-10-13
E	3	4	4	2019-10-15	2019-10-17	2019-10-21	2019-10-24
F	3	5	1	2019-10-14	2019-10-16	2019-10-21	2019-10-24
G	4	6	0	2019-10-14	2019-10-17	2019-10-20	2019-10-24
H	5	6	6	2019-10-18	2019-10-22	2019-10-25	2019-10-29
I	4	0	0	2019-10-18	2019-10-24	2019-10-18	2019-10-24
J	2	0	0	2019-10-25	2019-10-26	2019-10-25	2019-10-26
K	3	0	0	2019-10-27	2019-10-29	2019-10-27	2019-10-29

Fig. 15. eRCPM System: CPM Results.

After applying the three heuristics (LS, Enhanced LF, and ES), the eRCPM system selected the Enhanced LF-based schedule as default (recommended) and updated the P6 project based on this heuristic output. Fig. 16 shows the results of the comparison performed by the eRCPM system when selecting the default schedule. Even though the Enhanced LF and LS-based schedules have the same finish date, the Enhanced LF-based schedule was selected as default because it has lower values of Mx for the two types of resources (Mx1 = 189; Mx2 = 64.5). Due to the sequence of the activities, the resource allocation of the Enhanced LF-based schedule is better than that of the LS-based schedule.



RCPM based	LF Date	Mx 1	Mx 2	No. Critical Activities	Average FF	Recommended
LS + D + TF + ID	2019-10-31	66.5	216	8	0.19	
LF + Pn + ID	2019-10-31	64.5	189	10	0.1	Yes
ES + ID	2019-11-04	60.5	169	8	0.46	

Fig. 16. eRCPM System: Comparison of schedules.

Fig. 17 shows the resulting Enhanced LF-based schedule drawn in a fenced bar chart after re-running the eRCPM in the progressed schedule. The PCT was extended by two days (from 23 days to 25 days) after mitigating the resource supply-demand problem with the Enhanced LF heuristic (from Oct 29, 2019 to Oct 31, 2019). Five RLs were identified and activities C, E, H, and K are critical.

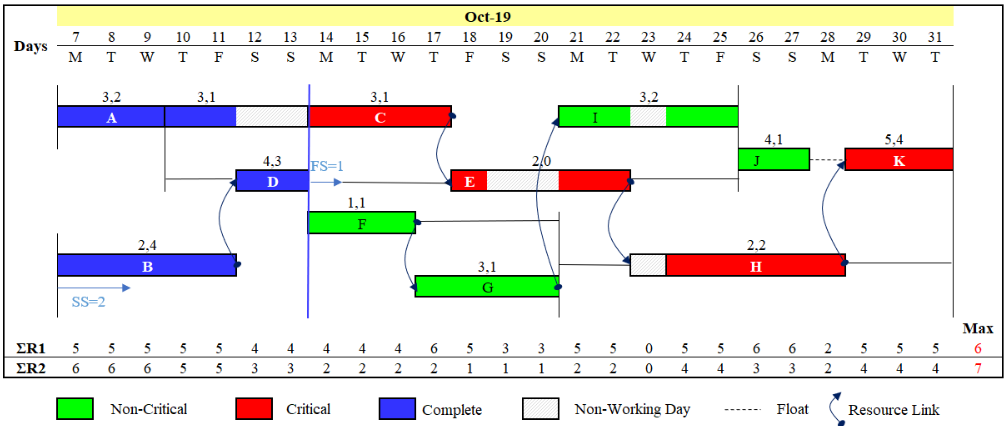
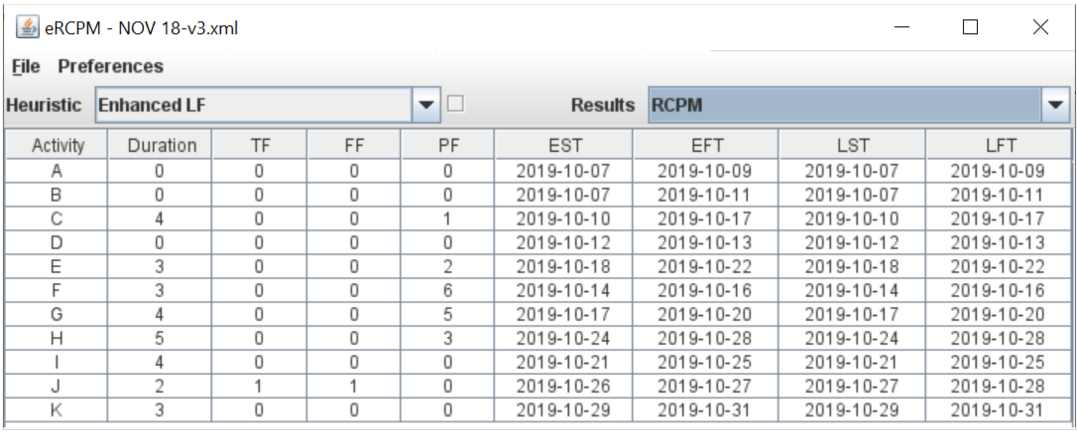


Fig. 17. eRCPM (Enhanced Late Finish Sort): Fenced Bar Chart.

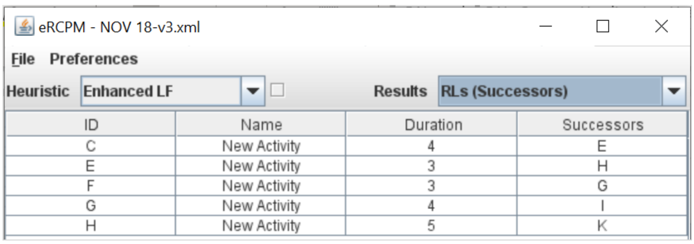
The LS and Enhanced LF-based schedules have the same finish date (Oct 31, 2019) but the sequence of the activities differs and thus, the RLs, and critical path. In the LS-based schedule, activities G, E, F, H, and K are critical. Worthy of note, after the data date, the Enhanced LF-based schedule has a fewer number of critical activities than the LS-based schedule (4 vs 5) but a higher number of RLs (5 vs 4). Otherwise, the PCT was extended by six days (from 23 days to 29 days) after mitigating the resource supply-demand problem with the ES heuristic (PCT: Nov 4, 2019). In this schedule, activities C, E, I, J, and K are critical.

Fig. 18 shows the output of the program after performing the Enhanced LF. Before adding the resource links into the schedule, five activities had Phantom Float (PF) (C, E, F, G, and H). Since the sequence of the activities changed, the RLs identified after re-applying the eRCPM are different from the ones the schedule had before the update and which were removed before re-running the method (see Fig. 19).



Activity	Duration	TF	FF	PF	EST	EFT	LST	LFT
A	0	0	0	0	2019-10-07	2019-10-09	2019-10-07	2019-10-09
B	0	0	0	0	2019-10-07	2019-10-11	2019-10-07	2019-10-11
C	4	0	0	1	2019-10-10	2019-10-17	2019-10-10	2019-10-17
D	0	0	0	0	2019-10-12	2019-10-13	2019-10-12	2019-10-13
E	3	0	0	2	2019-10-18	2019-10-22	2019-10-18	2019-10-22
F	3	0	0	6	2019-10-14	2019-10-16	2019-10-14	2019-10-16
G	4	0	0	5	2019-10-17	2019-10-20	2019-10-17	2019-10-20
H	5	0	0	3	2019-10-24	2019-10-28	2019-10-24	2019-10-28
I	4	0	0	0	2019-10-21	2019-10-25	2019-10-21	2019-10-25
J	2	1	1	0	2019-10-26	2019-10-27	2019-10-27	2019-10-28
K	3	0	0	0	2019-10-29	2019-10-31	2019-10-29	2019-10-31

Fig. 18. eRCPM System: RCPM Results of the Enhanced LF-based Schedule.



ID	Name	Duration	Successors
C	New Activity	4	E
E	New Activity	3	H
F	New Activity	3	G
G	New Activity	4	I
H	New Activity	5	K

Fig. 19. eRCPM System: Resource Links of the Enhanced LF-based Schedule.

Once the user opens the file and runs the project, P6 updates the early and late CPM dates (EST, EFT, LST, and LFT), as well as, the float values (FF, TF) of each activity. As a result, a continuous critical path can be identified in the P6 resource-constrained schedule. The resulting values displayed by P6 match with the ones obtained by the eRCPM system (see Fig. 17 and 18).

Fig. 20 shows the updated project in P6. The eRCPM system creates resource links in P6 as Finish-to-Start relationships without lag (FS = 0). These new relationships can be identified in a P6 Project by adding the user-defined column called “RL Successors”. This column indicates the successor resource-driving activity of the activity being considered. For example, in Fig. 20, a new link between activity C and E was added to the schedule (Activity I was already a successor (technological relationship) of activity A before performing eRCPM).

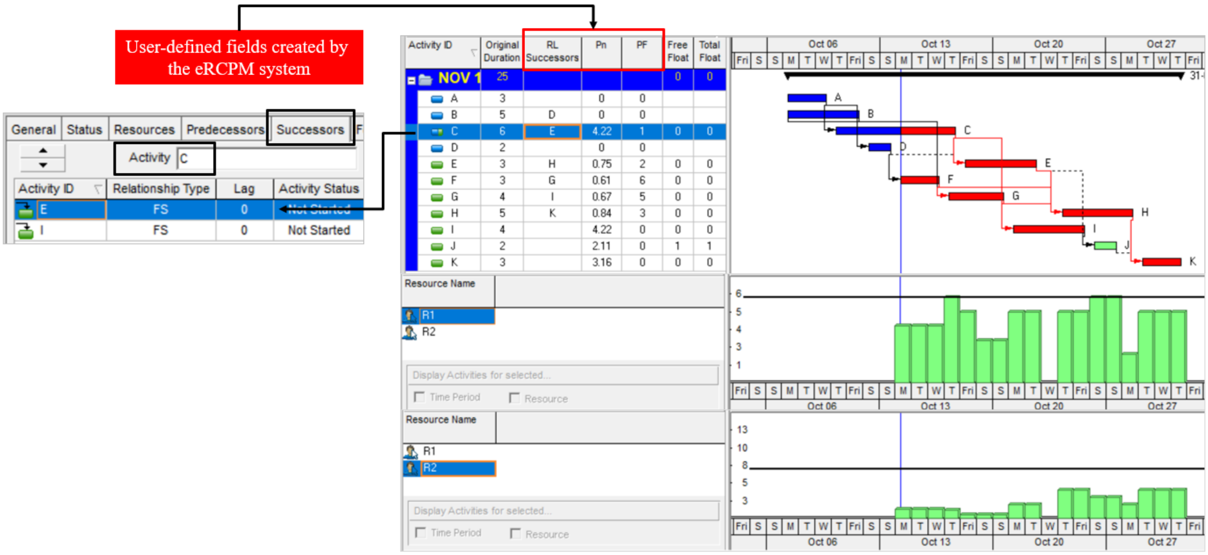


Fig 20. P6 Schedule: Enhanced LF-based Schedule.

The eRCPM also creates a user-defined field called “PF” to display the phantom float values of each activity before adding the resource links into the schedule. P6 users can add another user-defined column called “Pn”. This column shows the Priority Number values used by the eRCPM to perform the Enhanced LF heuristic. The Pn values are only added to the P6 file when the default schedule selected by the eRCPM system is the one obtained with this heuristic (Enhanced LF). The PF and Pn values match with the values displayed in Fig.18.

6. Conclusions

Traditional Resource-Constrained Scheduling techniques fail to provide correct float values and a continuous critical path in resource-constrained schedules. The lack of resource relationships in a resource-constrained schedule leads to the calculation of wrong late start/finish dates and the creation of non-existing floats (phantom float). Therefore, all activities must be considered as influential in the project completion time.

This paper presents the application of the Enhanced Resource Critical Path Method (eRCPM) in a progressed resource-constrained schedule. Primavera P6, a scheduling software frequently used by the construction industry, is not equipped to identify and create resource links when performing an RCS technique. The development of the eRCPM computerized system, which was integrated with Primavera P6, allows the removal of phantom float and the identification of a continuous critical path in P6 resource-constrained schedules.

The eRCPM addresses the fact the activity sequence of a resource-constrained schedule may change after a progress update. The eRCPM system incorporates functionality to keep and remove specific resource relationships of a progressed schedule. This functionally allows the application of the Time Impact Analysis (TIA) methodology for the evaluation of delays. Since this is a contemporaneous analysis, each time a delay is inserted into the schedule specific resource relationships will be kept, removed, and identified.

Additionally, the incorporation of three different heuristics into the eRCPM provides more alternative and flexible schedules that could meet better the project requirements. Moreover, the system selects as default schedule, the one with the shorter duration or with better resource allocation.

6.1 Future research and limitations

Due to the nature of each heuristic, schedulers and project managers should expect to obtain different resource-constrained schedules. The eRCPM performs three different heuristics under a serial approach - activities are sorted as a single group and then schedule one at a time. The incorporation of another well-known RCS method such as the parallel method in the algorithm will provide schedulers more flexibility when selecting the schedule that better meets the project requirements and conditions. Under the parallel approach, the activity sequence is determined and updated at the start of a specific period [11].

Otherwise, the three scenarios defined in the eRCPM to identify resource-driving activities when having several concurrent activities with several predecessor activities were not incorporated in the eRCPM system. Additional work should be carried out to add these criteria to the program.

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Construction Industry Perspective on Planning and Scheduling Content

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Abstract

This paper succinctly reports a study performed to explore planning and scheduling as the two key components of every project. Construction project managers devote a major portion of their daily time to develop, revise, and update their schedules. The same emphasis exists in construction education where the content is provided in one or two major courses through which students learn the basics and practice to develop project schedules with a high level of accuracy. To get inputs from industry and use them in the scheduling training process, a quantitative research method was utilized in the summer and fall 2019. The results indicated that scheduling as a major division has a strong presence in companies with different sizes, number of projects, and work experience. The results also indicated that different subcontractors have different levels of knowledge and competency in knowing and using time management tools. In addition, the results emphasized the importance of traditional time management techniques and methods. Better coordination between entities, more scheduling training for all, and team support of planners are reported as effective ways to improve the scheduling level. The outcomes help construction educators to revise their training material to correspond to the construction industry's needs.

Keywords: construction, education, planning, scheduling, time management

1. Introduction

Modern construction management makes extensive use of traditional scheduling for planning and control of projects. Gantt charts, critical path method, and short-term schedules still appear to be the preferred choice of contractors in the US and UK. However, recent years have seen increasing suspicion that traditional scheduling may have limitations in its ability to accurately forecast long-terms plans. Industry advocates of social-based collaborative planning such as Last Planner System™, Agile Project Management, and Lean Construction, share a view that traditional construction scheduling is too rigid and deterministic to provide long-term forecasting across project lifecycles. Some believe the prevalence of delay and disruption is often related to the planning and scheduling function, with little regard for the caliber of operational execution behind the program strategy. Despite this, traditional construction scheduling is still mostly specified by clients and used by contractors in the construction industry today.

2. Literature review

In construction, the Critical Path Method of project planning and scheduling remains the most commonly used technique in project environments [1], despite newer methods such as Lean Construction, Last Planner® System, and Agile Project Management being promoted and made available to industry practitioners. However, if recognizing the 1950s as a general start point of modern project management via the development and adoption of logic network analysis the planning, management, and control of construction projects was traditionally presented in Gantt chart format with critical trades identified. Originating from post-war industrial, military, and production environments the transposition of critical path method (CPM) scheduling technique into the construction and allied industries was recorded in "A non-computer approach to the critical path method for construction" [2]. With similarities to Program Evaluation and Review Technique (PERT), CPM is based on mathematical and algorithmic models of logic networks applied to production scheduling [3]. Construction activities, key milestones, and critical trades are sequentially mapped and are used to forecast the project planned intent, with this deterministic approach remaining a significant method of planning and project control in modern construction management [4]. Government-commissioned construction reports are intentioned to provide best-practice strategies on key issues of the time. Influenced by wider economic pressures many focus on project and program delivery improvements through partnering and collaborative working [5], program performance and efficiency [6], reports to check and measure the success of previous reports [7] to force a generational-level shift in cost and program production improvements [8]. While demanding responses from industry on productivity problems Government reports can offer little insight into the granular reasons behind program and production limitations in industry. Official codes of practice provide established written frameworks for project management and delivery, however these lean towards being largely procedural in nature [9]. The Project Management Body of Knowledge [10] similarly fails to address the complex nature of construction planning and scheduling in complex and fragmented contracting environments. The Code of Practice for Program Management in the Built Environment [11], despite being an authoritative manual, poorly interprets the practical application of the planning role in contracting environments and sets out guidance similar to construction texts. Project planning can face a challenge in organizations where projects are strongly commercially led, often due to a culture of weak project management and leadership. The responsibility for undertaking the planning and scheduling role in construction can vary from a dedicated planner / scheduler, or a project manager, or construction manager. Depending on project size and company culture there may be no formal allocation of the project planning role. This loose definition, weak support, and poor recognition of the role led [12] to question what project planners do. Similar direct querying on whether construction project planning was doing its job [13] demonstrates some misunderstanding of the nature of the execution of the planning role and the responsibilities of the wider team in supporting the project planning function. Poor attitudes towards a strong and centralized planning entity has seen a creeping disdain and the search for alternative planning methodologies. Imported from automotive and production industries from the 1990s onwards alternatives to traditional planning and scheduling, and broadly categorized as collaborative planning, such modern methods as Lean Construction [14] and Last Planner® System [14] are purported to provide a trust-based collaborative alternative to the rational-technical nature of critical path method planning. Other modern methods aimed at supplementing or in many instances replacing traditional planning and scheduling are Agile Project Management, AgiLean Project Management, Six Sigma, and Lean Six Sigma. While characterized by continuous improvement processes, reduction of waste, collaborative working, greater social trust in project teams, greater inclusivity of site work-crews, and work schedule agility these methods have not established themselves as successors to the traditional construction planning and scheduling methods that are still first-choice of employers and contractors in the construction industry.

3. Methodology

The main purpose of this study was to explore the status of scheduling tools and approaches used in industry. This study was a joint effort taken by two research universities in the U.S. and U.K. to investigate the similarities and differences between the construction companies in these two countries. To reach this study's objective, the following research questions formed the research approach:

- What scheduling tools, methods, and methods does the construction industry utilize?
- How do scheduling professionals perceive subject content taught in construction programs?
- What are the similarities and differences between construction companies in the U.S. and U.K?

Construction scheduling is a core course in construction programs, which is being taught consistently across various schools; however, the notion of scheduling in different companies is not perceived in a similar way. One main reason for this situation is the variety of scheduling tools, techniques, and methods that are employed by construction companies. Knowing these two points helps construction educators to adjust their course content and the tools and methods they use to convey the scheduling concept and its application to their students. In a broader scope, it would be even more helpful to know the best practices in the U.S. and compare it with another country. For brevity, this paper strives to only answer the first two questions, and the third question is discussed in another publication. Two research groups from Mississippi State University – U.S. and Liverpool John Moores University – U.K. joined in Spring 2019 to discuss problem statement, research objectives, methodology, and administration. After a preliminary series of discussions, a timeline was provided, and a quantitative research method was chosen to conduct the study. A survey was designed to cover the main tools, methods, and approaches used in scheduling. The survey was designed in four sections. Section one included the demographic and general information of respondents. The second section explored the awareness and competence of various entities involved in construction projects. The third section examined the importance and use of different time management methods and tools. And finally, in section four, factors to improve the outcome of project time management and scheduling were investigated in the fourth section. The survey was sent to different construction companies who serve as an industrial advisory board member at Mississippi State University and as a result, thirty-four responses were received. The gathered data were compiled and modeled in a statistical software. Through the first round of data modeling, a few outliers were identified, and some data imputations were utilized.

4. Results

Survey responses were collected within a month from different companies. Except for one respondent, all other participants fully responded to the survey where 91% of them were male. As shown in Table 1, the frequency of all age groups is almost evenly distributed.

Table 1. Percentage of each age group

Age Group	Under 26	26-35	36-45	46-55	56+	*Total*
Percentage	9	28	21	18	24	*100*

The majority of participants (88%) were working in GC companies and the rest were working in trade/subcontractor companies. The reported work experience of participants is shown in Figure 1. The results also showed that 53% of participants reported their positions as project manager, 38% as scheduler, and 9% of participants had other positions. The size of companies that participants worked in is specified in Table 2. As shown, the majority of sample group were involved in medium and large size companies.

Fig. 1. Frequency of work experience groups

Table 2. Percentage of each size of company

Size of Company	10 or less	11-50	51-200	201-500	501+	*Total*
Percentage	3%	12%	32%	3%	50%	*100*

Participants also specified how often they update schedule. Possible responses were "No update", "Weekly or less", "Biweekly", "Monthly", and "Every 3 months", and the percentages were 3%, 9%, 56%, 32%, and 0%, respectively. This indicates that the majority of schedules are updated every two weeks. Moreover, participants were asked to rate what percentage of their projects are completed based on the initial duration. The provided percentages were 10% or less, 11-20 %, 21-40 %, 41-60 %, and 61+ %. The percentage of each category is reported as 0%, 9%, 9%, 15%, and 68%, respectively. In the next section, participants were asked to specify the main use of their schedules. For this question, participants were allowed to select only one item. Figure 2 shows the percentage of each possible use of the schedule based on the participants' report.

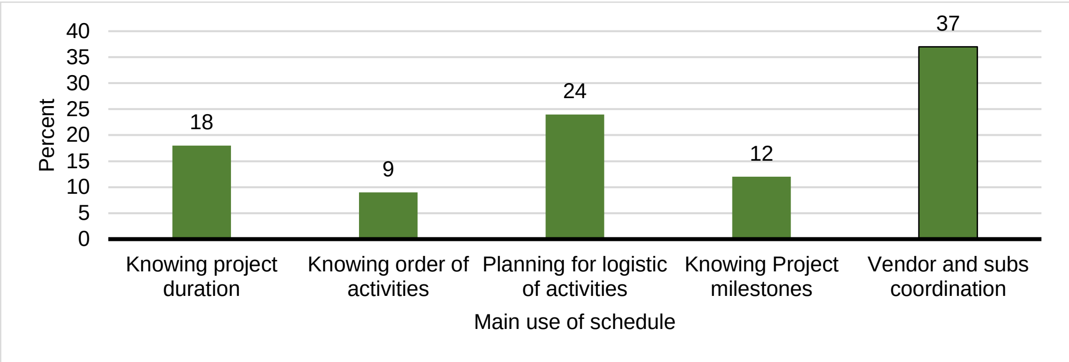

Fig. 2. Percentage of possible uses of schedule

Participants also reported the main issue with Critical Path Method (CPM) in their project scheduling, Table 3 shows the percentage of possible issues, reported by participants.

Table 3. Percentage of each possible issue derived from using CPM

Issue	Inaccuracy	Complexity	Time consumption	Too much info	Different software	*Total*
Percentage	24%	29%	35%	6%	6%	*100*

Additionally, participants were asked to specify the importance/usage of following time management methods/tools using a 5-level Likert scale from 1: Very Low to 5: Very High. Figure 3 illustrates the average score of each tool/method out of 5.

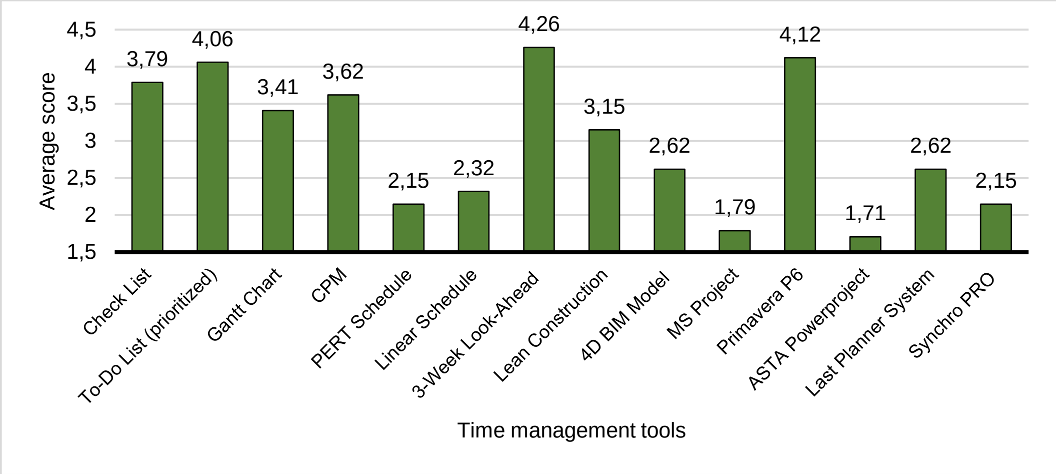

Fig. 3. Average score of time management tools

Finally, participants were asked to rate the importance of possible factors to improve the outcome of project time management/scheduling. The relative average weight of each improvement factor is shown in Table 4 in which "Better coordination between entities" with a considerable difference with other factors has gained the highest score.

Table 4. Relative average weight of each improvement factor (out of 5)

Improvement Factor	Relative Average Weight
Better coordination between entities	4.47
Using more experienced people in scheduling	4.12
More Scheduling training for all	4.09
Team support of Planner/ Scheduler	4.06
Using advanced technology	3.79
Better Program Schedule Ownership (Planner or Project Manager)	3.76
Earlier Development of Construction Program	3.71
Quality of Subcontractor Generated Program	3.68
More frequent schedule updates	3.56
Simplifying the schedules	3.53
Accurate Resourcing of Program	3.21
Formal Stages of Program Development (Gateways)	2.97
Putting rewards and penalties for time deviations	2.79

5. Discussion

Planning and scheduling are a core component of construction curricula, which are typically offered in one course at junior or senior level. Unlike many other construction subjects, the content of scheduling courses has been relatively unchanged for a long time in academia. However, the construction industry constantly strives to improve planning and scheduling methods to attain higher quality, shorter durations and lower costs. These two situations necessitate a bridge to connect these two sectors and bring both to the same pace and direction. One major input for such modification is industry professionals' feedback on common scheduling tools and methods used in construction programs. The current study aims to provide input for construction educators and administers in planning and scheduling courses. One noticeable point is the frequency of age and work experience of participants. The results show that those who are involved or in charge of scheduling are of different age groups and with different work experiences. This balanced mixture can make scheduling an agile sector of the construction companies. However, the meaningful difference between items categorized based on the time spent for scheduling tasks indicates two important points: a high level of involvement (i.e. developer) or a low level of interaction with scheduling tasks (i.e. coordinator). Another important point derived from the response is the relatively low score of new scheduling tools/methods used in companies. For example, 4D BIM, ASTA, and Synchro have been scored considerably lower than traditional check list, to-do list, and Gantt chart. Finally, as indicated by the results, the main improvement approach is a more effective coordination. For construction students preparing to enter this area, this translates to a better communication, working in multidisciplinary teams, and having holistic perspectives.

6. Conclusion

Scheduling is a vital task in construction project management. Cost and time are two major drivers for every project which can be properly managed through an accurate schedule. Knowing how professionals think about the different aspects of the scheduling process, tools and methods, and best practices helps construction educators to provide students with the course content accordingly. This study was designed to obtain the construction perspective on the scheduling area and exhibit the trends, similarities, and differences between various construction entities. The results indicated that complexity and time consumption are the two main obstacles in using scheduling techniques and methods. Construction students should learn how to efficiently develop a schedule and incrementally revise it. Another noticeable point is the importance of simple and traditional time management tools. Although new advanced scheduling tools, techniques, and methods seem intriguing and can absorb students' attention, it should be noted that construction graduates should be competent in developing and using the common – and sometimes outdated – tools to communicate with other individuals, especially their seniors. Finally, it is important to note the relatively level of familiarity with time management tools in trades/ subcontractors. Knowing the current situation enables construction graduates to more effectively communicate with this group. Although the results highlight different aspects of scheduling in the construction industry through the lens of professionals, this paper does not generalize the outputs due to the sample size. Having a larger sample size warrants more reliable results. The next phase of this study will include more companies across the nation with various expertise.

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Improving the Information Flow in the Construction Phase of a Construction Project

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Abstract

In a company and project level it has been noticed that the fluent flow of information will be an essential part of streamlined processes. In the construction phase of a construction project, the information transfers between numerous parties, via different platforms and between people and systems. As the information field in the construction business is highly dispersed, managing the information flow within it is important in terms of efficient workflows.

The study focuses on the problems perceived in the flow of information and the methods of improving the information flow with Lean and Building Information Modeling (BIM) in the construction phase. The study consists of a literature research and an empirical section, which is conducted as a case study. The data collection methods used in the case study are interviews, documents and direct observations made by the researcher. The results of the case study are analyzed and compared with literature findings. There are three cases from different construction phases and altogether six site managers and engineers from the case company are interviewed.

The case study indicates that the element fabrication schedule and manufacturing status of prefabricated elements is prone to change during the project and thus cause a need for a change to the construction process and management. Therefore, it is beneficial that the latency of information regarding prefabricated elements is cut down to minutes instead of hours or even days. As a result, the information flow in the construction phase can be improved especially by 4D scheduling with the use of Last Planner System, the visualization of digital assembly and schedule information in BIM environment and the integration with the Enterprise Resource Planning (ERP) system of prefabrication suppliers.

Keywords: building information modeling, information flow, last planner, lean

1. Introduction and theoretical background

1.1. Information flow

Information flow is required to transfer information between the transmitter and the receiver. It represents the information moving between different parties. Information can be transferred for instance by communication via cell phones or face-to-face conversations, documents or digital information between different systems. The parties of information flow can be humans, systems or a mixed combination of those. It can be either one-way or two-way flow meaning that the information can flow in one or both directions.

In company and project level, information flow has been noticed to be an essential part in developing streamlined processes. One of the common problems within organizations is that the information does not reach the right subject. In addition to that, even if the information is available at the right time at the right place, it is not necessarily efficiently accessible and flawless, since information tends to distort as it flows through multiple parties[1]

In construction business, smooth information flow is important on sites that have a constant need for communication between main contractor, site foremen, project management, subcontractors, designers, prefabricated building element suppliers and other material suppliers. The research made by The Box [2] indicates that the information economy is significantly more shattered in construction business compared to manufacturing, software or media and entertainment industry. Mukaddes et al. [3] see the information flow as the enabler of product flows and thus is in an important role in terms of functionality and controlling the whole.

Information flow is increasingly based on digital data transmission. That means that for instance a paper document based data transmission is decreasing in numerous industries as digital data transmission is significantly faster and safer way to share information to other people and organizations [3]. In the construction industry, this trend is not as strong as in other industries and especially site operations are still strongly based on paper documents [4]

Demian and Walters [5] reported test results of the flow of information using four information systems including e-mail, a construction project extranet tool, an Enterprise Resource Planning (ERP) system and a Building Information Modeling (BIM) system. Albeit the number of projects was small the results showed that BIM foster accurate, on-time and appropriate exchange of information between parties involved in projects.

Harstad et al. [6] researched the use of mobile devices as a method to improve information flow in construction projects. According to the study, existing technology reduces information outages and loss of information in projects. The use of mobile devices improves the information flow between designers and contractors and reduces waste caused by construction works executed using faulty information.

Zeng, König and Teizer [7] reported that BIM based planning of material deliveries is worthwhile as it enables more real-time and solid knowledge to support decisions. In addition to that, the use of BIM did not disturb the normal operation of the site organization.

1.2. Lean construction

Lean is based on a thought of doing more with less. In practice, this means that every resource, such as labor, equipment, time and space are used to increase the value of the product. In addition to that, supporting activities are identified [8]. If the resources do not produce added value, they are considered as waste (often referred with a Japanese word *muda*) [9].

Manufacturing industries have been utilizing lean philosophy for a while. Womack, Jones and Roos [10] and Womack and Jones [11] researched the development of Japanese car industry and came up with the term lean. The philosophy is based on production methods developed by Toyota's executives Taiichi Ohno and Eiji Toyoda.

One of the main principles of lean is the use of methods that improve the efficiency [12] without damaging the quality of the final product [13]. Continuous improvement [13], Just in Time (JIT) production and deliveries [14] and the use of Last Planner System [15] is strongly related to that. It means that the production process is constantly improved based on experiences on the subject.

Even though lean philosophy originates from the manufacturing industry, it is not only applicable in factories. The whole philosophy can also be adapted to other industries, such as highly project-based construction industry. The same methods can not be always used so there is a need to modify the methods to use the philosophy in the construction industry.

1.3. Building information modeling

Building Information Modeling is a whole containing information about the building, its life cycle, production process and other related subjects. The exact definition of BIM has been discussed widely, but there is a consensus that it describes the change from using analog tools to the use of digital tools. [16] Laiserin describes BIM as "a process of representation, which creates and maintains multidimensional, data-rich views throughout a project lifecycle to support communication (sharing data); collaboration (acting on shared data); simulation (using data for prediction); and optimization (using feedback to improve design, documentation and delivery)" [16].

Building information models consist of components, such as windows, doors, walls, slabs, stairs, ducts, pipes, cable trays, piles et cetera. A varying amount of information about the object's properties can be included in the model. To get a comprehensive insight about the building, at least architectural, structural, HVAC and electrical models have to be available. A federated model is created from these separate models to present them as one unified model. [17]

The building information model can be seen as a database of the building since it enables all kinds of information, such as 2D drawings, 3D representations, quantities, measurements et cetera to be taken from the same database. Since all the information derives from the same database, clashes between different representations are eliminated. When an update is conducted, the information can be updated to all documents that are derived from the model. The building information model can cover the project data from planning to construction, operation, maintaining and demolition. [18]

1.4. The interactions between Lean construction and BIM

Sacks et al. [19] have researched the interactions between BIM and Lean construction. In the study, 24 Lean principles and 18 BIM operations were examined and altogether 56 interactions were found of which 52 were positive interactions. 29 of these interactions are related to information flow and 23 of them are present in the construction phase of a construction project. A majority of these interactions seem to affect other interactions as well through the improved information flow.

Sacks et al. [19] and Fosse, Ballard and Fischer [20] concluded that lean principles and BIM had a strong connection. That is why BIM needs to be utilized when implementing lean principles in the construction industry. BIM covers wholes that are connected to data transmission, so it should be utilized in controlling and improving the information flow.

2. Research objectives and methodology

The objective of this research was to clarify how information flow could be improved at the construction phase using Lean construction methods and BIM as an intensifying technology. Based on the literature search the researchers defined the characteristics of a good information flow by the following criteria. A good information flow:

- Is easily and efficiently available,
- Contains high quality and flawless information,
- Is up-to-date and timeliness,
- Reaches the right subject,
- Is in digital format, and
- Utilizes BIM, mobile devices and applications to share information.

Then the researchers propose the hypothesis of dependencies and interconnections with Lean construction methods, BIM and the characteristics of a good information flow. The hypothesis of the dependence between methods used to improve the flow of information is presented in Table 1.

Table 1. Hypothetic dependencies between methods and characteristics of good information flow.

		Easy and efficient access	High quality and accuracy	Timeliness	Reaching the right subject
Lean	Last Planner	Improved	Improved	Improved	Improved
	JIT	---	---	Improved	Improved
	Visual Management	Improved	Improved	---	---
BIM	Design information availability on-site	Improved	Improved	---	Improved
	Quantity take-off and procurement	Improved	Improved	---	---
	4D scheduling and actual progress control	Improved	Improved	Improved	---
	BIM order and assembly visualization	Improved	---	---	Improved

The first author worked as a Chief Digital Construction Officer in the back office of a construction company and the second author worked as a BIM Coordinator in building projects making his master's thesis at the same time. The basic information of cases is presented in Table 2 The progress of the study is shown in Fig 1.

Table 2. The basic information of cases .

Case	Building type	Information flow research subject	Data collection methods
1	Residential	Scheduling	Two interviews, empirical observation
2	Commercial & residential	Precast element assembly	Two interviews, empirical observation
3	Residential	Precast element orders	Two interviews, empirical observation

A preliminary literature study was carried out to get an insight into the relevant temporary theoretical background for the definition of research objectives and hypothesis. An empirical study in three cases was carried out by using action research approach with interviews. The cases were selected from the ongoing BIM projects that have a suitable management system for information flow regarding this research. The second author had an important role observing, interviewing, testing and developing the methods and systems used in the cases. The interviews were executed as semi-structured interviews centralizing in two main themes; information flow and the use of BIM. The interviewer made notes, taped and transcribed the interviews and analyzed the results.

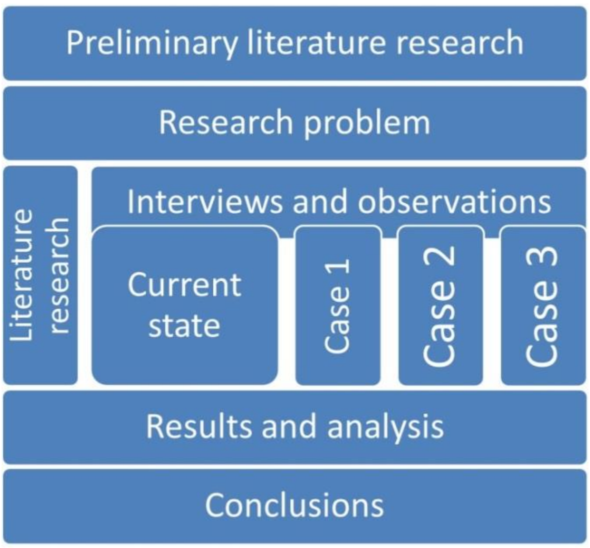

Fig. 1. The progress of the study.

Empirical part was typically a case study research and qualitative research approach was used. A prior understanding of the information flow and its quality factors is formed based on literature study. In practice, the results of each case were compared with the literary definitions of the characteristics of the information flow and the hypothesis whether the information flow has improved on the basis of these definitions. As the researchers compared and analyzed the cases, pattern matching [21] method was used. If the results of the cases corresponded to the expected results, it could be noted that the dependence on the empirically observed factor in the case was strong. Thus, the impact of the methods used in this study on the flow of information could be determined by comparing the effectiveness of information flows with a definitively good flow of information.

3. Results and analysis

3.1. Interviews: Current state of the information flow management on site

The results of interviews and perceptions on site showed that the whole information flow at the site is under the control of the general foreman or the site manager, but the information is transferred between the foremen quite spontaneously. The information flow is strongly based on face-to-face situations and meetings. Each foreman is usually responsible for a certain part of the works on site and maintains the schedules and the information needed in activities themselves. The general foreman or the site engineer keeps a document based or a digital calendar in which all common meetings and personnel holidays are set. Typically, general project information, such as organization charts, general building schedule and contract and procurement information are maintained digitally in the company's project management system or in a digital document store.

At the moment, the design information is generally transferred from the site office to the site using paper documents physically stored in the office or using a digital document store maintained by a service provider and the designers. Some foremen use mobile devices to collect, store and distribute data on site. Emails with attachments and phone calls are used to communicate with designers, subcontractors, material suppliers and engineered to order (ETO) product providers. Site personnel mentioned that the access to the right, accurate and updated design information in the drawings is the most common dispute of information. The lag between the request of information to the time to getting the revised information to site was all too long. Senior foremen felt the flow of information more fluent than junior foremen.

The Lean construction philosophy was poorly understood by the foremen. Junior foremen recognized and explained the core of Lean construction more understandable than senior foremen. Despite the above, the foremen were well aware about Last Planner system and for example the meaning of Big Room. The impact of Last Planner on enhanced information flow and thus better scheduling has been acknowledged.

BIM was familiar to all foremen interviewed, and the foremen said they were using BIM in their work. The 4D schedule was also familiar to almost everyone interviewed. All the interviewees stated that BIM is useful for their work in at least some of the tasks. The main advantage was the ease of visual examination of buildings compared to 2D drawings. In other words, the use of BIM aims to facilitate and benefit the transfer of design information for construction works on the site. For example basic geometrical information and quantities of elements would be needed for the planning of assembly schedule and works. A good 3D site layout facilitates the flow of information of a real-time site situation much easier than 2D drawings.

3.2. Case 1: Information flow on planning and controlling the schedule of frame and finishing works

The project presented in Table 3, the construction phase general schedule was planned using a 2D-based scheduling software by the general foreman. Using that as a starting point, site engineer planned local-based (that is building floors) 4D schedule for construction works including critical path frameworks and finishing works. The finishing works were planned as major activities where the total length of activity was composed of the separate length of the works of sub activities. Activities were connected with the objects in the structural BIM for the simulation and visualization of the schedule. In addition, the schedule included activities without the connection to the BIM objects. Site engineer controlled the progress of activities and wrote back the information in BIM objects visualizing and reporting the progress of activities. The week and location based schedule of finishing works was planned, controlled and maintained using Last Planner system by main and subcontractors. The schedule was located on the wall in the main contractor's' meeting room on site. 4D schedule and BIM model was saved in the main contractor local network and it could not be shared with subcontractors, ETO and material suppliers due to the IT policy and the software version used by the designer.

Table 3. The characteristics of the project in Case 1.

Type of the project	Two identical residential buildings, block of flats, company's own production, Fig. 2 a).
Research subject	Information flow on planning and controlling the schedule of frameworks and finishing
Methods used	Last Planner, Visual Management, 4D scheduling and 3D site layout
Site organization	One general foreman, two foremen and one site engineer
Digital environment	Personal mobile phones, pads and laptops
The knowledge about BIM and Lean methods	Above the average level

During the construction phase, information about time schedules was well managed in the main contractor's organization on site. As well, the information flow between main and subcontractors was well managed in meetings and in Last Planner sessions. The lack of easy and efficient access of 4D schedule was an obvious obstacle to transfer the information to subcontractors on site. The previous was also an issue between the main contractor and designers, material and ETO suppliers. Between the construction parties, the time schedule information was transferred via emails, email attachments and phone calls.

High quality and accuracy of information based on the suitable level of schedule and BIM object content. When using a 4D scheduling too detailed activities and object content to maintain could be an issue, because gathering and writing the progress information in BIM objects takes a lot of site engineer's resources. In this case, the level of 4D schedule and suitable BIM object content was well planned and managed.

The timeliness of 4D schedule depends on the reality of progress information saved in the model. The progress information could be updated without any lag if it is saved immediately after the activity will be finished or, it could be updated once per month before the end of the reporting period. In the case, the progress information was saved daily or weekly and in that way 4D schedule visualized the progress of works on reasonable timeliness.

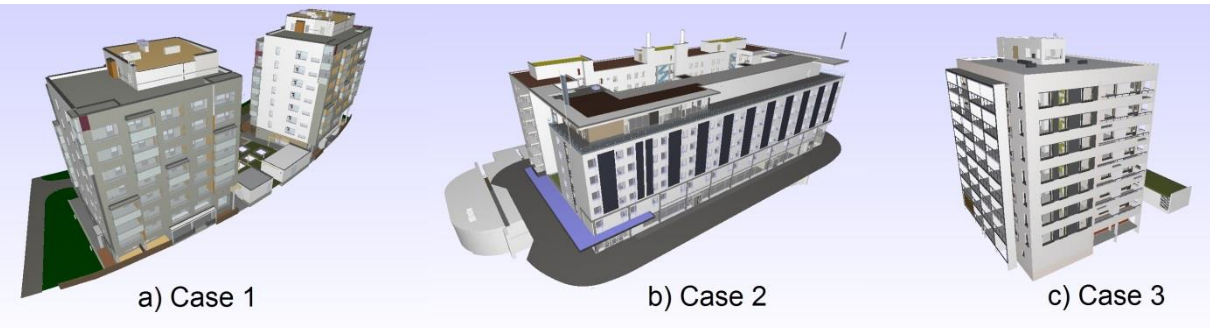

Fig. 2. Cases illustrated

The use of Last Planner suited well to manage the weekly scheduled works between the main and subcontractors. The level of detail of activities was accurate enough. The timeliness of information flow was up-to-date and the information reached all the subjects and parties needed to make decisions in sessions.

3.3. Case 2: Information flow on building element assembly

In the project presented in Table 4,a cloud-based BIM software platform was tested to manage and control the flow of information within site organization for the assemblies of prefabricated and cast-in-place concrete elements, windows and lightweight walls made of prefabricated expanded clay elements.

Table 4. The characteristics of the project in Case 2.

Type of the project	One residential and one commercial accommodation building, block of flats, Fig. 2 b)
Research subject	Information flow on building elements assembly
Methods used	Visual Management and 3D site layout
Site organization	One general foreman, five foremen and one site engineer
Digital environment	Personal mobile phones, pads and laptops
The knowledge about BIM and Lean methods	Average

Building information models and documents were saved in a digital document store for contractors. Main contractor's BIM coordinator integrated architectural, structural and HVAC model as a production model for the controlling of assemblies. Tablet application and laptop software was used to share the model within main and sub contractor organization. The easy and efficient access to the model information was accomplished through the use of cloud-based software platform.

Within sub contractors' organization, there were some interest to use the model but the lack of tablets prevented the active use of the model. The main contractor's site organization used both laptops and tablets to visualize the model and assembly works in the site office. Unfortunately, the foreman in the charge of prefabricate concrete element assembly works could not use any BIM tools to manage the assemblies, and he would not like to cooperate and share information with BIM coordinator. For that reason BIM coordinator was forced to collect controlling information using the BIM software platform on site even the activity was delegated to the foreman. The information flow did not reach right participants in a satisfying way.

Table 5. Status values, their visualizations and interpretations.

Status value	Visualization	Interpretation
None	Grey	No interpretation: Used to cover possible faulty status entries
Started	Orange	Cast-in-place structure is in formwork or rebar phase or expanded clay wall element is installed
Paused	Red	The assembly of the component is paused
Completed	Green	Precast element, window or glass wall is installed; cast-in-place structure is cast or expanded clay wall surface is finished

For the controlling of the phases of assembly works, a work status tool was used in BIM software platform. Several views to the model were planned and saved beforehand in the platform by the BIM coordinator. In the BIM platform each individual building object or a building element could have several status values as shown in Table 5. The controlling information was collected using tablet once per week as the BIM coordinator walked through the site and changed and saved the statuses of building elements in the model. There were several days lag between the actual assembly of building elements and saving of the status information in the model, so the timeliness of the information flow and the visualization of the actual schedule was out of date.

The use of BIM software platform was practical enough to save the information quickly on site and foremen can learn to use the platform easily. Unfortunately in this particular case, the high quality and accuracy of information flow could not be reached.

3.4. Case 3: Information flow on precast concrete element production

In this project presented in Table 5, the same cloud-based BIM software platform as in the case two was used to manage and control the information flow between the main contractor and an ETO prefabricated concrete element provider. The ETO provider maintained and shared the production model that was based on the structural model for the main contractor. The production model was connected with the provider's ERP system. The structural designer transferred concrete element drawings from the designing software to ERP system automatically. The ETO provider, main contractor and the structural designer had an easy and efficient access to the information in the production model.

Table 6. The characteristics of the project in Case 4.

Type of the project	Two identical residential buildings, block of flats, Fig. 2 c)
Research subject	Information flow on precast concrete element production
Methods used	Visual Management
Site organization	One general foreman, three foremen and one site engineer
Digital environment	Personal mobile phones and laptops
The knowledge about BIM and Lean methods	Below the average level

For the controlling of the fabrication and supply situation to the site, the status tool was used in BIM software platform. Also, the statuses had the information where the prefabricated elements should be produced. The provider defined the statuses as they were used in the ERP system so the information flow in and out of ERP system to the elements in the production model was automated. The status values are presented in Table 7. The fabrication and supply situation was visualized practically, and the timeliness of the information flow could be reached.

Table 7. Status values used to visualize the production status and their interpretations in prefabricated element production.

Status value	Visualization	Interpretation
Enable	Light blue	The element data and drawing is imported to the ERP system
Commit	Dark blue	The element is programmed to be cast
Started	Orange	The element is cast
Paused	Red	Casting is prohibited
Completed	Green	Element has been delivered

Unfortunately, the high quality and accuracy of information could not be accomplished using the production model information. This was due to the missing information with prefabricated concrete element naming and identification numbering in the structural model. The naming and numbering of elements based on types of elements, and several same type of element had the same name and identification number. ERP system and the production model used by the provider could not itemize the elements with locations without Assembly Control Numbering (ACN).

Due to the fact above, the contractor had to order the elements batches using table formatted order form. When the batch arrived at the site, the contractor combined the information between the order and delivery forms and marked the delivery batch items on the layout drawings as delivered. Deliveries could not follow JIT principle, and a temporary prefabricated concrete element store was needed on site.

4. Results summary and discussion

The interviews pointed in the direction of traditional face-to-face communication, meetings and document-based information flow between project parties. Emails with attachments and phone calls are used to communicate with designers, subcontractors, ETO providers and material suppliers. On sites, limited access to the accurate and flawless design information and long response time to the request of information is an information flow issue according to the interviews and observations.

Step by step, digital information flow between parties and the knowledge to use desktops, tablets and mobile devices is changing the traditional site organization, roles, authority and power relationship on site. Observations showed that junior foremen can learn and takeover BIM software tools faster than senior foremen. There is no threshold to accept a new way of working with information flow if technology based obstacles are removed. The interviews revealed that the core of Lean philosophy was not fully understood, that is, no mentions of waste. Both the interviews and the cases identified several 'non value adding' functions — that is waste — during the information flow process. However, Lean tools like Last Planner System, Big Room, JIT principles were familiar with the interviewees and some of them were used successfully in the cases.

In the Table 8, the case results are summarized and presented. The proposed hypothesis of dependencies and interconnections with Lean construction methods, BIM and the characteristics of a good information flow can not been disproved by the results analysed by the researchers.

Table 8. Dependencies between methods and characteristics of good information flow in the cases.

		Cases	Easy and efficient access	High quality and accuracy	Timeliness	Reaching the right subject
Lean	Last Planner	1, 2	Improved	Partially improved	Improved	Improved
	JIT	3	---	---	No effect	No effect
	Visual Management	1, 2, 3	Partially improved	No effect	---	Partially improved
BIM	Design information availability on-site	1, 2, 3	Improved	Partially improved	---	Partially improved
	Quantity take-off and procurement	1, 3	Partially improved	No effect	---	---
	4D scheduling and actual progress control	1,	Improved	Improved	Improved	No effect
	BIM order and assembly visualization	2, 3	Partially improved	---	---	Improved

The interpretation of results shows that the use of Last Planner System, BIM-based design information, and 4D scheduling improve the information flow through easy and efficient access to information needed on site. High quality and accuracy of information in time scheduling could be improved using BIM method of 4D scheduling and actual progress controlling. The use of Last Planner and BIM-based design information improve the accuracy of information content and flow partially. The timeliness of information could be improved using Last Planner and 4D scheduling. The use of Last Planner and BIM order and assembly visualization could improve the flow of information to reach the right object.

At first, the researchers recommend the use of Last Planner and 4D scheduling in the project on site. Last Planner System is a visual and standardized tool for managing the information needed in work phase planning. Project parties share the information needed to reach the objectives of the project. 4D scheduling improves the timeliness and accuracy of the general and phase scheduling of activities and visualizes the content and the progress of construction works.

At second, the information gathered and needed in construction projects should be stored in digital format in a cloud-based system, which can be reached practically anywhere and with different devices, such as personal computers, laptops and mobile devices. The information should be stored in a machine-readable format. The information should also be as centralized as possible, in other words there should be as few different systems as possible to smooth the information flow within the site organization and between the project parties.

At third, every site should have a responsible person for collecting status information, updating the 4D schedule and doing other BIM-related tasks. This person should belong to the site organization and be located at the site to ensure the timeliness of the information.

At last, the researchers recommend implementing the Lean philosophy core of waste and continuous improvement in the project culture. Pilot projects should be arranged to test the use of lean principles, such as JIT deliveries. That could be used as an example of the method and its effect. By this existing example within the organization, site supervisors and project managers could be encouraged to utilize these methods in the future projects.

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Predicting Time Contingency in Construction Schedules for USACE Projects

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Abstract

'Time Contingency' in construction planning is an often overlooked aspect and little attention is devoted to it during contract negotiations. There is lot of research done on cost contingencies in construction. This is especially true in Army or DOD projects even where construction completion is very critical to the mission. However, little research exists in the way of contingencies for construction schedule delays. In this paper researchers attempt to find various reasons for delay in USACE projects. Number of days are added to the construction schedule for past projects is analyzed and later used in Monte Carlo Simulation to predict the contingency time that can be added to the projects. As such, the objectives of the research presented in this paper are to assess the factors that affect scheduling contingency and to develop a simple model that can be used in estimating the expected time contingency of a construction project. Data was collected from USACE database of 80 projects and found that 26 of those were delayed because of various reasons. A total of 40 different reasons of delay were found in those 26 projects researched. These 40 different reasons were further grouped into 7 major categories to create a simple model using @Risk and Monte Carlo Simulation to predict time contingency. The model predicted a 10% time contingency for USACE projects which was very close to the observed schedule delays on sample projects.

Keywords: contingency, Monte Carlo simulation, schedule delays, USACE

1. Introduction

The Success and Failure of any project is determined mostly by three elements Cost, Quality and time. Delays are a very common feature in Construction. Results of various studies suggest main causes of delay in construction can be attributed to Designers, User changes, weather, changed site conditions, delays in financial condition, payments for completed work and material deliveries [1]. All these factors lead to construction claims, disputes and ultimately cost a lot of money to the stakeholders. The United States Army Corps of Engineers (USACE) manages hundreds for construction projects worldwide and several of their projects are delayed and delivered after the initial contract completion date. These delays are caused by various reasons like different site conditions, financial approvals, errors by architect/engineer (A/E), contaminated soils etc. Presently all the project's completion dates are derived either from the time needs by the client or the historical data on the similar projects. The biggest question is how do we calculate the construction completion date? Are we accounting the activities which might delay the project in calculating the completion dates of the project? The aim of this research is to investigate the reasons for delay in USACE Alaska district projects and create a model using Monte Carlo simulation for predicting the 'Time Contingency' for USACE construction projects.

Construction delays are very common in a project's construction lifespan. Even with the advanced technology available to us and project management techniques, construction projects are delayed and project completion dates shift accordingly. There are many reasons for these delays including labor strikes, rework, poor organization, material short-age, equipment failure, change orders, act of God etc. In addition, all the delays are inter often connected and their relation is complicated and generally triggered by delay in one or two schedule activities. Even though the construction schedule has got a lot of attention from researchers, very little has been seen in the field of 'Time Contingency', especially is the USACE projects. All of USACE projects have a 'Cost Contingency' in the project budget and a line item for time contingency is not seen and adding a line item for 'Time Contingency' could give USACE further assurance to help in managing expectations of the client.

2. Literature review

A review of literature was conducted to understand underlying issues related to construction schedule delays and their impact on projects.

2.1. Construction delays

Construction delays is a worldwide phenomenon and is one of the most common problems in construction projects. It is also usually the most expensive and complex problem to solve due to domino effects related to construction schedules. Since the delays affect both the owner and the contractor, it is a main reason for disputes and claims leading to lawsuits. To mitigate this problem a construction contract is created and followed to avoid these lawsuits and claims. Various numbers of 'General Condition Clause' are included in the contract to address site specific issues. Contract law defines various concepts of reasonableness and fair business practices such as warranties, responsibilities etc. A general understanding of the concepts and applicable clauses involved are essential to help make right decisions and to take the appropriate action in those construction delay situations [2]. Usually delays don't happen because of one single event, they develop slowly during the course of construction. Smaller delays are usually overlooked until their cumulative effect starts to affect the overall schedule, thereby impacting the project budget. By the time contractor recognizes that there is a problem, many other activities start to see the impact and resulting in moving the project completion date [3].

For a construction project to be successful, project must complete on time, within the budget, and within the required quality parameters. These three goals are intertwined with each other and affect each other. To complete a project on time, an accurate construction schedule must be created. Every project is unique, time contingency and cost uncertainties are essential for an accurate schedule, which must be flexible enough to accommodate changes without negatively affecting the overall duration of the project. It is important to allow a contingency value to both cost and time [4]. Yet, there are situations where the delays are unavoidable in activities that result in a delay in the overall project duration. Therefore, an estimate of time contingency is a major factor for achieving successful project completion. Every estimate / Schedule seen at USACE always have a contingency for money, but not for time. Therefore, the objective of the presented research in this paper is to identify the factors that affect (time) contingency and develop a simple model that forecast the expected contingency of a construction project.

2.2. Contingency

It is well known that the construction completion date is often missed due to uncertain events, and their impacts were difficult to predict because every construction project is unique [5]. Contingency, as Patrascu, A. [1] defines in his book means different things to different people. To management, it hopes all the money will not be expended and is sitting in an account and will be returned at the end of project. Contingency may become profit for the contractor if they run an effective cost control program. For an Engineer it could be a savings account which can be used to cover the additional cost of underestimated or not-included-in-budget construction activities.

The contractor's contingency is represented by a fixed percentage of the contract value or percentage of total project cost or duration [4]. Touran [4] suggest two values of cost contingency: (1) 15% for underground construction activities and tunnelling and (2) 7.5% for the rest of the project. Others suggest time contingency to be used to assure the completion time of a project and provide a degree of confidence that the planned duration can be accomplished successfully [6]. Researchers have focussed efforts to consider Monte Carlo simulations to predict an appropriate time contingency [7], [8]. Monte Carlo simulation is a computerized mathematical technique that allows one to account for risk in analysis and decision making.

3. Research methodology

A mixed method research methodology was used in the conduct of this research. Archival data for a sample 80 construction projects was retrieved from the Alaska district's Resident Management System (RMS). RMS documents additional costs and time added to a project from the initial estimate and schedule respectively. This data was used to identify 26 projects that were delayed and as the records indicated a growth in schedule increases. The project managers / engineers for these projects were interviewed to understand factors influencing of time growth. These factors were used to generate Monte Carlo simulations to predict time contingency on construction projects.

4. Results

USACE maintains all construction project related data in RMS. This data was used to analyse data for 80 projects between 2017 and 2020. The projects ranged from $300,000 to $37 million. Of the projects considered, 26 of them were found to have time delays, as shown in Table 1. The percentage growth in schedules were seen from 1.3% to nearly 300%. The project managers for these projects were interviewed to understand issues related to the cause of these delays.

Table 1: Cost and time growth data for projects

Project Cost	Original Duration (Days)	Time Growth - Days	Time growth in %
$3,737,838	363	1,051	289.50%
$3,176,500	947	50	5.30%
$19,754,000	636	176	27.70%
$7,841,500	581	618	106.40%
$37,260,400	757	99	$0.13
$11,836,000	450	53	11.80%
$20,132,323	519	123	23.70%
$34,040,000	610	14	2.30%
$22,333,348	540	153	28.30%
$12,177,483	495	33	6.70%
$13,291,429	450	81	18.00%
$9,898,068	661	8	1.20%
$19,051,000	680	179	26.30%
$33,061,944	720	128	17.80%
$4,094,093	177	15	8.50%
$975,340	27	37	137.00%
$361,995	284	30	10.60%
$5,497,904	50	8	16.00%
$8,192,750	730	76	10.40%
$9,525,000	54	3	5.60%
$5,744,964	639	102	16.00%
$663,076	79	45	57.00%
$847,820	233	16	6.90%
$33,192,500	575	257	44.70%
$2,263,812	142	73	51.40%
$19,278,001	794	10	1.30%

The responses to the delays were broadly categorized under seven themes, from 40 reasons that project managers identified as the cause of those delays. The 40 responses from the interviews highlighting the causes of delay are shown in Figure 1 below.

No. of days added to the schedule	Reasons for Delay
1051	Environmental Management plan / Dewatering permission
50	Funding Issues
84	contaminated soil
49	Design Conflicts
30	Client requested Changes
13	Move detectors - Discrepency in Drawings
618	Perfafrost - unsuitable site Conditions
21	Fire protection system - Revised
20	Lift station size increase
58	Building Enclosure
53	Different site conditions
15	Interior ? Exterior Building Conditions
108	User requested Changes
14	Drawing Conflicts
153	Door detection system - Specification issues
33	Cercla - Contaminated soil disposal
81	Foam generator location - Design conflicts
35	Drawings Conflicts
8	Adding an additional Fire wall - Design conflicts
179	Contaminated soil changes
85	HVAC design Issued
38	Lead Casing Bullets found in soil - Contaminated soil
5	User request Change- Reprograming security system
15	RFP not clear
300	Design Inadequate
70	Funding
30	Specs / Drawing Conflicts
50	User requested changes
30	Funding
76	Drawings Conflicts
30	Asbestos removal - pipes
50	Contractor posseion of site delayed by user
41	Additional scope - Doors replacement
10	Hidden site conditions
45	unforseen weather conditions
16	Additional scope added after the removal of Hood
257	ADEC/EPA requirements
42	Clreaence to construct delays - User Issues
25	Design issues
10	Adminstratived delays

Figure 1: Interview data showing causes of delays

A sample of the data collected through the interviews and the frequency of occurrence of each of the themes is shown in Figure 1.

- Administrative
- Design Related
- Regulatory
- Funding
- Additional scope
- Different site conditions
- Unforeseen Weather

The frequency of occurrence of each of themes and their percentages was calculated and shown in Figure 2.

Unforeseen weather	1	3%
Administrative Related	4	10%
Design Related	15	38%
Regulatory Delays	2	5%
Funding Related	3	8%
User requested - Additional scope	6	15%
Different Site Conditions	9	23%

Figure 2: Frequency of Delay Occurrence and Percentages

The data collected was used to determine weightage or probability of a theme occurring on a project based on the occurrence of these 26 projects, as shown in Table 2.

Table 2: Time Growth in Percentage and Weightage for Monte Carlo Simulation

	Administrative	Design Related	Regulatory	Funding	Additional scope	Different site conditions	Unforeseen Weather
	8	8	289	5	5	13	57
	8	2	45	26	21	106	
	30	3		6	1	12	
	2	3			10	3	
		2			6	7	
		28			7	26	
		18				5	
		10				6	
		1				2	
		12					
		9					
		111					
		11					
		10					
		10					
Average	12	16	167	12	8	20	57
Weightage	1	3.8	0.5	0.8	1.5	2.3	0.3

A software program named '@Risk' was used to conduct the Monte Carlo simulation. A summary of the process and related results are discussed here.

- Calculate the average % of days added to the schedule.
- Assign the weights to the categories, reasons of delay based on the occurrence. The weights are based on the probability divided by 10.
- Multiply the weights by the average no of days added to the project.
- This total is the maximum most likely days added to the schedule.
- This number is used in the @Risk Calculations for calculating the 'Time Contingency' for the construction schedule showing the @ Risk spreadsheet calculations.
- After running the simulation we see the simulation predicts the time contingency of 10% should be added to the Construction schedule with the 95% probability, as shown in Figure 3.

Activities affecting the Schedule	Base Case	Minimum	Most Likely	Maximum	Minimum	Most Likely	Maximum	Sampled
Administrative	10	99%	100%	112%	10	10	11	10
Design Related	10	99%	100%	162%	10	10	16	11
Regulatory	10	99%	100%	184%	10	10	18	11
Funding	10	99%	100%	110%	10	10	11	10
Additional Scope	10	99%	100%	113%	9.9	10	11	10
Different site conditions	10	99%	100%	146%	9.9	10	14.6	10.75
Unforseen Conditions	10	99%	100%	117%	10	10	12	10
					0	0	0	0
Output								
Totals	70							
Summary statistics								
Probability of meeting base case value	95.00%							
Time required for 95.0% confidence	77							
Contingency required for 95.0% confidence	7	10%						

Figure 3: @Risk spreadsheet showing the calculations for Time contingency, using Monte Carlo Simulation

Figure 3 above shows the number of days added to the construction schedule in percentage. The results show that the 10% -13% of time was added to the schedule in 29 projects, 14%-20% of the time was added to 2 projects, and 20% or more of the time was added to balance 9 projects.

5. Conclusions

Looking at the results from risk model we can see that the model is suggesting a 10% Time contingency for the USACE projects, which is close to the results from our manual calculations which shows that 72% of the projects extended 10%-13% of time to the projects. This sample suggests that the model can be used to predict the time contingency to the construction projects. The variables in this model are the probability of occurrence and based on the location and region for the projects. Thus, using this type of model can be very useful in predicting the 'Time Contingency' we can add to the construction schedule. Future research may include running similar models in each of the USACE districts to explore trends. This could help USACE administrators understand regional and national trends as related to time contingencies.

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Project Crashing with Crash Duration Consumption Rate: An Illustrative Example

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Abstract

Completing on time, within the estimated budget and at the desired quality are three main constraints of construction projects. However, construction projects become nowadays more complex than ever, so they are subjected to uncertainties and changes throughout the project life cycles. These uncertainties and changes may lead to severe delays in project duration. Therefore, project managers desire to reduce the project duration without changing scope of the project. Crashing a project is an advanced project management strategy, which aims to achieve the maximum reduction in project duration with the minimum additional cost without changing the scope. However, project crashing is a difficult task and should be used if it is necessarily needed. This paper proposes a model that considers crash duration consumption rates of activities for solving the project crashing problem. The crash duration consumption rate is the percentage that is set to determine the maximum amount of crash duration that an activity can consume with safety margin. The proposed model enables the schedulers to assign crash duration consumption rates to each activity that can be used during the project crashing procedure. Having applied the proposed model, the Monte Carlo simulation is also performed to determine the probability of completion of the project at the latest in crashed project duration. The applicability of the proposed model is presented along with an illustrative example. The proposed model is supposed to minimize the likelihood of delays, while maintaining schedule flexibility. In addition, the proposed model provides schedulers a new perspective in solving project crashing problems.

Keywords: crash duration consumption rate, illustrative example, Monte Carlo simulation, project crashing

1. Introduction

Delays are one of the most serious and common problems in construction projects [1]. Delays not only affect the project duration, but also increase the total cost of the project and reduce the project quality [2]. In general, the performance of a construction project is measured by three main constraints; the completion of that project on time, within the estimated budget and at the desired quality [3]. In order to decrease or eliminate the delays that have a negative impact on the project performance [4], project managers desire to reduce the project duration without changing scope of the project to meet the specified project deadline [5]. One of the effective ways to reduce the project duration is the project crashing [6]. The duration of a project can be shortened by accelerating the normal critical activities' durations with minimum additional cost by allocating more or efficient resources (labor, equipment or materials), working multiple shifts, and extending working days [7-12]. Implementation of these strategies increases the direct costs associated with such activities, but also decreases total indirect costs by reducing the project duration [7]. Therefore, project crashing has a direct impact on two of the project's three main constraints, which are time and cost. As a result, the project crashing problem can be defined as 'the time-cost trade-off problem, which aims to achieve the maximum reduction in project duration with the minimum additional cost without changing the scope' [13].

The reduction of project duration has always been a difficult task for project managers, so a number of researchers have developed different mathematical models, heuristic and meta-heuristic algorithms to solve the time-cost trade-off problem for years [9]. In addition, the time-cost trade-off problem has been extensively studied in the literature since the problem was first mathematically formulated by Kelly and Walker in 1957 [14,15]. Although the reduction of project duration day by day causes a decrease in the floats of non-critical activities, resulting in an increased risk of not the completion of project on time [16], most of the previous studies focusing on project crashing do not address maintaining schedule flexibility. Few studies (e.g., Rabie and El-Sayegh, 2017 [16]; El-Sayegh and Al-Haj, 2017 [17]) have evaluated float loss as cost to provide schedule flexibility in time-cost trade-off problems. In time-cost trade-off problems, there is still a need for developing more efficient models that will provide schedule flexibility while project duration is reduced. Therefore, the main objective of the study to fill this gap. The proposed crashing model aims to provide a flexibility for the normal critical activities to be re-crashed if necessary during execution phase of the project. This paper proposes a model that considers crash duration consumption rates of activities for solving the project crashing problem. In order to demonstrate how the proposed model can be applied in a real life project, an illustrative example was also performed.

2. The proposed project crashing model

The proposed model was developed through Visual Basic Programming Language integrated with Microsoft (MS) Excel. An Excel-based model was preferred because it is reliable and transparent through easy observation of the program's performance at every stage of the process. The proposed model mainly consists of seven main steps, which are briefly explained below:

Step 1: In this step, the necessary inputs for the developed model are determined. The inputs of the proposed model and their notations are presented in Table 1.

Table 1. The inputs of the proposed model and their notations.

Notation	Definition
i	Predecessor of activity j
j	Successor of activity i
N	Total number of activities in the project
t_i	Normal duration of activity i
mct_i	Maximum crash duration of activity i
cr_i	Crash duration consumption rate of activity i (between 0 and 1)
act_i	Allowable crash duration of activity i
nc_i	Normal (direct) cost of activity i
dnc_i	Daily normal cost of activity i
cc_i	Daily crashing cost of activity i
ic_p	Daily indirect cost of the project

Step 2: In this step, basic calculations are performed using the normal durations of activities to set up a CPM schedule. Once the scheduler inputs the necessary information identified in the first step, the model automatically calculates the project duration, start/finish times and floats of the activities in the project network. After the start/finish times and floats of all activities are determined, an initial CPM network can be plotted that displays both specific information for each activity and the critical path(s).

Step 3: In this step, two constraints are specified. The first constraint ensures that the crash duration of an activity cannot exceed the allowable crash duration determined for this activity. The allowable crash duration is equal to the maximum crash duration of the activity multiplied by crash duration consumption rate (Eq. 1). The crash duration consumption rate is the percentage that is set to determine the maximum amount of crash duration that an activity can consume with safety margin. The second constraint prevents violating the predecessor-successor relationships between activities by recalculating the start/finish times and floats of activities after each crashing step. By this way, shifting the normal durations of the crashed critical activities does not violate the precedence relationships in the network.

$$act_i = mct_i \times cr_i \quad (1)$$

Step 4: In this step, the crashing process starts and the proposed model is applied to this process. First, critical path(s) on the project network are identified with basic CPM calculations using the normal durations of activities. Secondly, crashing alternatives are determined, which can shorten all critical paths for one day. These alternatives can consist of one critical activity or critical activities, especially if there is more than one critical path. Thirdly, an alternative with a minimum daily crashing cost is selected. The daily crashing cost of an activity (cc_i) is calculated as a percentage (P_1%) of the daily normal cost of that activity (dnc_i) calculated by dividing the normal cost of an activity (nc_i) by its normal duration (t_i) (Eq. 2-3). Fourthly, the normal duration of the critical activity or activities in the alternative is shortened for one day and basic CPM calculations are performed again on the project network. Thus, the project duration is shortened for one day and this process continues in the same way until one of the critical paths on the project network becomes uncompressible.

$$dnc_i = \frac{nc_i}{t_i} \quad (2)$$

$$cc_i = dnc_i \times P_1 \quad (3)$$

Step 5: In this step, some transitional outputs are computed, as the project duration is shortened day by day and the crashing process is repeated until a feasible solution cannot be found. The transitional outputs involve updated project duration, the number of activities in each crashing alternative, daily crashing cost of each crashing alternative (Eq. 4), the number of crashed days for each activity, total normal (direct) cost (Eq. 5), total indirect cost (Eq. 6), total crashing cost (Eq. 7) and total project cost (Eq. 8). The transitional outputs of the proposed model and their notations are presented in Table 2.

Table 2. The transitional outputs of the proposed model and their notations.

Notation	Definition
UPD	Updated project duration
L	The number of activities in the crashing alternative *a*
cc_a	Daily crashing cost of crashing alternative *a*
x_i	The number of crashed days for activity *i*
TDC	Total normal (direct) cost
TIC	Total indirect cost
TCC	Total crashing cost
TPC	Total project cost

The equations used to compute the transitional outputs are presented in Equations 4-7.

$$cc_a = \sum_{i=1}^{L} cc_i \quad (4)$$

$$TDC = \sum_{i=1}^{N} nc_i \quad (5)$$

$$TIC = UPD \times ic_p \quad (6)$$

$$TCC = \sum_{i=1}^{N} x_i \times cc_i \quad (7)$$

Step 6: In this step, the objective function for project crashing process is determined. For this purpose, first the total project cost (Eq. 8) is calculated, which is the sum of total direct cost, total indirect cost and total crashing cost.

$$TPC = TDC + TIC + TCC \qquad (8)$$

The objective function (*Z*) is the minimization of the total project cost (Eq. 9).

$$Z = min\ (TPC) \qquad (9)$$

Step 7: In this step, a Monte Carlo simulation is performed to see whether the proposed model is useful or not. In order to use in the Monte Carlo simulation, the optimistic and pessimistic durations of activities are calculated using their updated normal durations after completing the crashing process. Therefore, first, the normal durations of activities are updated. The updated normal durations of activities (ut_i) are calculated by subtracting the crashed durations from their initial normal durations (Eq. 10). The optimistic durations of activities (ot_i) are assumed to be equal to their updated normal durations (Eq. 11). The pessimistic durations of activities (pt_i) are assumed to be (P_2%) higher than their updated normal durations (Eq. 12). However, if an activity is crashed, the pessimistic duration of that activity is also considered equal to the updated normal duration. In the model, the triangular distribution is used to generate random activity duration using the optimistic, updated normal and pessimistic durations of activities in each iteration. After the scheduler inputs the necessary duration information for the activities, the model automatically calculates and records the project duration for each iteration. As a result, the probability of the project's completion at the latest in crashed project duration is determined via the Monte Carlo simulation.

$$ut_i = t_i - x_i \qquad (10)$$

$$ot_i = ut_i \qquad (11)$$

$$pt_i = ut_i \times (1 + P_2) \qquad (12)$$

3. Illustrative example

A network consisting of 18 activities from the literature is used to demonstrate how the proposed model can be applied in a real-life project [18]. Some assumptions accepted before applying the proposed model to the illustrative example are as follows:

- Daily crashing costs of activities are accepted as 40% (P_1) of their daily normal (direct) costs.
- The daily indirect cost is determined as $100.
- The optimistic durations of activities are assumed to be equal to their updated normal durations.
- The pessimistic durations of activities are assumed to be 5% (P_2) higher than their updated normal durations.

In addition, two limitations of the proposed model are as follows:

- The proposed model considers only the finish to start (FS) relationship, which is the traditional and most common dependency relationship between activities in the project network.
- The proposed model considers only "normal critical activity" out of the nine critical activity types defined theoretically by Hajdu et al. in 2016 [12] for use in the project crashing process.

The network of the illustrative example, which displays predecessor-successor relationships, normal durations (in days), early start/finish times (ES_i, EF_i), late start/finish times (LS_i, LF_i), and total floats (TF_i) of the activities is presented in Figure 1. The inputs for the illustrative example is presented in Table 3.

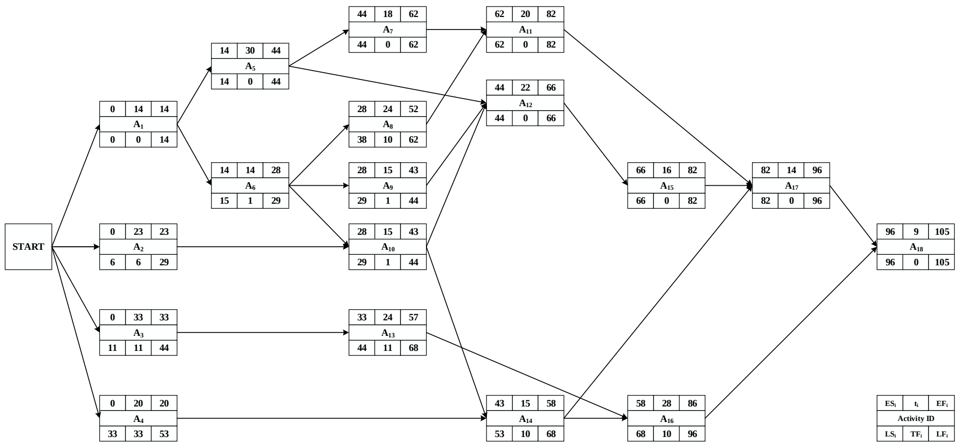

Fig. 1. Network for illustrative example.

Before running the project crashing model, the model asks for assigning a crash duration consumption rate to the activities. In project crashing model, the scheduler is allowed to assign crash duration consumption rate to each activity according to a preferred criterion. In this example, the maximum rate is set as 80% for the crash duration consumption of the activities that are scheduled to start before and on the 52^{th} day. In other words, setting a crash duration consumption of 80% implies that an activity that is scheduled to start in the first half of the project cannot consume more than 80% of its maximum crash duration in project crashing. On the other hand, a lower maximum crash duration consumption rate (i.e., 50%) is assigned to the activities that are scheduled to start after the 52^{th} day. This crash duration consumption rate implies that an activity that is schedule to start in the second half of the project cannot consume more than 50% of its maximum crash duration in project crashing. The preferred trade-off strategy intends to provide more flexibility for the critical activities scheduled to be completed in the second half of the project to be re-crashed if necessary. Providing this flexibility may help prevent severe delays in the project completion, which in turn improve the overall project performance.

Table 3. Inputs of the illustrative example.

Activity ID	IPA*	t_i (Day)	mct_i (Day)	cr_i	act_i (Day)	nc_i ($)	dnc_i ($/Day)	cc_i ($/day)
A_1	Start	14	4	0.8	3	3,500.00	250.00	100.00
A_2	Start	23	5	0.8	4	11,500.00	500.00	200.00
A_3	Start	33	8	0.8	6	8,250.00	250.00	100.00
A_4	Start	20	4	0.8	3	2,500.00	125.00	50.00
A_5	A_1	30	6	0.8	4	3,000.00	100.00	40.00
A_6	A_1	14	3	0.8	2	2,800.00	200.00	80.00
A_7	A_5	18	6	0.8	4	1,800.00	100.00	40.00
A_8	A_6	24	7	0.8	5	1,800.00	75.00	30.00
A_9	A_6	15	3	0.8	2	2,625.00	175.00	70.00
A_{10}	A_2, A_6	15	3	0.8	2	375.00	25.00	10.00
A_{11}	A_7, A_8	20	4	0.5	2	1,500.00	75.00	30.00
A_{12}	A_5, A_9, A_{10}	22	5	0.8	4	2,750.00	125.00	50.00
A_{13}	A_3	24	8	0.8	6	4,500.00	187.50	75.00
A_{14}	A_4, A_{10}	15	5	0.8	4	4,500.00	300.00	120.00
A_{15}	A_{12}	16	0	0.5	0	3,500.00	218.75	87.50
A_{16}	A_{13}, A_{14}	28	8	0.5	4	5,250.00	187.50	75.00
A_{17}	A_{11}, A_{14}, A_{15}	14	3	0.5	1	2,800.00	200.00	80.00
A_{18}	A_{16}, A_{17}	9	2	0.5	1	2,025.00	225.00	90.00

*IPA: Immediate Predecessor Activity

When the required information is inputted and the proposed model is run, first of all, early/late start times, early/late finish times, and total floats of the activities are calculated and the initial schedule plotted (Figure 1). The project duration is calculated to be 105 days. After plotting the initial schedule, critical activities are automatically identified by the proposed model. Then, the developed model automatically selects the crashing alternative, with the lowest daily crashing cost. In the developed model, the project duration is shortened day by day. The process is repeated until a feasible solution cannot be found. It should also be noted that in project crashing, each activity can be crashed as much as the allowable crash duration, not as much as the maximum crash duration.

In the proposed model, it is assumed that allowable crash durations of the activities are taken into account during the crashing process. After the implementation of this model, the findings concerning the updated project durations, the sequence of crashed activities, daily crashing costs, cumulative crashing costs, total normal cost, total indirect costs and cumulative total project costs are presented in Table 4.

Table 4. The findings obtained by applying the proposed crashing model to the illustrative example.

Project Duration (Day)	Sequence of Crashed Activities	Daily Crashing Cost ($/day)	Cumulative Crashing Cost ($) (1)	Total Normal Cost ($) (2)	Total Indirect Cost ($) (3)	Cumulative Total Project Cost ($) (1+2+3)
105	-	0.00	0.00	64,975.00	10,500.00	75,475.00
104	A_5	40.00	40.00	64,975.00	10,400.00	75,415.00
103	A_{11}, A_{12}	80.00	120.00	64,975.00	10,300.00	75,395.00
102	A_{11}, A_{12}	80.00	200.00	64,975.00	10,200.00	75,375.00
101	A_{17}	80.00	280.00	64,975.00	10,100.00	75,355.00
100	A_7, A_{12}	90.00	370.00	64,975.00	10,000.00	75,345.00
99	A_7, A_{12}	90.00	460.00	64,975.00	9,900.00	75,335.00
98	A_{18}	90.00	550.00	64,975.00	9,800.00	75,325.00
97	A_1	100.00	650.00	64,975.00	9,700.00	75,325.00
96	A_1	100.00	750.00	64,975.00	9,600.00	75,325.00
95	A_1	100.00	850.00	64,975.00	9,500.00	75,325.00
94	A_5, A_9, A_{10}	120.00	970.00	64,975.00	9,400.00	75,345.00
93	A_5, A_9, A_{10}	120.00	1,090.00	64,975.00	9,300.00	75,365.00
92	A_5, A_6, A_{16}	195.00	1,285.00	64,975.00	9,200.00	75,460.00

The traditional project crashing model was also applied to the illustrative example. In the traditional model, it is assumed that allowable crash durations of the activities are not taken into account during the crashing process. After the implementation of this model, the findings concerning the updated project durations, the sequence of crashed activities, daily crashing costs, cumulative crashing costs, total normal cost, total indirect costs and cumulative total project costs are presented in Table 5.

Table 5. The findings obtained by applying the traditional crashing model to the illustrative example.

Project Duration (Day)	Sequence of Crashed Activities	Daily Crashing Cost ($/day)	Cumulative Crashing Cost ($) (1)	Total Normal Cost ($) (2)	Total Indirect Cost ($) (3)	Cumulative Total Project Cost ($) (1+2+3)
105	-	0.00	0.00	64,975.00	10,500.00	75,475.00
104	A_5	40.00	40.00	64,975.00	10,400.00	75,415.00
103	A_{11}, A_{12}	80.00	120.00	64,975.00	10,300.00	75,395.00
102	A_{11}, A_{12}	80.00	200.00	64,975.00	10,200.00	75,375.00
101	A_{11}, A_{12}	80.00	280.00	64,975.00	10,100.00	75,355.00
100	A_{11}, A_{12}	80.00	360.00	64,975.00	10,000.00	75,335.00
99	A_{17}	80.00	440.00	64,975.00	9,900.00	75,315.00
98	A_{17}	80.00	520.00	64,975.00	9,800.00	75,295.00
97	A_{17}	80.00	600.00	64,975.00	9,700.00	75,275.00

Table 5 (cont'd). The findings obtained by applying the traditional crashing model to the illustrative example.

Project Duration (Day)	Sequence of Crashed Activities	Daily Crashing Cost ($/day)	Cumulative Crashing Cost ($) (1)	Total Normal Cost ($) (2)	Total Indirect Cost ($) (3)	Cumulative Total Project Cost ($) (1+2+3)
96	A_7, A_{12}	90.00	690.00	64,975.00	9,600.00	75,265.00
95	A_{18}	90.00	780.00	64,975.00	9,500.00	75,255.00
94	A_{18}	90.00	870.00	64,975.00	9,400.00	75,245.00
93	A_1	100.00	970.00	64,975.00	9,300.00	75,245.00
92	A_1	100.00	1,070.00	64,975.00	9,200.00	75,245.00
91	A_1, A_{13}	175.00	1,245.00	64,975.00	9,100.00	75,320.00
90	A_1, A_{13}	175.00	1,420.00	64,975.00	9,000.00	75,395.00
89	A_5, A_9, A_{10}, A_{13}	195.00	1,615.00	64,975.00	8,900.00	75,490.00
88	A_5, A_9, A_{10}, A_{13}	195.00	1,810.00	64,975.00	8,800.00	75,585.00
87	A_5, A_9, A_{10}, A_{13}	195.00	2,005.00	64,975.00	8,700.00	75,680.00
86	A_5, A_6, A_{13}	195.00	2,200.00	64,975.00	8,600.00	75,775.00
85	A_2, A_5, A_6, A_{13}	395.00	2,495.00	64,975.00	8,500.00	76,070.00

After the project crashing process is completed, the findings obtained by the proposed model are compared with those obtained by the traditional model. The relationship between the project duration and the total project cost after the implementation of these models is presented in Table 6.

Table 6. Comparison of the two models in terms of total project cost and project duration.

Project Duration (Day)	The Traditional Model	The Proposed Model
105	75,475.00	75,475.00
95	75,255.00	75,325.00
92	75,245.00	75,460.00
85	76,070.00	-

Based on Table 6, the following results can be interpreted:

- In the initial schedule, the project duration is 105 days and the total project cost is $75,475.00.
- In the proposed model, the minimum duration that the project can be crashed is 92 days and the corresponding total project cost is $75,460.00.
- In the proposed model, the minimum total project cost is $75,325.00, and the corresponding project duration is 95 days.
- In the traditional model, the minimum duration that the project can be crashed is 85 days and the corresponding total project cost is $76,070.00.
- In the traditional model, the minimum total project cost is $75,245.00, and the corresponding project duration is 92 days.

Once the project crashing process is completed, a Monte Carlo simulation is carried out to prove that the proposed model is useful. First, normal durations of the activities are updated. Then, the optimistic and pessimistic durations of activities are calculated using their updated normal durations. For the Monte Carlo simulation, the number of iterations to be applied is specified as 1000, and the triangular distribution is used to generate random activity duration using the optimistic, updated normal and pessimistic durations of activities in each iteration. After the scheduler inputs the necessary duration information for the activities, the model automatically calculates and records the project duration for each iteration. As a result, the probability of completion of the project at the latest in crashed project duration is determined via the Monte Carlo simulation. This process is applied similarly in both the proposed model and the traditional model to make comparison. In the proposed model, as the minimum duration that the project can be crashed is the 92^{nd} day, the 92^{nd} day of the project is determined as a reference point for the comparison to be meaningful and interpretable. As a result of the Monte Carlo simulation, the project completion durations and the frequency values of these durations according to both models are presented in Figure 2.

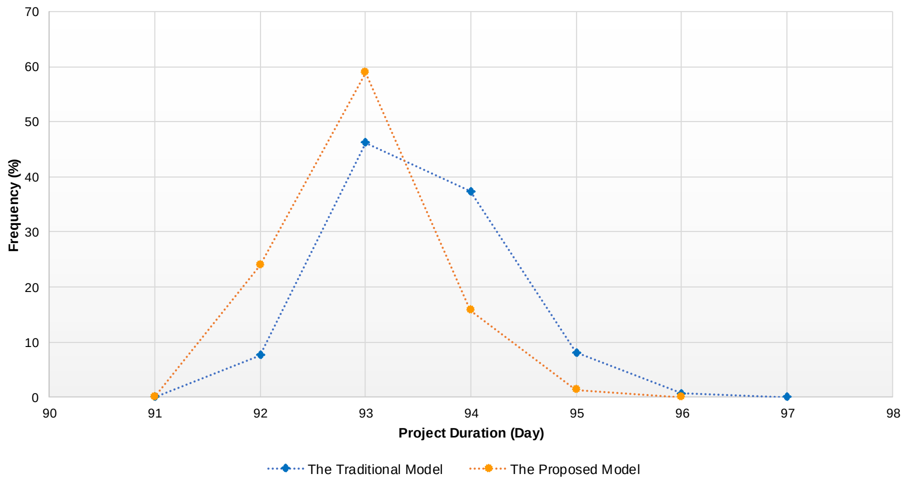

Fig. 2. Comparison of the two models in terms of project durations and their frequency values.

Based on Figure 2, the following results can be interpreted:

- In the proposed model, the probability of completing the project at the latest in 92^{nd} day is 24.00%.
- In the proposed model, the probability of completing the project at the latest in 95^{th} day is 100.00%.
- In the traditional model, the probability of completing the project at the latest in 92^{nd} day is 7.60%.
- In the traditional model, the probability of completing the project at the latest in 95^{th} day is 97.30%.

As a summary, shorter project duration and lower total project costs are achieved in the traditional model compared to the proposed model for project crashing (see Table 6). The main reason for this finding is that in the proposed model, each activity can be crashed as much as the allowable crash duration, not as much as the maximum crash duration. However, it should be noted that the proposed model provides flexibility for schedulers to avoid delays during execution phase of the project through this trade-off strategy. Therefore, the difference between the total project costs of the two models on the same project day can be considered as "a cost of flexibility" for the future of the project. Furthermore, when the findings of the Monte Carlo simulation applied after project crashing are carefully examined, it can be seen that the proposed model offers a better distribution than the traditional model for the possibility of the project completion durations and the frequency values associated with these durations (see Figure 2). For example, on 92^{nd} day of the project, although the proposed model in terms of total project costs is $215 more than the traditional model, the probability of completion of the project on the same day in the proposed model is 16.40% higher than the traditional model (see Table 6 and Figure 2). As a result, in the light of the findings of this study, the proposed model has proven to be a useful tool for use in project crashing problems.

4. Conclusion

Project crashing is an advanced project management strategy that refers to a particular type of project schedule compression and it is an important topic that has attracted the attention of numerous researchers for many years. In most of these studies, crash duration consumption rates of activities are neglected. This study proposes a model, which considers crash duration consumption rates of activities, for solving the project crashing problem. For this purpose, the proposed model was developed through Visual Basic Programming Language integrated with Microsoft (MS) Excel. The applicability of the proposed model is presented along with an illustrative example. In addition, the traditional project crashing model was also applied to the illustrative example. Once the project crashing process is completed, the findings obtained by the proposed model are compared with those obtained by the traditional model. As a result, shorter project duration and lower total project costs are achieved in the traditional model compared to the proposed model for project crashing. The main reason for this finding is that in the proposed model, each activity can be crashed as much as the allowable crash duration, not as much as the maximum crash duration. On the other hand, the findings of the Monte Carlo simulation applied after project crashing revealed that the proposed model offers a better distribution than the traditional model for the possibility of the project completion durations and the frequency values associated with these durations. In sum, while the proposed model maintains schedule flexibility, it minimizes the likelihood of severe delays. The findings of this study indicated that the proposed model is a useful tool to be used in project crashing problems. In addition, the proposed model can be used in crashing any construction project as well as non-construction projects. This study has some limitations. First, different findings may be obtained by applying the proposed model to different cases or by assigning crash duration consumption rates based on a different strategy for activities in the same problem. Second, the assessment of different dependency relationships between activities (i.e., start to start, start to finish, finish to finish) and different critical activity types can be addressed in future studies that will focus on project crashing problems.

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Project Planning by Modified Gauss S-Curve

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Planning is the prediction of the future erfrmed most often by a gantt chart as a graphical representation of the activity with respect to the temporal abscissa component. In addition to the activity ordinates, there is also a cash-flow or S-curve given by the one-dimensional nonlinear equation. Today, there is a growing demand for two-dimensional or 3D modeling, including 3D planning through a vector cummulative S-curve. Monitoring the distribution of the situation on formerly realized projects creates an image of certain model behaviour of the 3D S-curve defined by the modified Gaussian curve. By developing fifteen project plans from the buildingconstruction industry and from the construction project through the Microsoft project, the discrete S-curve connects to the modified Gaussian S-curve (MGSC). Analyses are made that indicate the equivalence of the S-curves of plans and realization, which defines the function of the parameters λkv and b in the variable of investment amounts of projects. Therefore, modeling and simulating a new Gaussian curve-modified method creates an nM model for project development with the ability to optimize plans and an S-curve future projects and adjusting online technology.

Keywords: planning, cash flow, 3D modeling, modified Gaussian S-curve, optimization

1. Introduction

Every system, especially construction production, takes place in time-span units, and every natural process also takes place in time-span values. Predicting system behavior over time is called planning in the system. Physicists and structural engineers have long since discovered the distributions of the density function [1,2,3,4] for a number of natural processare the Gaussian and Erlang distributions. Planning in construction is inevitable, but it still relies on a low engineering principle. Many construction engineers have tried to define the S-curve of the project polynomially so that, based on its uninterrupted continuous sequence, they can predict the further course of the project. After a statistical survey of the realization S-curve in Međimurje Graditeljstvo Company, as part of the doctoral study in the course Project Management, an equation called a modified Gaussian S-curve is revealed. It is almost identical to the practice discrete statistics. However, the problem is in the small sample, so the constants in the equation are insufficiently quantified. Therefore, research is continuing into other plans of the familiar regional construction companies, namely TEAM Čakovec, which is specialized in building construction, and CARIN specialized in building construction using robotic technology. Due to better definining of constants and the modified Gaussian curve based on planning data, it has been proven for the implementations of over a dozen of large projects to match the planned values with only small discrepancies. Based on these discrepancies, the first modified curve has been supplemented and it is yet to develop until stability. In addition, the planned data of the prefabricated elements producing construction company Tehnobeton and from the civil engineering company TEGRA were added to complete the set of construction activities.Today, research is interested in monitoring deviations from the plan, i.e. in creating intervals of the range of variations and in the standard deviation of the observed magnitude which also behaves according to the Gaussian curve. This provided for the main precondition for planning precision and reducing business risk. Past experiences prove the riskiness of projects, especially in the first cycles of implementing a new project. The contribution of the representation of the S-curve by the modified Gaussian curve in relation to the existing polynomial ones s revealed in its ability to define the probability statistics arising from the Gaussian curve as the most common distribution of natural events and thus of construction production as well; furthermore, the formula is iterative in the function of cost and time, so when contracting a deal, a situational financial scheme can be made immediately for the investor, who can create a monthly financial scheme without a plan and make arrangements with the bank within a specified period and with a certain amount of credit. The third industrial revolution, computerization, that is, the softwarization of business systems with new CAD tools, has contributed to innovations in technology and organization of enterprises, especially with the discovery of 3D or vector organization [5]. Such novelties with cyber equations of a plan-modified Gaussian S-curve with recurrent DSP equations create a cyber system [6,7] that can be defined from any system by sensing and adjusting the system within time. The goal of MGSC is to create a project management (PM) simulation to define and regulate the system as precisely as possible, i.e. to automate a group of PM processes, to plan, execute and control the project quality.

2. Planning of projects by linear models

In many construction companies in the late 20th century and at the end of the Third Industrial Revolution, an integrated information system (IIS), or software for managing the entire business system on an Oracle relational database, was designed, designed on designer devenloper tools, which creates the comfort of managing all the data of medium and giant companies. . Global companies have already introduced their own Model Based Systems Engineering (MBSE) standard models [8], derived from a well-known IBM corporation. The Maris system is IIS or a possible module in Building information modeling (BIM) [9]. Other software packages such as SAP, Optima Primavera, Gala and the Critical Path Method (CPM) and CPM combinatorics have also appeared in the market [10]. They all have their advantages and disadvantages in terms of project management use. Microsoft Project took over the market and developed the CPM method into various graphical representations and outperformed all competitors with its simplicity and ease of connecting to other systems. The software is rich in various versions and capabilities, so an expert should devote a lot of time to the software package to take advantage of all its options options. Reports and overviews in the editor can be great, but then you need to provide each resource with its quantitative data, which is a big drawback; however, with the feedback link to IIS, it all works successfully.

The simplest variable for project planning and monitoring is money as a function of time, that is, a 2D S-curve. Thus, various authors have addressed the definition of the S-curve. Equations from source [11,12] and equation (1) Ostojić-Škomrlj, Radujković define a S-curve by a nonlinear polynomial curve.

$$Y_i^{vis.} = -0{,}0643212823 \cdot x_i - 0{,}0278540885 \cdot x_i^2 + 0{,}0016474856 \cdot x_i^3 - 0{,}000023498997 \cdot x_i^4 + 0{,}0000001165 \cdot x_i^5 - 0{,}0000000001 \cdot x_i^6 \quad (1)$$

Whereas, to model and simulate the development of robots in Japan, an exponential curve with a discrete constant (2) was elaborated (Fig. 1) [13].

$$Y_t = \frac{539}{1+e^{-0{,}3033(t-19{,}1211)}} \quad (2)$$

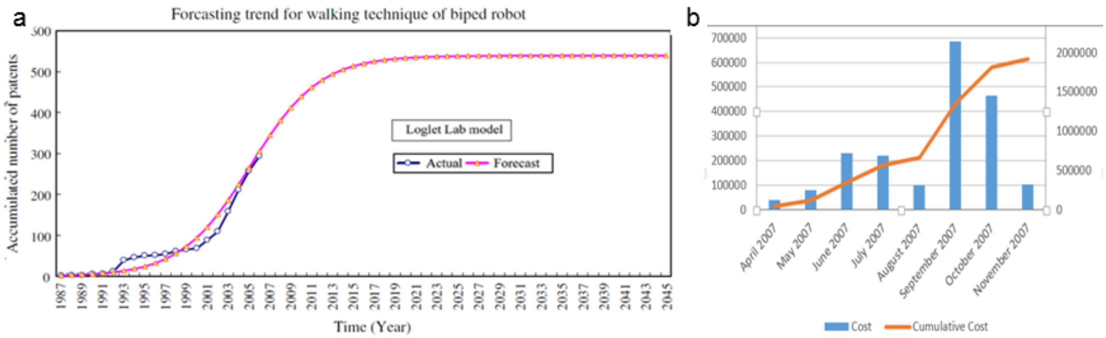

Fig. 1. (a) S-curve a) of the robots development in Japan [14]; (b) of a construction project (author).

The key problem of the given curves function is their one-dimensiona quality. This problem is solved by a modified Gaussian curve as it is in the function of two variables x as an abscissa at time t shoving the months of production and ordinate T as the cost variable or value of the investment.

3. Planning the projects by a modified Gaussian curve from realisation plans

Today's trend in informatics is the old mathematical method of numerical interpolation and approximation of functions, which has its root in mathematical algebra, that is, mathematical induction. The original definition of the S-curve by the Gaussian distribution function based on the bell-shaped event probability density function of the event shows a great coincidence in defining the S-curve. In MGSC [14], by replacing constant 2 in the fraction of power with a kv constant 10000, the so-called ironing of the S-curve function is instantly enhanced(3).

$$sGt = \frac{1}{\sigma \cdot \sqrt{2 \cdot \pi}} \cdot e^{\frac{-(x-\mu)^2}{kv \cdot \sigma}} \qquad (3)$$

By introducing the constants kv, λkv and a and b as the coefficients of the equation of the standard deviation σ (4) within the modified Gaussian S-curve (5), a high precision or a coincidence of the MGSC with the discrete S-curve of the realization plans was attained..

$$\sigma = a \cdot T + b \qquad (4)$$

$$skvGr(x, T) = \lambda kv \cdot \int_0^x \frac{1}{(a \cdot T + b) \cdot \sqrt{2 \cdot \pi}} \cdot e^{\frac{-(x-\mu)^2}{kv \cdot (a \cdot T + b)}} dx \qquad (5)$$

MGSC is a function of two cost variables T and variable x, i.e., the time of the situation in month t, whereas the arithmetic mean or expectation of x is a constant μ corresponding to half of the project variable x. The dispersion σ has been replaced by the line in function of T. Thus we obtain an iterative equation or a recurrent equation having the variable T on both sides. Currently, probabilistic prediction of project performance and the use of stochastic S-curves by a software package to generate stochastic S-curves by a simulation approach shows the dispersion deviation [15] of the S-curve by the Gaussian function of the density of cost and time distribution (Fig. 2). However, the problem of the unidimensionality of these curves or 2D representations of functions remains.

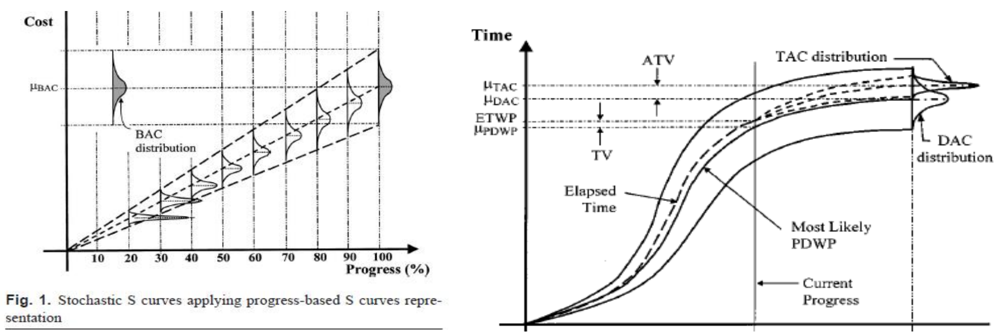

Fig. 2. Probabilistic dispersion of cost and time¸in implementing a project [15]

4. Planning of projects by modified Gaussian S-curve from project planning

Observing the Gantt charts of various MS projects over a couple of years for some completed projects shows that in the first part of the implementation time, the activity of constructions takes place and finally the equipping and finishing works on projects of new high-rise construction, whereas maintenance closes the circle when reconstructions in civil engineering are concerned (Fig. 3).

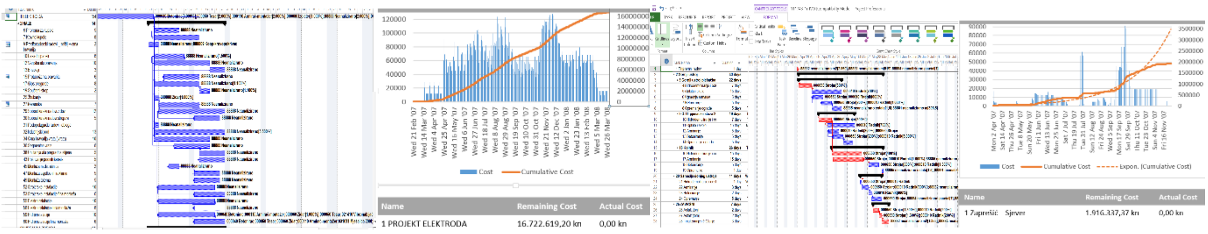

Fig. 3. TEAM – Elektroda Zagreb and the reconstruction of the bridge over the Sava at Zaprešić - CARIN Zagreb and a series f characteristic plans with supremum and i infimum in the S.curve distribution (author)

The assumption is that a modified Gaussian curve can express all project plans. By considering the dimensions of the variables and constants before mentioned (a, b, T, t, x, kv, λkv, μ) from the project plans of various authors and various construction activities, a certain dependence of variables is created in the increased interval of the value of variables in relation to the realized projects of Međimurje Construction . From thinned Table 1 it can be seen that the value of project T is mainly in proportion to the variables t, λkv and b whereas the constant a is constant and remains as in (4) and t / 2 replaces μ (table 1).

Table 1. The intervals of constants and variables in the MGSC dispersion of pians

T = situiranje u 1000	t	λkv	b
393	4	0,055	0,0001
10585	8	3	0,0004
18486	5	8	0,0004
18636	13	55	0,00075
2878446	18	7000	0,0008

The given intervals of variables of the modified Gaussian distribution allow the creation of an idealized planning S-curve proportionally - i.e. linearly - for given constants in relation to the value of the investment. Further iterative increments in activities in SMEs or resources optimize the plan of a project. However, these are not all the factors that affect the value of a project but they are among the leading variables. Creating a real curve equated to actual real data from the data distribution proves that the constant kv amounts 10000 and λkv, a, and b are discrete values for each case that is in turn defined separately and discretely.

The planned values of the S-curve thus coincide with the realization plans of the projects addressed in the original survey. In the examples given, a discrete S-curve (kumR) was extracted and by ironing with variables a modified Gaussian curve, a (skvGrR) curve with a discrete graphical overlap was identified (Fig. 4). This proves the approximate value of the definition of an S-curve as a discrete polynomial and a functional modified Gaussian curve with actual project values (5).

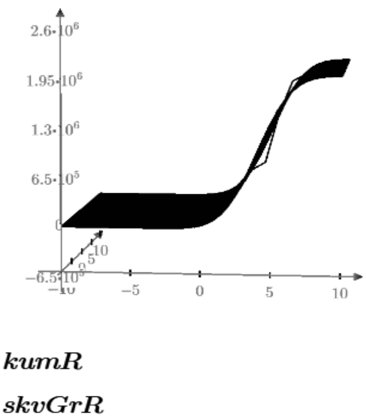

Fig. 4. Analytc ad graphic overview of Elektroda Zagreb project with the real discrete values (kumR) and modified Gaussian S-curve (skvGr, skvGrR) (author)

Another assumption is the automation of the MGSC design so that the parameter λkv and b can be defined with a linear or parabolic function. From the data (Table 2) and (Fig. 5) it can be seen that the value of the project T is mainly proportional to, i.e. linear with the variables t and the parameters λkv and b, while the parameter a is constant remaining as in (4) whereas t / 2 replaces μ.

Table 2. The intervals of constants and variables in the MGSC dispersion of Tehnobeton plans (similar. Tegra)

n	b	λkv	T
8	0,00075700	1,35	3220,00
9	0,00075700	1,35	3200,00
11	0,00075700	9,30	8150,00
10	0,05000000	440,00	24830,00

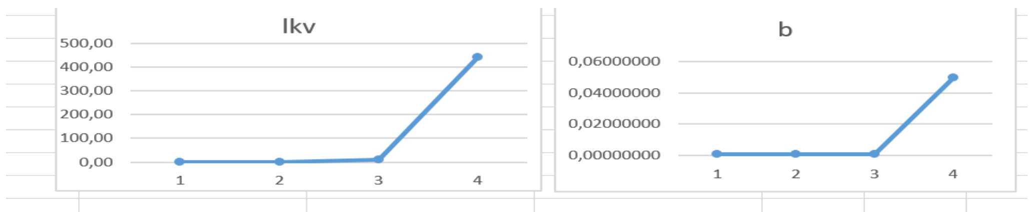

Fig. 5. Variables in function of T – amounts (author)

By elminating the extreme values, the parameter λkv takes on the value of equation (6), which has yet to be supplemented with new research.

$$\lambda kv = 0.295 + 2.287 \cdot 10^{-4} \cdot T + 7.982 \cdot 10^{-9} \cdot T^2 \tag{6}$$

An attempt to automate the MGSC equation with parameter λkv partially satisfies the solutions whereas parameter b does not behave in accordance with the examples given. Thus, parameter b is still unexplored yet it does contribute in the exponential and the fraction, so it has a visible effect on the value of the equation.

5. Conclusion

The given equation is just a prototype for a real two-dimensional S-curve as a function of T (cost or situation or investment) and x as a time variable t. More field data is needed to study the nonlinear models that are proposed and to define coefficients a and b with as much precision and probability as possible. In relation to the realization intervals of constants and variables, the MGSC from the plan data creates an extension of the intervals of variables and constants with proportional dependence. Further elaboration and use of curve data as limiting conditions over activities creates a new area of optimization in activity-level planning as a project differentiator. Therefore, as a by-product, the optimal density of the modified Gaussian curve can be defined, which also achieves the optimal σ or standard deviation of the project plan. For the safety and precision of the given hypotheses, it is necessary to have an appropriate database used to determine the probability distribution, that is, to provide a direct calculation of the impact of the risk on the duration, cost and quality of the project [16,17]. MGSC is therefore in function of two variables T and t, cost and time, respectively. Creating a real curve equated to the actual real data from the data distribution proves that the constant kv in the amount of 10000 does not change, and λkv is defined by the equation that approximates the values of the S-curve to the given models. The approximate parameter λkv is a landmark for faster selection of MGSC. The disadvantage is that attempting to prove the parameter b functionally with T did not give the desired effect, so there is no an automatic definition of the S-curve, but b has to be assigned manually as the initial condition until parameter b satisfies the S-curve. It is expected that a more accurate forecast of project planning is to be created and that it is to define a more precise deviation, i.e. plan dispersion and realization. Thus defining the general equation of the S-curve in a multidimensional space gives the whole set of S-curves as the supremum and infimum of the data set in a project. This in turn creates a probability area using statistical curves, so better risk management is possible in the project [18] terefore online technology. Conversely, it also provides production management with a premised MGSC, which opens a new field of research. Further research is recommended that will relieve the present lack of MGSCs in realization as there is no shift in the cost variable due to a shift in the time variable. Thus, not only project planning should be defined but the equation of MGSC simulations at the time of project realization as well. Accordingly, the new equation can lead to simulation based on MGSC differential equations, which is similar to the finite element analysis of ANSYS software [19] that is in turn based on numerical mathematics [20] just like MGSC itself.

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Workflow Optimization with Construction Scheduling under a Lean Perspective

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Abstract

Construction scheduling produces the most important construction documents as they disclose the total project duration, project stages and times of work packages, activity costs per time period, logical sequence of activities and corresponding consequences for quality and safety. The production model displayed by the schedule should address Lean principles of production, mainly the reduction of waste created by idle time of crews due to a non-optimized workflow and takt-time planning. In a Lean Construction perspective, the project schedule should address the workflow of activities and of construction crews through the workspaces of the building. Location-Based Management System (LBMS) is a recent and innovative method that aims at planning and managing construction projects in a process-oriented way. This approach is based upon the Location Breakdown Structure (LBS), a hierarchical categorization of the workspaces where construction activities are performed by trades. As different trades need different types of workspaces, the LBS should be trade and time dependent. In an on-going research an improved scheduling method for construction operations has been developed, based on a CPM - Precedence Network plotted on a Resource–Space chart. Space Units of the project work are identified by a Location Breakdown Structure (LBS), and project activities are identified by two dimensions coordinate system based on Resources (i.e. construction crews) and working spaces (e.g. floors of a multi-storey building). Therefore the network model can be structured understanding resource and space constraints. Space Units can be modified in different stages of the execution according to trade – specific requirements, therefore creating a time-dependent LBS, and resource-based activity plotting can enhance workflow modeling through locations. Takt time of workflow in each space unit can be easily detected and optimized through balancing the duration of the sequenced activities of the space unit. The aim of the proposed approach is to increase the quality of the produced schedule by addressing Lean principles concerning work-flow optimization and takt-time detection and planning. The scheduling approach has been tested on a sample project.

Keywords: takt time, construction, lean construction, project schedule, Location Breakdown Structure

1. Introduction

Construction projects are very specific industrial projects. One of the most important features of construction production is related to building site,as building construction is an industrial process in which workers build not only the product but also the working location, i.e. the construction site. Therefore, space for construction activities, including materials, machines and fabrication stations, traffic routes and welfare facilities must be designed, organized and planned [1]. Lean production philosophy originated in Japan in the 1950' and its first application was the "Toyota Production System". Lean construction mainly addresses work-flow optimization, quality control, value management and waste elimination [2]. Seeing production as a flow of materials, information, work and products is a main concept of lean philosophy [3]. Ballard and

Howell [4] proposed a new approach to production management based on production planning and control where main attention is on integrative work structuring by key partners such as designers, contractors and suppliers [5] to adopt lean principles. Recently, takt planning and control has gained a lot of interest and it is seen as a next important development step [6]. The term “takt” means a certain pre-selected regularity with which something gets done; for example one week can define rhythm, according which every line can move in sync with others resulting in a continuous flow process. Takt time planning means defining a pace of production process that best suits clients need [7], [8]. This is another important contribution of the lean approach to project scheduling that has the aim of understanding and designing a better workflow structure within the schedule model. Lean approach to project scheduling focuses on the understanding of the organization of the various materials, trades, and subcontractors in the project processes [8] and of the flows of work, materials, information, products in the project. This can be achieved only by considering the construction workspace. Construction workspace is at the same time one of the main components and constraints of construction scheduling, due to production context and building product characteristics. Also, space requirements can have very important effects on occupational safety and production quality [9], [10]. Workflow and workspaces are generally difficult to proactively plan and manage, because of the dynamic nature of construction production where trades work moving into a site layout that changes continuously as processes progress. Another feature that adds complexity to workflow planning is that trades of different kinds (i.e. civil, mechanical, electrical, etc.) need different patterns of workspace, therefore location modeling should be dependent on time and trades. As standard planning and scheduling of a construction project can be achieved through networking techniques, the workflow and space – related components of the schedule are difficult to model and to consider efficiently, even by an experienced project scheduler. This is because space is not represented in the network model. The objective of the research work behind this paper is to propose a resource and space-oriented scheduling approach that can help project scheduler to understand takt times of the project and to adopt lean principles in construction scheduling.

2. Point of departure

Many scheduling methods have been proposed in literature in order to improve construction project workspace management with a scheduling model. As crews perform activities from a space unit of the project to another one, it might be advantageous to arrange for such crews to work continuously, without interruptions, thereby preventing idle intervals of equipment and manpower. Riley and Sanvido [1] observed that current space planning in multi-storey building construction is limited to site layout and logistics, and needs to be improved addressing work sequence. Koskela [2] observed that traditional network planning requires the division of workflow into specific activities thus making more difficult workflow optimization. Kahkonen [11] developed a scheduling model that focuses on the logic of building construction and activity dependencies due to resources and locations. El-Rayes and Mosehli [12] suggested that resource – driven scheduling accounts directly for crew work continuity and facilitate effective resource utilization. Yi, Lee and Choi [13] presented a heuristic method for network construction and development for repetitive-units project, with the aim of minimizing total project duration by reducing idle time of resources and spaces. Ballard [5] proposed the Last Planner System of Production Control composed of two phases, the planning phase and the execution or control phase. In the planning phase customer needs are determined and translated into design criteria, then work structuring is performed. Work structuring is defined as the process of activity identification, sequencing and scheduling. In the execution or control phase work-flow control and unit production control are performed. The seminal work of Akinci et alii [9] investigated the time-space conflicts in construction projects. Six type of spaces required by construction activities were detected. As activities can have time overlaps, time – space conflicts may occur. The basic method suggested by researchers and practitioners for time – space construction project modelling is the linear scheduling method, flow line or linear planning, integrated with a network model. A Location-Based Management System was introduced by Kenley and Seppanen basing on a Location Based Structure (LBS) that creates a work-oriented hierarchical decomposition of project work site locations [14]. Tsao et alii [15] presented a work structuring research methodology. Work structuring in Lean Construction is defined as the development of operation and process design in alignment with product design, structure of supply chains, allocation of resources, and design for assembly efforts [5]. The aim of work structuring is making the workflow more reliable and quicker while delivering value to the customer. Frandson et alii [7] and Tommelein [8] highlighted the need of developing not only the overall construction schedule, usually delivered with a CPM – based activity network, but also the schedule for production as an output of production system design, i.e. work structuring. Work structuring can be achieved through takt time planning, meaning the pace of production process that best suits clients need [7], [8]. Tommelein [8] indicates that the design of zones in the workspace to enhance lean workflow with takt time planning needs to take into account different trades, as different trades needs different workspace patterns. Garcia-Lopez et alii [16] presented a work structuring method that allows field managers to explicitly represent construction activities, flows and flow movement through the project, the Activity-Flow Model (AFM). In summary, apparently due to its significance there are continuous interests around construction scheduling amongst academic scholars and industry experts. These efforts have produced interesting results that have also started to address topics and principles of importance within lean construction. The research presented in this paper is providing new insights for this continuum of research and development of methods for construction scheduling. The research presented in the following proposes a method to understand workflow and work-space characteristics of a construction project for takt planning purposes, thus creating a process-oriented environment for construction schedule production, and enabling high quality scheduling.

3. Proposed approach

3.1. REPNET: Repetitive Networking technique

In an on-going research an improved scheduling method for construction operations has been developed, based on a CPM – based Precedence Network plotted on a Resource–Space chart termed Repetitive Networking Technique (REPNET), integrated with time-space diagrams. Locations or Space Units of the project are identified by a Location Breakdown Structure (LBS) like in the LBM System, and project activities are identified by a two dimensions coordinate system based on Resources (i.e. construction crews) and trade-oriented working Spaces (e.g. floors of a multi-storey building) [17]. The REPNET heuristics provide optimized activity scheduling maintaining the work continuity constraint and the As-Soon-As-Possible total project duration calculation. The proposed method consists of a Precedence Diagram Network of the construction project plotted on a resource – space chart, with the x-axis representing resources and the y – axis representing space units of the project. The two coordinates identify each network node representing an activity performed in a specific space unit: the first coordinate is the main resource performing the activity and the second coordinate is the work-space in which the activity is to be performed. Resources in the x-axis of the chart are work crews or equipment that is planned to perform activities. Resources can be grouped by work item i.e. masonry, plastering, floor concrete slab etc. In this way, in every column of the chart repetitive and non-repetitive network activities are grouped by resources (Fig. 1 and 2 (a)).

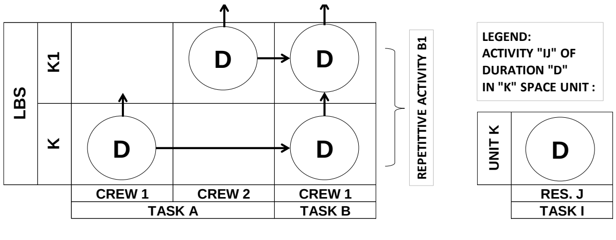

Fig. 1: Network Diagram plotted on a Resource-Space Chart [13], [17].

The LBS indicates the hierarchical decomposition of space units of the project that are plotted on the y-axis. Space units are the locations where only one crew can perform one activity at a time, and in every line of the chart activities are grouped by workspaces. Note that the LBS structure depends on the work decomposition and project phase, meaning the phase in which resources with the same workspace pattern are involved [8]. Therefore, the REPNET chart should be specific for each construction phase (Fig. 2 (a)). The output of the project schedule can be displayed with a time – space diagram where the x-axis represents time and y-axis represents the LBS of the project (Fig. 2 (b)).

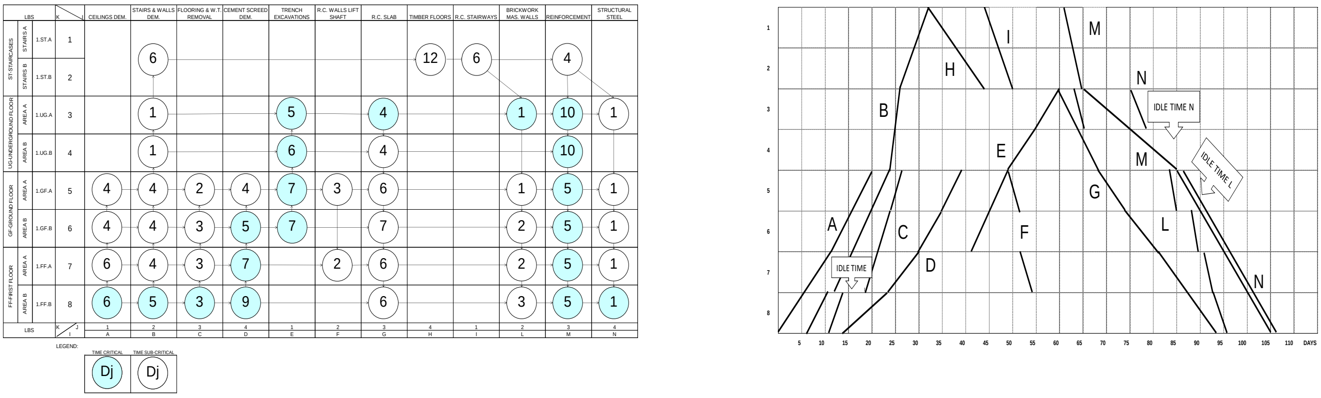

Fig. 2. (a) Sample project scheduling with REPNET, (b) Time -space chart of the REPNET sample project.

3.2. Takt time planning with REPNET

Takt time planning is method of work structuring that has the objective of setting a pace, known as Takt time, at which each trade can complete its work in each assigned work zone [7], [8]. The word “Takt” or “Taktzeit” in German means “beat”, the regularity with which something happens or get done [6], [8]. In the Lean construction context Takt time is the unit of time within which a unit of production must be produced in order to match the rate at which that product is needed by the customer. Takt time is the supply rate needed to satisfy the customer, the demand rate. The idea of the Lean approach to takt planning and control is to bring the processes necessary for creating value into a uniform flow [6]. Takt planning can be carried in five iterative steps: 1) data gathering; 2) zone and takt definition; 3) trade sequence identification; 4) determination of individual trade durations; 5) workflow balancing; 6) production schedule finalization [7]. Takt time in construction can be identified with a top-down approach or a bottom-up approach. The top – down approach identifies the time frame within which the work has to be completed, assuming it set and known, and then the needed resources are loaded to activities. The bottom – up approach identifies the available resources and then identifies the maximum production capacity of the slowest trade and therefore identifies the takt time [8]. Resources of different trades can be balanced to improve the overall output in a feed-back check of production design alternatives. As uniformity and consistency between trades can never be achieved in practice, project processes need to be adjusted to a uniform project takt if possible. Takt is dependent on process variability, but is not constrained by this, and in practice a weekly takt is often selected for construction projects [6]. Takt time can be defined for a specific work-space or for an entire project. A space unit is where each trade performs its work in the planned sequence, therefore takt needs to be the same for each trade working in that space unit. Takt for one phase of construction to another one of the same project can be different, even from the takt of each space units. Theoretically it can be said that the most desirable phase or project takt should be the Least Common Multiple (LCM) of the takt times of the different production lines, i.e work-spaces. Due to construction project complexity, pertinent literature suggests a unique project takt time of one week [6]. Possible takt time can be easily understood in the REPNET resource - space chart, just identifying the highest duration of each trade in each workspace unit, i.e. each line of the chart. When the slowest activities of each workspace have been detected (see Fig. 3, green nodes), the possible takt times of each work units can be found (see table 2). Therefore, resource balance can be pursued to improve takt time planning in each space units. This means that resources can be added to the slowest activity to decrease takt time in a work-space unit, or a resources can be subtracted from faster activities to adapt them to the takt time and save resources. Anyway, this optimization process should take into account another lean workflow principle, the continuity of resource flow, i.e. the continuity of crew work in the REPNET columns.

3.3. Sample application

A case study of a building rehabilitation project has been used to test the proposed procedure. Only the demolition and structural reinforcement phases have been considered to keep constant the LBS (Fig. 2 (a) and (b), table1). The REPNET chart makes possible to detect easily takt times for each space-unit following the rule of the slowest trade in the space path (Fig. 3 (a), tab. 2). It should be observed that the work continuity requirement for each crew is already fulfilled for almost all trades, as displayed in the time –

space chart. In fact, crews in activities B and C have very short interruptions of work, and only in activities L and N crews have some idle time (Fig. 2 (b)). All the remaining activities fulfill the work continuity requirement, meaning there are no waiting times in the workflow of crews. Therefore, the modification of the schedule in terms of balancing the duration of activities in the space units to fulfill takt time requirements should take into account the need of continuity of resource flows in the project. In the pilot study only activities B and I have been balanced in space path 1-2 as they were at the end of the resource path and they did not modify the project total duration (Fig 3 (b)).

Table 1. Sample Project activity list.

Id	Activtit description	*Duration of repetitive activity*	Duration in space units *1-2*	*3*	*4*	*5*	*6*	*7*	*8*
A	Ceilings demolition	20				4	4	6	6
B	Stairs & walls demolition	25	6	1	1	4	4	4	5
C	Flooring and wall tiles removal	11				2	3	3	3
D	Cement screed demolition	25				4	5	7	9
E	Trench excavations	25		5	6	7	7		
F	Reinforced concrete walls of lift shaft	5				3		2	
G	Reinforced concrete slab	33		4	4	6	7	6	6
H	Timber floors	12	12						
I	Reinforced concrete stairways	6	6						
L	Brickwork masonry walls	9		1		1	2	2	3
M	Reinforcement of brick masonry	44	4	10	10	5	5	5	5
N	Structural steel	5		1		1	1	1	1

Table 2. LBS and Takt time detection.

Floor	Space unit	LBS code	LBS Id	Takt Time
1^ F-First Floor 1.FF	area B	1.FF.B	8	9
	area A	1.FF.A	7	7
GF -Ground Floor 1.GF	area B	1.GF:B	6	7
	area A	1.GF.A	5	7
UG – Underground Floor 1.UG	area B	1.UG.B	4	10
	area A	1.UG.A	3	10
ST – Staircases 1.ST	area A + B	1.ST.	1-2	12

4. Conclusions

Takt time is a Lean Construction approach to work structuring aimed at improving process performance by balancing the workflow. A process-oriented approach for construction scheduling can be used as a starting point to balance the workflow of resources through takt time planning and control. The REPENET heuristic displays project activities in each space unit of construction process with a Precedence Diagram plotted on a resource-space chart. Therefore, possible takt times of each space unit can be easily detected, but the work continuity requirement in each resource path should be taken into account for the optimization process. In fact, due to construction project complexity the two flow optimizations, takt time search in the space units and idle time elimination in the resource paths may need different work structuring choices. Future research work will be aimed at the optimization process of both workflows, of resources to avoid idle time of crews and of work through the sequence of activities and their takt times in each workspace of the project.

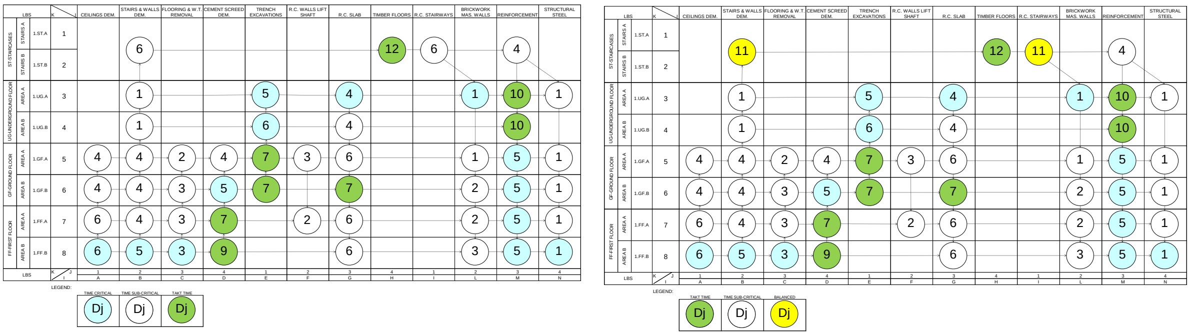

Figure 3: Pilot study: (a) Takt time detection (b) Balancing of activities.

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A Damage-Based Analysis of Rework in Reconstruction of Infrastructure Projects Due to Natural Disasters

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Abstract

The number of reworks and their corresponding costs are usually much higher for reconstruction projects than for construction projects. Even though a significant amount of research has been conducted to identify the causes and factors of rework, none have been based on post-disaster reconstruction. Therefore, it is the aim of this study, is to identify and categorize the critical factors that initiate the rework and affect the cost of post-disaster reconstruction of transportation infrastructures (PRTs). To fulfill that goal, a survey of 46 questions was developed and distributed. Thirty (30) completed responses were collected from a group of respondents who were owners, program managers, project managers, and engineers with experience in working on a reconstruction project. The responses were analyzed statistically, and it was found that when the reconstruction of a transportation project is complex, the number and cost of reworks rise significantly. It was also found that the number of reworks is directly related to the level of damage to the infrastructure, which means that skilled and experienced project managers must be assigned to the project so that the fast decision-making process can be ensured to avoid the excessive amount of reworks. The findings of this study will help decision-makers and program managers prevent undue expenses and delays in the restoration of damaged infrastructure after natural disasters and hurricanes.

Keywords: cost of rework, level of damage, post-disaster reconstruction, reconstruction of transportation infrastructure

1. Introduction

Rework is one of the major causes of cost and schedule overruns of construction projects [1, 2, 3, 4]. In 2011, research was conducted by the Construction Industry Institute, and it was found that the direct cost of reworks of a construction project reach 20% of the project's contracted amount [5]. Shahparvari and Fong [6] found that the cost of rework, which is different for each project, can be up to 70% of the total project cost. Hence, the cost of rework is considered an indicator of the execution performance of a project [7, 8, 9]. Rework also acts as a catalyst in the reduction of organizational performance by demotivating the workers [10, 11]. Even though rework affects different projects in different ways [12], the sources of the reworks with substantial impacts are not drastically different [13].

Post-disaster reconstruction projects often suffer from unwanted and unprecedented reworks [14]. The number of reworks, as well as the cost of rework, is usually much higher in reconstruction projects compared to construction projects [7, 15]. The construction industry is one of the industries with most uncertainties in the world [16], and reconstruction projects are even riskier, as they encompass additional safety requirements and time, cost, and space limitations [17]. The cost and time-sensitive nature of the projects require that they be performed in such a way that the negative impacts on the budget and schedule can be avoided [18, 19, 20]. Reworks in post-disaster reconstruction of transportation infrastructures is especially harmful, as it not only slows down the recovery of the damaged transportation infrastructure, but also indirectly slows down the overall recovery of the community [21]. Despite a significant number of researches in the literature regarding the causes and factors of reworks in the construction industry [22, 23], there are few such studies based on post-disaster reconstruction.

The aim of this study is to identify and categorize the critical factors that initiate reworks and affect their cost in the post-disaster reconstruction of transportation infrastructures (PRTs). To fulfill the goals of this study, several research objectives were formulated: i) identify potential PRTs leading to rework in post-disaster reconstruction projects of transportation infrastructures, ii) determine significant PRTs leading to rework of reconstruction projects, and iii) determine significant PRTs affecting the cost of reworks associated with the damage level of the infrastructure. The findings of this study will help decision-makers and program managers prevent undue expenses and delays in the restoration of damaged infrastructures after natural disasters, and hurricanes in particular.

2. Literature review

Almost every community suffers from casualties and losses due to natural disasters at some time [24, 25] and there has been an increase in the number of natural disasters over the last couple of decades [26, 27]. One of the most devastating natural disasters are hurricanes, which are increasing in intensity and frequency [28]. On average, every year, the United States of America suffers from two hurricanes [29]. They disrupt community life by causing physical, psychological, and environmental distress, especially when the society is not sufficiently equipped to handle the disaster [30]. For example, Hurricane Katrina in New Orleans caused $1845 billion of damage, and Hurricane Rita caused $120 billion of damage in 2005 in areas surrounding the Gulf of Mexico [31, 32].

These disasters usually cause the greatest damage to the transportation infrastructures, which makes the reconstruction costly and time-consuming [30, 33, 34]. Functioning transportation systems are a prerequisite for the mobility of the public and for economic growth [35]. A damaged transportation system cannot facilitate the usual traffic flow, hinders emergency response, causes indirect losses, and increases the sufferings of the people in the affected community [36, 37, 38]. In 1991, the Northridge disaster disrupted critical highways in the Los Angeles area, and a ripple effect caused the closure of several parts of Interstate 10 and resulted in $1 million of economic loss each day for several days [39]. To avoid these unwanted and unforeseen economic losses and human suffering, it is vital that damaged transportation infrastructures be reconstructed as soon after the disaster as possible [40].

Resource constraints are a common side effect of post-disasters [41], and the shortages can have a major impact on the recovery of transportation infrastructures [27, 42, 43]. A project can be identified as successful when the completion time and cost are within the initially estimated schedule and budget, respectively [44, 45]. However, reconstruction projects are not only complex, but also have a chaotic and dynamic nature that can cause unpredictable changes in the middle of a project and require reworks [46, 47, 48]. Aljailawi and Shariatmadar [49] defined rework as efforts that are unnecessary and only required when the activity was not done properly the first time. The number of reworks can highly increase the cost and time of the project [18]. Conversely, the reduction of reworks ensures sustainable development, as less rework means that fewer materials are wasted [49]. Amaratunga et al. [50] found that reducing reworks can highly improve the performance of reconstruction projects.

In a nutshell, the success of post-disaster reconstruction depends upon the project being on time, within budget, and with the least possible number of reworks. However, many researchers have identified factors that might cause cost overruns, schedule overruns, and an extensive number of reworks, and a list of them is presented in Table 1.

Table 1. Challenges that affect cost, schedule, and number of reworks of a post-disaster reconstruction project

Challenge	Previous Study
Resources are not delivered within the deadline	[51]
Not having sufficient funds	[52]
Faulty assessment of the situation	[53]
Lack of communication and disorder in coordination	[54]
Faulty design	[55]
Transportation	[56]
Difficulty in arranging temporary paths	[57]
Faulty assessment of the level of damage	[58]
Shortage of laborers	[18]
Shortage of materials	[18]
Inability to make impromptu decisions	[59]
Inexpert inspectors	[60, 61]

3. Research methodology

The four-step methodology shown in Figure 1 was adopted for this study. The first step was focused on a review of the existing literature. A preliminary search via popular search engines resulted in 500 articles. The secondary screening process was conducted by scrutinizing the titles and abstracts of the papers, and 89 articles were shortlisted. The shortlisted articles were studied and, based on the information gathered, a list of 30 potential PRTs was prepared. In the second step, a survey was developed and distributed after pilot testing, and 30 completed responses were collected. In the third step, a descriptive analysis of the cost of the reworks and level damage of the infrastructure was conducted. In the last step, the data were analyzed quantitatively and the significant PRTs were identified.

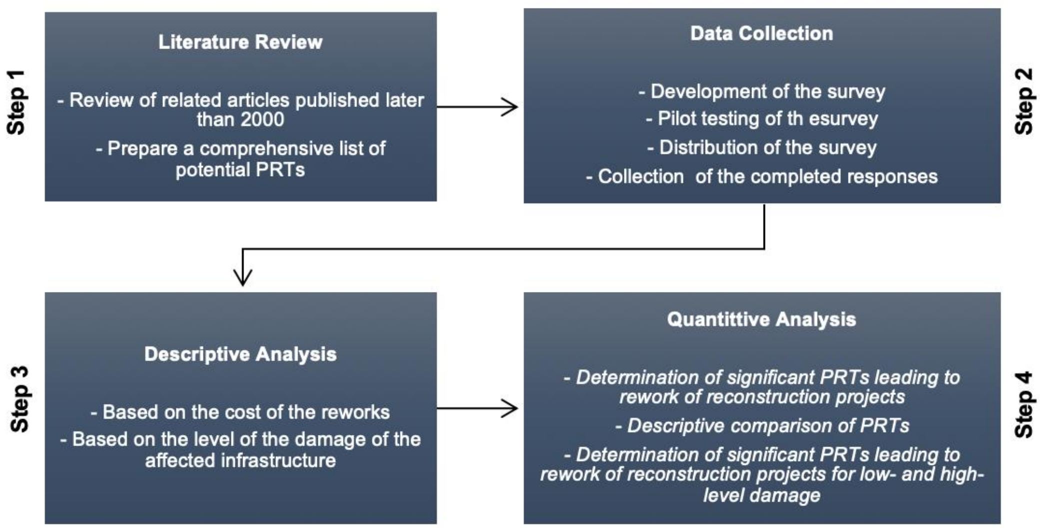


Fig. 1. Research methodology

4. Data collection

4.1. Development of the list of PRTs

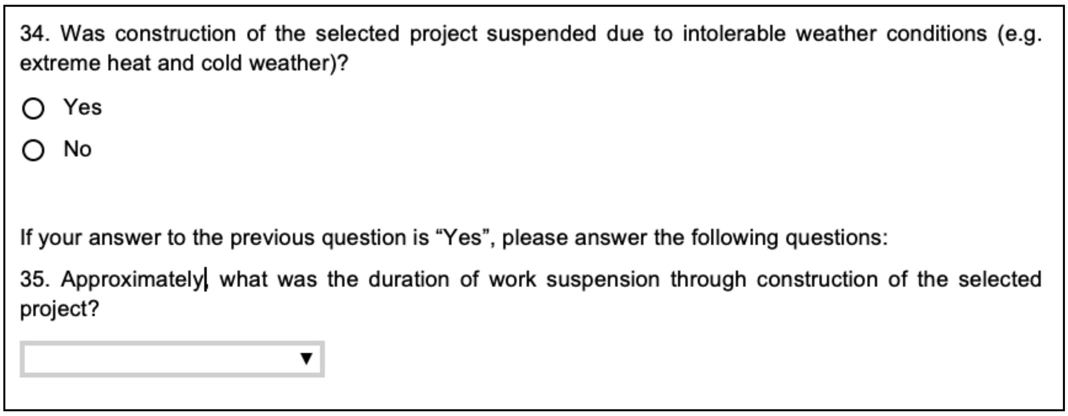
A keyword search method through popular search engines like Google Scholar, JSTOR, ProQuest, etc. resulted in the collection of approximately 500 scholarly articles. The titles and abstracts of the collection were scrutinized, and 89 articles that were considered the most relevant were shortlisted. The shortlisted articles were studied thoroughly, and pertinent information was entered into a database that was used, along with the expertise and experience of the authors, to prepare a list of 30 potential PRTs. Table 2 shows the identified PRTs.

Table 2. list of potential PRTs

List of PRTs	*List of PRTs*
PRT1. Number of main/truck lines	PRT16. Quality issues of materials
PRT2. Total length	PRT17. Quality issues of equipment
PRT3. Level of complexity	PRT18. Frequency level of logistics management issues
PRT4. Distance from highly populated area	PRT19. Quality of on-site inspections
PRT5. Level of damage	PRT20. Frequency of on-site inspections
PRT6. Level of traffic disturbance	PRT21. Information management
PRT7. Shortage of experts	PRT22. Pace of decision-making process
PRT8. Shortage of field laborers	PRT23. Implementation level of risk management
PRT9. Productivity level of contractors	PRT24. Coordination
PRT10. Shortage of materials	PRT25. Pace of workers' mobilization
PRT11. Shortage of equipment	PRT26. Volume of debris
PRT12. Inflation of labor wages	PRT27. Environmental/safety issues prior to execution of the project
PRT13. Availability level of on-site infrastructure	PRT28. Work suspension through execution of the project
PRT14. On-site accommodation level for staff	PRT29. Regulatory requirement
PRT15. Shortage of supplier	PRT30. Availability of required temporary pathways

4.2. Survey development, distribution, and collection

After identifying the potential PRTs, a structured survey was constructed that converted each PRT into a question. The participants were also asked to provide demographic information and to name a post-disaster transportation reconstruction project that they had worked on. The survey consisted of 46 questions of three kinds: i) continuous questions, ii) seven-point Likert scale questions, and iii) binary questions. Two sample questions of the survey are presented in Figure 2.


34. Was construction of the selected project suspended due to intolerable weather conditions (e.g. extreme heat and cold weather)?

Yes

No

If your answer to the previous question is "Yes", please answer the following questions:

35. Approximately, what was the duration of work suspension through construction of the selected project?

Fig. 2. Sample survey questions

The survey was pilot tested to determine its suitability for the participants, and it was modified, based on the responses of those participating in the testing.

A list was developed of potential respondents who were owners, project managers, program managers, and engineers. The respondents were contacted by email, and upon their agreement the survey was sent to them electronically. After several follow-up emails, 30 completed responses were collected.

5. Descriptive analysis

5.1. Based on the cost of the project and the cost of rework

Table 3 shows the minimum, mean, and maximum values for the cost of the projects and the cost of the reworks. The mean and maximum cost values of the reworks were roughly $270,000 and $1 million, respectively.

Table 7: Descriptive Data Analysis

		Minimum	Mean	Maximum	Standard Deviation
Cost	Baseline Budget	$300K	$22,930K	$100,000K	$33,200K
	Actual Cost	$500K	$36,540K	$150,000K	$53,110K
Rework	Cost	$50K	$264K	$1,000K	$361K

5.2. Based on the level of damage

In response to a query about the level of damage sustained by the infrastructure that the survey respondents were involved with following a natural disaster, they revealed almost 30% of the projects had infrastructures that were damaged more than 80% and around 20% of the projects had infrastructures that were damaged less than 40%.

6. Quantitative analysis

6.1. Determination of significant PRTs leading to rework of reconstruction projects

The PRTs that significantly lead to reworks in reconstruction projects are shown in Table 4. The two-sample t-test, Kruskal-Wallis, and Chi-squared test were performed according to the appropriate type of data. To avoid any bias created by including large projects in the results, the cost of the issued rework was normalized based on project size. To calculate the normalized cost of rework for any project, the cost of the rework was divided by the baseline budget for the construction phase. These costs were recorded and used for the remainder of the analyses conducted for this study. Table 4 presents that 22 PRTs were recorded as significant in deriving reworks in reconstruction projects.

Table 4. Results of significant PRTs leading to rework in reconstruction projects

Category	List of PRTs	*P*-Value
Physical Characteristics	PRT1. Number of main/truck lines	0.021**
	PRT2. Total length	0.256
	PRT3. Level of complexity	0.062*
	PRT4. Distance from highly populated area	0.011**
Damaging Level	PRT5. Level of damage	0.018**
	PRT6. Level of traffic disturbance	0.637
Resource	PRT7. Shortage of experts	0.033**
	PRT8. Shortage of field laborers	0.014**
	PRT9. Productivity of contractors	0.072*
	PRT10. Shortage of materials	0.054*
	PRT11. Shortage of equipment	0.036**
	PRT12. Inflation of labor wages	0.333
	PRT13. Availability of on-site infrastructure	0.044*
	PRT14. On-site accommodation level for staff	0.078*
	PRT15. Productivity of suppliers	0.002**
Quality	PRT16. Quality issues of materials	0.029**
	PRT17. Quality issues of equipment	0.066*
Project Management	PRT18. Number of logistics management issues	0.088*
	PRT19. Quality of on-site inspections	0.034**
	PRT20. Number of on-site inspections	0.019**
	PRT21. Information management	0.093*
	PRT22. Pace of decision-making process	0.080*
	PRT23. Implementation level of risk management	0.019**
	PRT24. Coordination	0.077*
	PRT25. Pace of workers' mobilization	0.155
Environment & Safety	PRT26. Volume of debris	0.474
	PRT27. Environmental/safety issues prior to execution of the project	0.212
	PRT28. Work suspension through execution of the project	0.652
Legal	PRT29. Regulatory requirement	0.001**
Local	PRT30. Availability of required temporary pathways	0.177

*** denotes significant differences with 95% confidence*
** denotes significant differences with 90% confidence*

As presented in Table 4, the lack of frequent on-site inspections (PRT-20, belonging to the category of project management) and low quality of on-site inspections (PRT-19, belonging to the category of project management) leads to decreased productivity and waste of limited post-hurricane resources. The lack of adequate quality and sufficient quantity of on-site inspections results in inadequate documentation and records and often causes duplications of efforts and an increase in the number and cost of reworks.

Table 4 indicates that when the reconstruction of a transportation project is complex (PRT-3, belonging to physical characteristics), skilled and experienced site laborers and project managers need to be involved in the project. After a disaster, clients are usually faced with a shortage of human resources; therefore, when the reconstruction project is complex, the probability of reworks being needed might remarkably increase.

6.2. Descriptive comparison of PRTs affecting rework of reconstruction projects

A descriptive comparison of the mean values of reconstruction projects with low costs of reworks and high costs of reworks associated with continuous data are shown in Table 5. The mean values of PRTs 1, 4, and 5 are significantly different. For instance, the average distance of a project's location from a highly populated area (PRT-4) in a project with a low cost of rework (12.5 miles) is very different from the same project with a high cost of rework (30.5 miles). The mean of the damage level for reconstruction projects with a low cost of rework was 50%, while the same average for projects with a high cost of rework was 70%. Therefore, it was concluded from Table 5 that reconstruction projects with poor performance are more complicated than those with good performance.

Table 5. Comparative analysis of PRTs affecting cost of rework – continuous data

List of PRTs	Average	
	Low Cost of Rework	High Cost of Rework
PRT1. Number of main/truck lines	9	3
PRT4. Distance from highly populated area	12.5 mi	30.5 mi
PRT5. Level of damage	50%	70%

6.3. Determination of significant PRTs leading to rework of reconstruction projects for low- and high-level damage

In this step, the PRTs that significantly affect the cost of reworks associated with the two groups (highly damaged and low-level damage) were statistically determined and presented (Table 6). Three types of statistical analysis methods, the two-sample t-test, Chi-Square, and Kruskal-Wallis test were adopted according to the type of data. Table 6 indicates that 24 of the 29 PRTs were determined statistically significant for highly damaged reconstruction projects, and 20 PRTs were recorded as statistically significant for low-level damaged reconstruction projects.

As presented in Table 6, the availability of PRT-1 (number of main lines), PRT-3 (level of complexity), and PRT-4 (distance from the highly populated area), belonging to the category of physical characteristics, make reconstruction projects more complicated and increase the number of uncertainties and risks. These issues lead to suspension of the projects, frustrate the team members, and foster low productivity, thereby increasing the number and cost of the reworks.

Information management (PRT-21) also plays a critical role in post-hurricane reconstruction projects by tracking projects' resources, improving budgeting and cost analyses, and mitigating risks. Lack of information management seriously affects the quality of project management and results in more reworks.

Table 6. Results of significant PRTs affecting rework regarding damage level in reconstruction projects

Category	List of PRTs	*P*-Value	
		Highly Damaged	Low Level Damaged
Physical Characteristics	PRT1. Number of main/truck lines	0.029**	0.025**
	PRT2. Total length	0.254	0.359
	PRT3. Level of complexity	0.092*	0.083*
	PRT4. Distance from highly populated area	0.028**	0.013**
Damaging Level	PRT6. Level of traffic disturbance	0.634	0.179
Resource	PRT7. Shortage of experts	0.011**	0.016**
	PRT8. Shortage of field laborers	0.091*	0.055*
	PRT9. Productivity of contractors	0.071*	0.059*
	PRT10. Shortage of materials	0.020**	0.089*
	PRT11. Shortage of equipment	0.014*	0.001**
	PRT12. Inflation of labor wages	0.199	0.435
	PRT13. Availability of on-site infrastructure	0.007**	0.031**

	PRT14. On-site accommodation level for staff	0.088*	0.633
	PRT15. Productivity of suppliers	0.059*	0.074*
Quality	PRT16. Quality issues of materials	0.016**	0.027**
	PRT17. Quality issues of equipment	0.037**	0.015**
Project Management	PRT18. Number of logistics management issues	0.056*	0.072*
	PRT19. Quality of on-site inspections	0.066*	0.028**
	PRT20. Number of on-site inspections	0.080*	0.017**
	PRT21. Information management	0.069*	0.077*
	PRT22. Pace of decision-making process	0.022**	0.759
	PRT23. Implementation level of risk management	0.082*	0.032**
	PRT24. Coordination	0.022**	0.075*
	PRT25. Pace of workers' mobilization	0.058*	0.153
Environment & Safety	PRT26. Volume of debris	0.195	0.174
	PRT27. Environmental/safety issues prior to execution of the project	0.647	0.357
	PRT28. Work suspension through execution of the project	0.019**	0.754
Legal	PRT29. Regulatory requirements	0.033**	0.001**
Local	PRT30. Availability of required temporary pathways	0.391	0.351

*** denotes significant differences with 95% confidence*
** denotes significant differences with 90% confidence*

7. Conclusion

The number of reworks has an appreciable negative impact on the construction, as well as post-disaster reconstruction, of transportation infrastructure systems. Even though there are a significant number of researches in the literature that identify the sources and factors of reworks in construction projects, few identify the factors that affect the reworks of post-disaster reconstruction. Therefore, this study aimed to identify and categorize the factors that lead to reworks in the post-disaster reconstruction of transportation infrastructures. For this purpose, a survey was developed, and 30 completed surveys were collected. The survey result was analyzed both qualitatively and quantitatively and revealed that when the reconstruction of a transportation project is complex, the number and cost of reworks is high, and skilled and experienced project managers must be assigned so that a rapid decision-making process can be ensured. It was also found that the number of reworks is directly correlated with the level of damage to the infrastructures. When the level of damage is comparatively high, skilled site laborers and project managers need to be involved in the project to avoid an excessive number of reworks. The findings of this study will help decision-makers and program managers prevent undue expenses and delays in the restoration of damaged infrastructures after natural disasters, particularly hurricanes.

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A Methodology for Risk Assessment and Management for SMR Nuclear Power Plant Hit by High Explosive Warheads

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Abstract

Within its 2050 energy plan, Israel examines the demographic implications of a Nuclear Power Plant (NPP) in Shivta Rogem site in the Negev. NPP would have a great contribution to the diversity and robustness of energy sources in Israel. A Small Modular Reactor (SMR) is designated to be safer than existing NPPs and will have better resistance to external hazards due to inherent passive safety features. This study develops a risk assessment methodology for a Nuclear Power Plant (NPP), in particular, SMR, to withstand a large conventional warhead explosion (GBU-28). The methodology comprises: hydro-dynamic simulations, validation of the dynamic simulations using numerical analysis compared to the simulations, risk analysis and damage assessment given the reference scenario of a detonation of a GBU-28 inside the underground water pool of a NuScale SMR. Discrete fragility curves were developed to evaluate the capacity of the SMR critical components. The overall probability of failure was assessed based on a Fault-Tree-Analysis (FTA). Results of the 3 m explosion from the reactor bay wall showed a displacement of 13 cm, breaching of the SMR bay wall and the water pool wall, and 12 cm deflection of the Containment Vessel (CNV). Sensitivity analyses of the uncertainty values were carried out by posting HCLPF (High Confidence Low Probability of Failure) values to the fragility curves. Combination of the results of the study with the failure criteria of NuScale for seismic hazards reveals that given the hazard scenario, core damage is expected accompanied by release of radioactive materials to the atmosphere. The study concludes that building the SMR in Israel will require adapted protective solutions. Future research may examine protective alternatives such as adding a reinforced concrete protecting layer or the possibility to set the SMR at a deeper underground elevation.

Keywords: explosions, fragility curves, resilience, risk management, SMR

1. Introduction

The demand for energy across the world is constantly rising. Energy can be derived from a variety of sources; limited sources such as fossil fuels or renewable sources such as solar, hydroelectric and wind energy. Another significant source of energy is nuclear energy. Ronen [1] stated that while renewable energies are perceived by the public as cleaner than nuclear energy, nuclear energy has its advantages. "Energy Density" is the amount of area needed for the production of an energy unit. Nuclear energy has significantly higher energy density than renewable energies; and therefore is preferred. Despite its advantages, a significant disadvantage of nuclear energy is long-lived radioactive waste after a Nuclear Power Plant (NPP) activity is decommissioned, leading to a high life cycle cost. Production of nuclear energy is economic, cost-effective and has clear environmental benefits [1]. It can diversify energy sources, reduce greenhouse gases emissions and ensure the robustness to the energy economy [2]. A NPP failure would have severe economic, environmental and social consequences. Thus, the need to assure the plant's ability to withstand extreme events in general and the threat scenario in particular is obvious. According to Ornai et al. [3], an extreme event of a direct missile hit could lead to an overall failure of the NPP, which in turn could lead to core meltdown followed by the release of radioactive materials.

1.1. Research rationale and objectives

The research followed twofold objectives:

- Damage assessment of the threat scenario: review of failure modes representing the vulnerability of the SMR to the threat scenario. The prospected outcomes of the research include a comprehensive review of the state-of-the-art of the NuScale SMR technology with respect to the resilience of the SMR to an external event of munition hit causing internal explosions.
- Risk analysis according to the threat scenario. Definition of probabilistic values and development of fragility curves for critical components of the NPP to the threat scenario. The novelty of the research lays in the integrated methodology that combines: adapted fragility curves based on seismic data taken from NuScale's SMA, hydro-dynamic simulations, validation and sensitivity analyses. This allows for high validity of the risk analysis and provides a tool for assessment.

2. Vulnerability of the NPP to core damage and large release to explosive warhead hit

2.1. SMR

SMR stands for either Small Modular Reactor or Small and Medium Reactor, with an output of 300-700 MWE. Its main economic advantage is based on full factory manufacturing and short construction period. Other advantages are its passive safety systems, the possibility to install it underground and the long periods between refueling. SMRs are based upon positioning all the components of the steam generation system integrally inside the prefabricated reactor vessel, to decrease manufacturing cost and to improve safety [4]. In the Westinghouse SMR for example, all safety systems which demand an electrical source, were changed to those based on passive physical principles such as – gravity, circulation, evaporation, condensation, or convection [5]. Smith & Wright [6] determined that underground positioning of the Westinghouse SMR decreases the chance to an event, which will affect the safety of the SMR and, that the passive safety systems can safely stop the nuclear reaction, remove the decay heat and ensure cooling and safe system shutdown in case of an emergency event.

2.2. NuScale SMR

The NuScale SMR is a modular PWR NPP, consists of up to 12 modules. Each module consists of a 45 MWE reactor and 2 steam generators. The nuclear fuel is UO2 enriched up to 4.95% and the duration of the fuel life cycle is 24 months. An optional configuration is 540 MWE for 12 modules. Most of the NPP main building is underground, made of high stiffness concrete structure to address earthquakes and aircraft crash impact scenarios. Each power module includes a containment and a reactor vessel, interior helical coil, two steam generators and a pressurizer, all factory manufactured [7]. Each module is installed in its own isolated bay in an underground, stainless steel-lined concrete pool, also referred as Ultimate Heat Sink (UHS).

2.3. NuScale SMR geometry

Due to security-related issues the geometry of NuScale SMR reactor building is not available for the open public. However, NuScale had published in Chapter 3 "Design of Structures, Systems, Components and Equipment" [8], sufficient data about the finite-element modeling used for estimating the dynamic loadings on the building and for seismic design. The finite-element models provide information such as walls length, walls thickness, building height and more. The most relevant geometrical data is presented in Table 1.

Table. Nuscale SMR reactor building and module dimensions.

Reactor building (RXB)		Module	
Parameter	Dimension [m.]	Parameter	Dimension [m.]
Total Height	~ 50.9	Height	~19.8
Total length	~ 106.7	Diameter	~4.4
Total width	~ 45.7	Thickness	~0.076
Ceiling thickness	~ 1.2		
Floor thickness	~ 3.0		
Pool height	~ 23		
Depth below ground	~ 26.2		

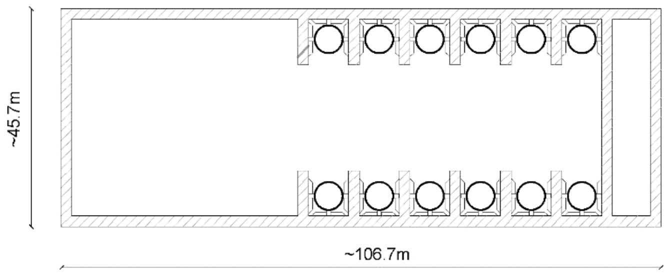

Figure 1: RXB horizontal cross-section – no to scale

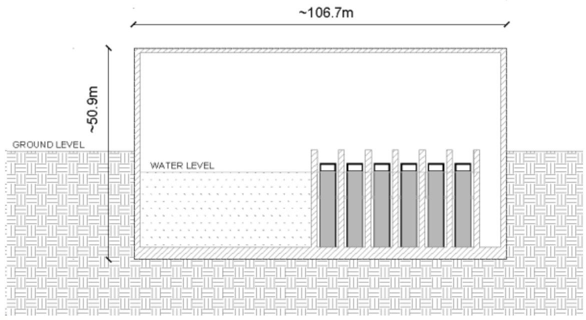

Figure 2: RXB vertical cross-section – not to scale

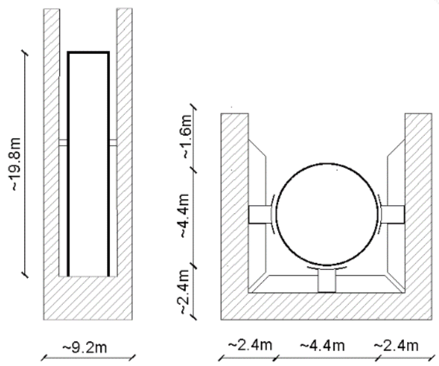

Figure 3: Module cross-sections - not to scale

2.4 External hits on NPP – missile hit

2.4.1. Missile hit on an NPP

Shohet et al. [9] examined munition hit of a GBU-28 missile on a Westinghouse AP-1000 NPP. Risk analysis and damage assessment were carried out and included specific definition of the threat scenario and analysis of the loads and impacts on the structure as a result of a nearby explosion. A method was developed to assess the vulnerability of the NPP's components due to the generated shock, according to existing data regarding aircraft impact. As part of the research, existing fragility curves (developed originally to evaluate seismic performances) were adapted and used to conduct a PRA, showing a large probability for LOCA scenario as a result of damage to critical components.

2.4.2. External hits on NPP - aircraft impacts

Lo Frano & Forasassi [10] examined, using FE models, the impact considerations of a commercial aircraft (Boeing 747) and a fighter jet (Phantom F4) on the containment structure of a Gen-III NPP, and conducted sensitivity analyses to improve the shielding of the containment. The research offered methods to improve the protection, such as enlarging the thickness of the concrete walls, increasing the quantity of reinforcement bars, increasing the usage of pre-stressed concrete and more. Saberi et al. [11] examined, using FE models, the impact of commercial aircrafts (Boeing 707 and Airbus A-320) and a fighter jet (Phantom F4) on different locations of the Reactor Core Containment Vessel (RCCV) of a Gen-III NPP. It was found that a hit on the center of the RCCV made the largest deformation of the concrete wall of the RCCV but would not cause a critical failure to the NPP.

Aircraft impacts on NuScale SMR

Since NuScale SMR is a new technology, very few studies regarding aircraft impacts on NuScale SMR were found and thus, the research entitled "Aircraft Impact Considerations for NuScale SMR Plant Design", by James et al. [12], was reviewed carefully. The goal of the research was to show that in case of a hit, either the primary containment system is not damaged in any way or the reactor core remains cooled, and either spent fuel cooling or spent fuel pool maintain their integrity. These goals are similar to the desired end state for a GBU-28 hit scenario. Methodology Two methods were employed to represent aircraft impact: Riera's method using a force time history applied over a representative contact area [13]. Missile-Target-Interaction method where a model of the impacting aircraft is included in the analysis [12]. The methodology included structural analyses, i.e. modeling of the reinforced concrete, and in addition, a fire and shock effects assessment was carried out, to determine if sufficient SMR SSCs (Structures Systems and Components) remain operational to ensure heat removal and core cooling. It was found that NuScale SMR would most likely achieve the goals above, meaning in case of an impact, the reactor core would remain cool and the spent fuel pool would remain intact. The loadings were considered sensitive information and could not be discussed in the research, which led us to analyze this paper in a qualitative and methodic point of view.

2.5. Earthquakes

Markou & Genco [14] developed 3D models and performed a finite element & nonlinear analysis to evaluate the seismic resistance of the reinforced concrete reactor building structure of the NuScale SMR to high seismic loads. Models were constructed on SAP2000 (2018) and Reconan FEA (v.1.00, 2010). Overall, the NuScale SMR reactor building was found to be earthquake proof due to its structural integrity and underground configuration. The reference scenario was Chile's 2010 earthquake which is the second strongest in magnitude of Chile’s seismic history, documented a maximum recorded PGA of 0.93 g and a corresponding 5% damped peak structural acceleration of 1.73 g for structures with a period of 0.1 sec. Dimensions have been evaluated from different sources (deviations between the two studies appear due to the gloomy data derived from the withheld information). Evaluation made according to Eurocode 8, assuming type "B" soil. The weight of the building above ground level was evaluated as ~150,000 kN.

2.6. Conclusions of the review

In NuScale SMR, a direct aircraft impact on the spent fuel pool and on the steam supply system could not occur due to its location underground. In addition, SMR designs have both advantages and disadvantages compared to conventional NPPs regarding aircraft impact: SMRs are less likely to be hit since the reactor vessels and containment are placed underground and due to the small size, it is easier and less costly to create a hardened and protected structure. However, the smaller size also means that transmission of shock through the structure could cause simultaneous damages, while in a larger NPP, components are located physically apart, and the risk for a comprehensive damage is smaller.

3. Methodology

Figure 4 delineates a 7-phase risk analysis and damage assessment methodology. The methodology uses Probabilistic Risk Analysis (PRA), Nuscale Seismic margin Analysis (SMA), and Fault-Tree-Analysis along with dynamic simulations and Fragility Curves for the damage assessment.

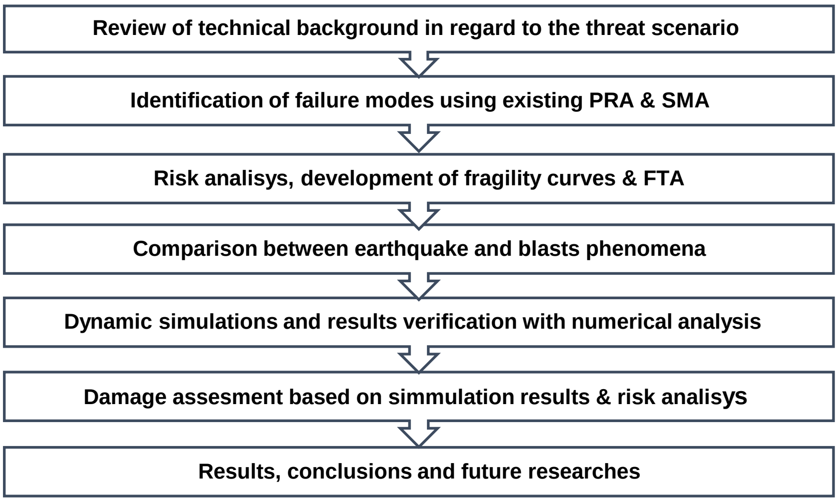

Figure 4: Risk analysis methodology

3.1. Material properties

- Concrete: Ec of 30 GPa and compressive strength of 50 MPa, Poisson ratio ν = 0.2;
- Steel reinforcement: Es of 190 GPa and yielding stress of 500 MPa.

3.2. Fault-Tree-Analysis (FTA) describing the postulated event

A standard FT was developed to graphically describe the failure mechanisms due to given damages to structural elements and consequently deduce their impact on the overall failure of the facility. Failure of structural elements are defined as the basic events in this FT, and CD is the top event. It is a simple FT without intermediate events. Figure 4 presents a FT of the failure mechanisms yielding "core damage" top event. In this FT the cutsets are short which in a qualitative analysis may indicate high vulnerability of the system. Though, this FT does not model all the possible scenarios of the system failure – rather, it focused only in the most vulnerable elements exposed to the severe scenario of a direct interior GBU-28 hit selected for this research. The FT is made of 5 "OR" gates meaning the probability is calculated as the union of all basic events using "The Morgan's Law" as described in Equation 1:

$$P(Failure) = P(E_1 \cup E_2 \cup E_3 \cup E_4 \cup E_5) \quad (1)$$

$$= 1 - P\overline{(E_1 \cup E_2 \cup E_3 \cup E_4 \cup E_5)}$$

$$= 1 - P(\overline{E1} \cdot \overline{E2} \cdot \overline{E3} \cdot \overline{E4} \cdot \overline{E5})$$

$$= 1 - P(\overline{E1}) \cdot P(\overline{E2}) \cdot P(\overline{E3}) \cdot P(\overline{E4}) \cdot p(\overline{E5})$$

$$= 1 - [(1 - P(E1)) \cdot (1 - P(E2)) \cdot (1 - P(E3)) \cdot (1 - P(E4)) \cdot (1 - P(E5))]$$

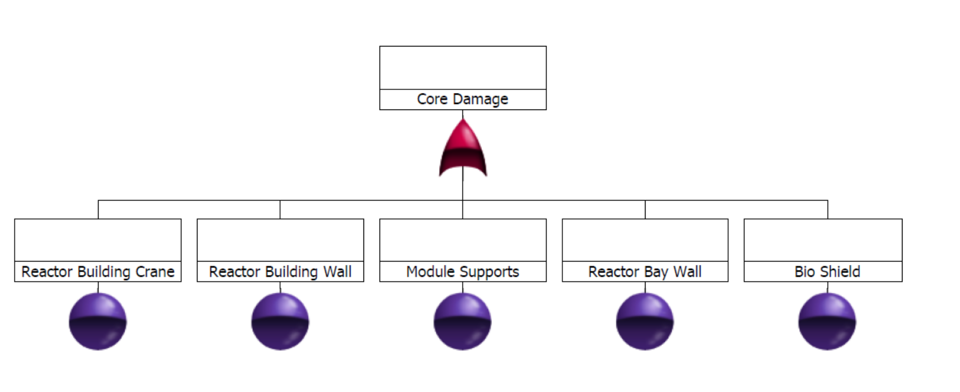

Figure 5: GBU-28 hit FTA

3.3. Discrete Fragility Curves

We can assume that the aiming point of aerial attack using GBU-28 will be the center of the reactor building (RXB), and around it we can define circular aerial rings with different radii for example at 1 m range (Fig. 6). The Circular Error Probability (CEP) is defined as the radius of the circular area around the aiming point in which 50% of the launched munition will hit. Each ring has a relative hit percentage according to its location and area according to the CEP radial distribution. The hit probability sum of all the rings is 0.5 (for half of the RXB). Each ring divided into ring segments of about 1 sq.m. Due to the building longitudinal symmetry, only half of the building should be analyzed in the latitudinal direction.

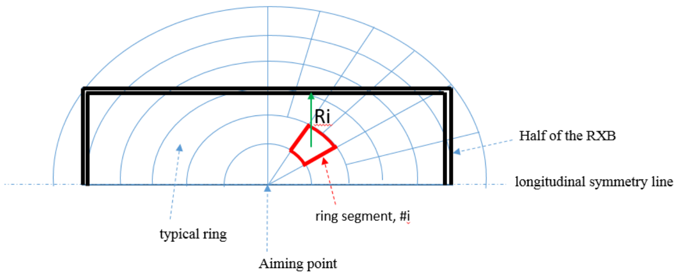

Fig. 6 Arial distribution to rings and square segments

Each ring segment i has the following characteristics: 1) a center, 2) a certain munition hit probability calculated by its relative part in its circular ring area- Pi, 3) the relative structural damage (in percentage)- SDij(%) caused to each of the SMR j critical components according to the distance (and also the angle can be considered) between the ring segment center and the critical SMR object.

The structural damage at different k levels, SDk% (k=1,2,3) is defined according to the relative structural element supports' rotation and the ductility, μ (equals to dynamic deflection divided by elastic deflection of the wall mid span) based on UFC3-340-02 [15]: SD_1% for cracking, SD_2% for elastic limit, SD_3%=100% for failure. In case of structural element with shear reinforcement, the failure is expected at supports' rotation of 4°, and the resulted ultimate deflection will be defined as SD_3%=100%. SD_2% and SD_3% are equal to the mid span deflections at cracking and at the elastic limit divided by the ultimate deflection respectively. Summation of all the ring segments with the same structural damage definition for each critical SMR object yields the various Structural Damage levels, SDk, versus the Structural Damage Probability (SDP_k%) caused by a single attack scenario. For each critical SMR object #j the Structural Damage Probability at certain level k (such as the pool wall) $SDP_{j,k}$(%) will be calculated according to Eq. 2.

$$SDP_{j,k}=\frac{2}{TRA}\sum_{\forall i} RSi,k \cdot HPi \quad (2)$$

The constant two in the nominator considers the symmetry and it is multiplied by the sum of the product of all the ring segments areas #i with the Structural Damage levels SDk% ($RS_{i,k}$[m2]) and their hit probability (HP_i[%]), all divided by the total rings area (TRA [sq.m.]. It yields the qualitative fragility curve presented in Fig. 7. As CEP is getting smaller SDP_k values are growing, means that the risk is higher.

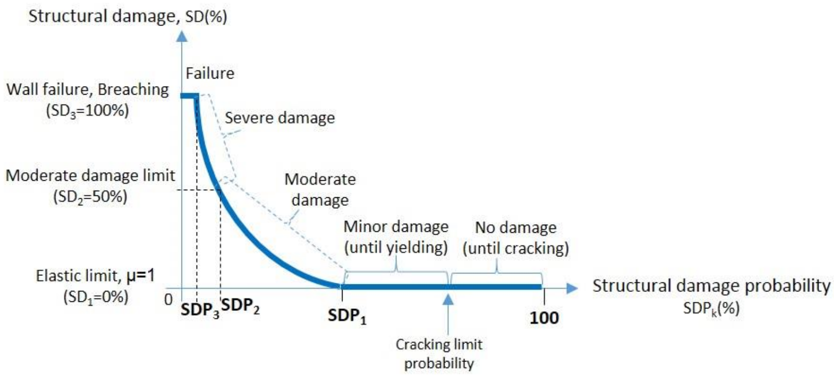

Fig. 7: Fragility curve of the reactor bay wall

4. Results

4.1. Scenario no. 1 –Blast effects on the CNV Description

- The bomb axis of symmetry is vertical and parallel to the CNV;
- Distance of 3 m from the CNV;
- Bomb centre at 5 m above the pool floor.

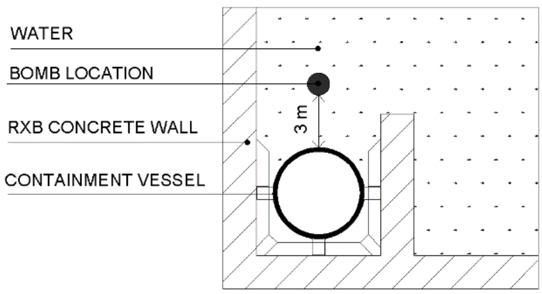

Figure 8: Description of scenario no. 1 (horizontal cross-section, not to scale)

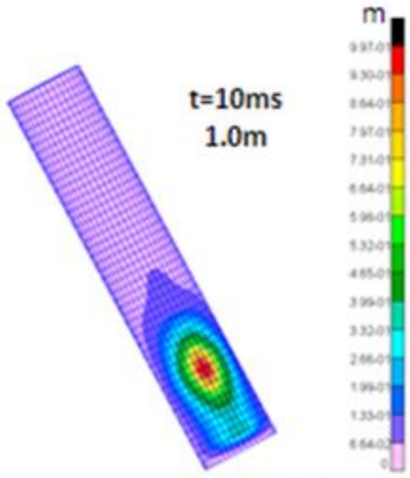

Figure 9: Scenario no. 1- Displacement map of the CNV surface

Summary of scenario no. 1

“*A preliminary analysis of GBU-28 explosion within the water pool of the SMR nuclear power plant shows that at a distance of 3 m between the bomb and the containment longitudinal axis a severe deformation of the containment exterior wall is expected to occur.*"

Results of scenario no. 1

- Maximum displacement of ~1.0 m is created in the CNV.
- Over-Pressures of 1000 bar were created for short periods.

4.2. Scenario no. 2 – Blast effects on the external walls of the RXB - Description

- The bomb axis of symmetry is vertical;
- Distance of 3 m from the internal sidewall (not supported by earth on its rear side);
- Bomb centre at 5 m above the pool floor.

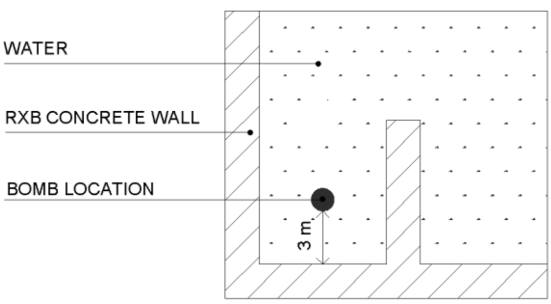

Figure 10: Description of scenario no. 2 (horizontal cross-section, not to scale)

Summary of scenario no. 2

"A simulation of bomb explosion within the water pool shows that a massive breaching of the concrete walls may occur. The present simulation was carried out under the assumption that the walls of the pool are above ground. This pertains to an explosion near the upper surface of the pool. It can be assumed, based on the present results, that breaching would occur also when the walls are below surface, i.e. supported by external earth cover. In order to validate this assumption, an additional simulation is required."

Results of scenario no. 2

The peak acceleration was found to be ~ 4860 g.

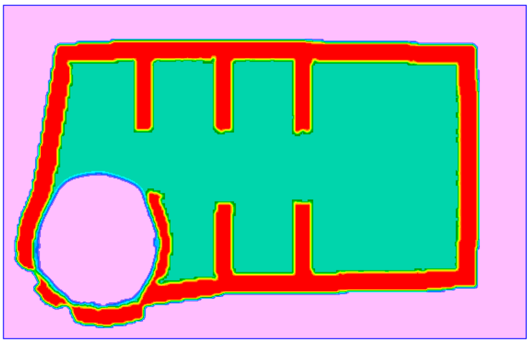

Figure 11: Scenario no. 2 - density map at 120ms - massive wall deformations

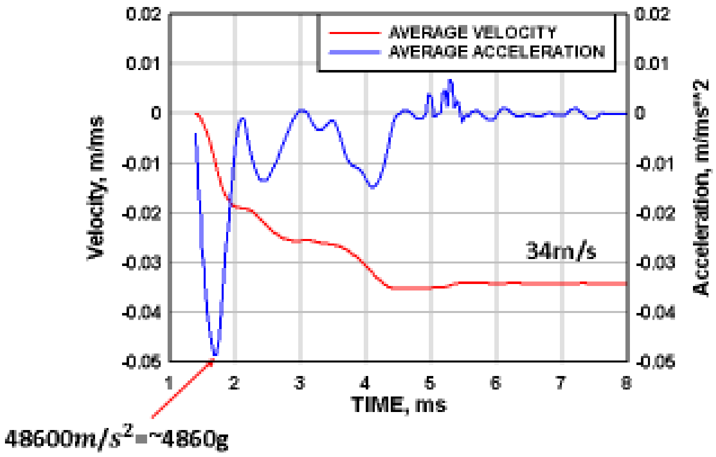

Figure 12: Scenario no. 2 - wall velocity and acceleration for the first 8 ms

It means that the pool water content will leak and radioactive materials can reach the atmosphere and the surrounding ground.

4.3. Scenario no. 3 – Blast effects on the Bay Wall

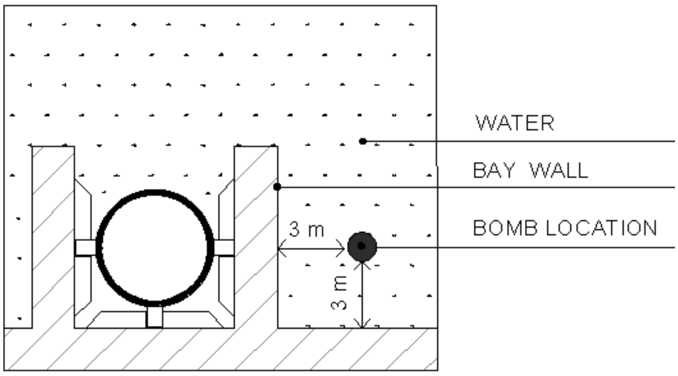

Figure 13: Description of scenario no. 3 (horizontal cross-section, not to scale)

Description

- The bomb axis of symmetry is vertical;
- Distance of 3 m from the sidewall and from the Bay Wall.
- Bomb centre at 5 m above the pool floor.

Summary of Scenario no. 3

"A simulation of bomb explosion within the water pool shows that a massive breaching of the concrete walls may occur. The present simulation was carried out under the assumption that the walls of the pool are above ground. This pertains to an explosion near the upper surface of the pool. It can be assumed, based on the present results, that breaching would occur also when the walls are below surface, i.e. supported by external earth cover. In order to validate this assumption, an additional simulation is required."

Results of scenario no. 3

The computer model showed severe breaching of the bay wall and pool wall as a result of the scenario. The Maximum displacement of the CNV was found to be 12 cm. By the dynamic analysis, the maximum bay wall displacement was found to be 14.6 cm.

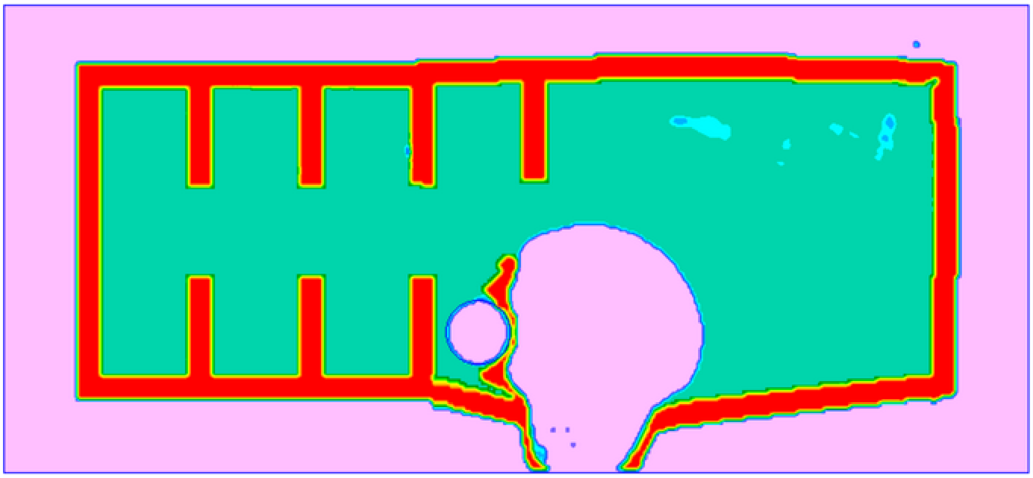

Figure 14: Scenario no. 3 - density map at 190ms – Breaching of the pool and the baywall acompanied by 12 cm deflection of the CNV .

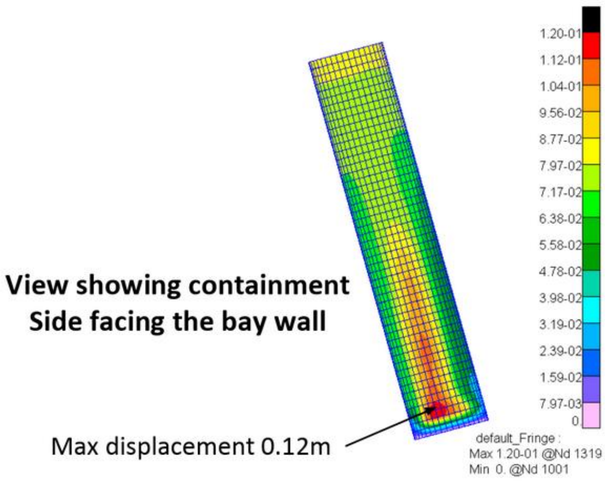

Figure 15: Scenario no. 3- displacement map of the CNV surface at 190 ms (Shohet et al, 2019)

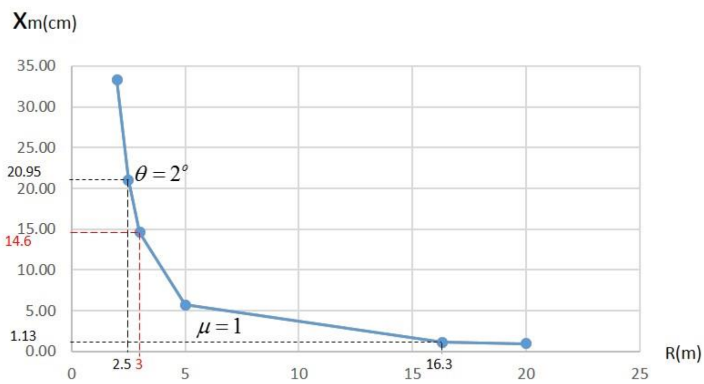

Figure 16: Scenario no. 3- dynamic deflection of the bay wall as a function of the distance from the underwater explosion.

4.4. Sensitivity analyses

The uncertainty of the design parameters were not detailed in the design documents. A best estimate was given for the fragility curve based on the β values and median acceleration given for the HCLPF. Fragility curves depend on the value of the median and are a function of the randomness. In order to improve the results and demonstrate the influence of the randomness, sensitivity tables using different values of β were carried out.

Table 2: sensitivity analysis for uncertainty values of the reactor bay wall (E2) failure to β

β	P(failure) 2 g	P(failure) 4 g	P(failure) 6 g
0.28	0.33	0.98	1.00
0.38	0.37	0.93	0.99
0.68	0.40	0.88	0.98

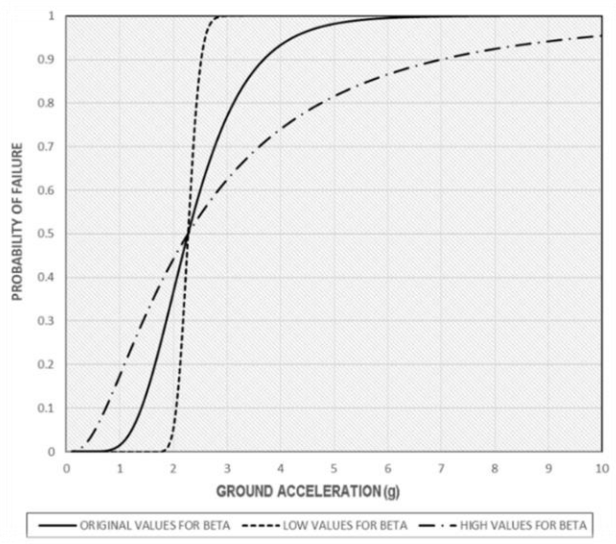

Figure 17: Reactor bay wall cumulative density function

4.5. Results of the sensitivity analyses

The higher β is, the larger the spread is - results emphasis the function of β as a measure of uncertainty. The highlighted β on Table 2 presents the original value taken from the SMA and its results are identical to the analysis carried out in this research. Similar sensitivity analyses were carried out to other critical components such as reactor building wall, power module supports, etc.

5. Conclusion and Discussion

The resilience of the SMR's structural elements (according to fragility curves developed in this reasarch for the scenario) is limited to 0.72 g which resonably suites NuScale's result of 0.88 g as described in the SMA results. The degradation of ~20% in the resilience could be explained either by the meticulous logic taken for the FTA in comparison to the min-max method used by the designers, or due to inaccuracies due to the reconstructed fragility curves developed in this research based on partial data and assumptions. Higher accelerations would cause core damage and a release of radioactive materials to the atmosphere. Therefore, the NuScale SMR cannot withstand external events resulting in long duration ground motions higher than 0.72 g. In order to achieve reliable capacity parameters for explosions, extremely high cost and well-designed experiments must be carried out.

A scenario of GBU-28 detonation at a distance of 3 m from the bay wall was examined. Simulation's results showed maximum deflection of the CNV was 12 cm and breaching of the bay wall and the pool wall. It was verified by dynamic calculation (equating blast kinetic and the bay wall strain energy) showed maximum bay wall displacement of 14.6 cm (see Scenario No. 3). These results, with regard to NuScale analysis for seismic events determine the consequences of the scenario as core damage and release of radioactive materials to the atmosphere - *"The SMA assumes that failure of major structures leads to sufficient damage to the modules such that core damage and a large release would result."* [16]. These findings leads to the conclusion of high vulnerability of the SMR to the scenario i.e. that the SMR cannot withstand the occourance of the given threat scenario and cannot be built in Israel without appropriate protection against a potential munition hit.

6. Acknowledgements

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A Socioeconomic-Based Analysis of Disaster Preparedness, Awareness and Education

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Abstract

Students are one of the most vulnerable subgroups of the general population in terms of disaster preparedness and response; however, many universities still lack strategies and planning for disaster preparedness, mitigation, and response. This study investigated students' perceptions of disaster awareness and preparedness, based on two demographic characteristics: where they lived (on campus or off campus) and their ethnicity. To carry out this research, a comprehensive literature review was conducted on disaster education. Next, a structured survey was developed based on the factors studied in the literature review, and it was distributed to university students above the age of 18 with the help of an online assessment tool, Qualtrics. A total of 111 responses to the survey were collected, and the data collected were analyzed by performing descriptive and statistical analyses. After conducting the analyses, it was found that the perspectives of the students living on campus towards disaster risk reduction (DRR) education was significantly different from those living off campus. There were similar distinct differences linked to their area of living and ethnic backgrounds. It was further revealed that based on both their location and ethnic background, students have very different perspectives on the role of their friends, parents, and the university in keeping them safe during a disaster. The findings of this study will help policymakers assess existing disaster preparedness programs and will help faculty members and the academic staff develop and implement effective disaster preparedness courses and drills at the university, based on the characteristics of the students.

Keywords: disaster education, students' disaster preparedness, students' perception, disaster awareness

1. Introduction

Every year disasters are responsible for major economic losses [1], damage to properties [2], and extensive loss of life [3,4,5]. Disasters were responsible for the loss of eight [6] million lives and economic losses of 700 trillion dollars from 1990 to 2015 [7]. In recent years, universities have been affected by many disasters that have disrupted classes and damaged school buildings. Many kinds of research have been done on disaster risk reduction [8] because of the extensive damage and disruptions caused by them [9,10,11,12,13] and other efforts have been made to increase disaster preparedness among the general community [14,15,16,17]. One study discussed the recent disasters that have affected universities [18], and a study by Tanner and Doberstein evaluated students' disaster preparedness by considering their inventory of emergency supplies [19]. Students are vulnerable to disasters both at their home and at the university [20], but few educational institutions have recognized the importance of making disaster preparedness education available to students [21]. Consequently, effective disaster prevention, mitigation, and preparedness strategies are still lacking. The primary aim of this study was to analyse and evaluate students' perceptions of disaster awareness, preparedness, and education based on two demographic characteristics (i.e., ethnicity and location). To conduct this research, a comprehensive literature review was conducted of disaster-education-related factors. Next, a structured survey was developed with the help of an online survey tool, Qualtrics. The survey was distributed to students more than 18 years old, and a total of 111 responses were collected. The results were interpreted after performing descriptive and statistical analyses of the collected data. The findings of this study will provide policymakers with better insights on how to update or develop effective disaster preparedness programs in the university.

2. Literature review

A disaster is a condition that causes an interruption in the effective functioning of society [22], including individuals, materials, economic losses [23], and impacts [24], that surpass the level at which society can cope [25, 26]. The United States has been affected by more than 10,000 mild and severe disasters in the past century [27]. Hurricane Katrina (New Orleans 2005) was among the disasters that impacted universities and was responsible for the loss of billions of dollars caused by damage to buildings, tuition loss, and declined enrolment [28]. Hurricane Harvey (Houston, 2017) and Hurricane Sandy (New York, 2012) were responsible for extensive loss of life [7]. Hurricane Mathew (North Carolina, 2016) affected five universities that were besieged by flooding, damage to buildings, and power outages that resulted in the campuses being shut for a week [19]. The coronavirus (Covid-19) pandemic is the most recent disaster that has caused disruptions to colleges and universities by leading to cancelation of in-person classes and providing online-only instructions all over the United States [29]. According to United Nations Educational, Scientific and Cultural Organization (UNESCO), the Covid-19 pandemic has impacted about 60% of the world's student population from pre-primary to tertiary education levels [30].

Natural disasters like earthquakes and hurricanes put students in difficult positions by disrupting their classes and damaging the school buildings [18]. They often damage the library buildings, cause the loss of administrative data, destroy the communication system, and inflict injuries upon the students and academic staff [18]. Despite the fact that students are one of the most vulnerable subgroups in the community to disasters, they are one of the most ignored ones [19]. A study by Nahayo et al. indicated that government entities are focused on engaging with the community in general and not specifically with the student population [7]. University students are a rare group of people with a flexible outlook and a unique ability to adapt to challenging situations [6]. Having these qualities allows them to learn disaster skills more quickly and effectively than the general population. A study in China suggested that available disaster courses are not currently meeting the students' needs [6]. As training sessions could significantly reduce the costs of the damages [31,32] and students can be useful resources for the community in general for disaster response, prevention, and mitigation, it is highly recommended to provide students proper training and education [20].

Universities are beginning to recognize the importance of being prepared for disasters [18]. Many studies have been conducted to assess students' emergency preparedness and describe the barriers that they face during a disaster [33]. A study conducted at the University of Texas studied students' perceptions of evacuation during a disaster and of returning to normalcy [34]. They found that international students face extreme difficulties during disasters, with lack of access to resources, and suggested that special consideration should be given to them during emergency preparedness and planning. A further study at the University of Waterloo revealed that a vast majority of students believed that they were responsible for their own safety during the first 72 hours of the disaster, while most of them did not have the required emergency preparedness kits or medical supplies [19]. Results of a previous study conducted in China suggested that universities should be provided with an effective and comprehensive disaster education course [6]. A similar study conducted in Indonesia discussed facilitators and deterrents for teachers to implement disaster risk reduction (DRR) education in their classes [35]. Therefore, insight into students' perspectives on disaster preparedness education is vital to developing an effective disaster risk reduction course and understanding their perspectives on disaster preparedness policies and procedures will lead to a better understanding of the effectiveness of the existing disaster preparedness programs [28].

Reviewing the previous literature reveals that little is known about students' disaster preparedness and the barriers faced by them during a disaster. Very few studies have been done in the context of how demographic characteristics affect students' perceptions of disaster preparedness; consequently, the basis of this research was to analyse and evaluate students' perceptions of disaster preparedness based on the demographic characteristics of students at the University of Texas at Arlington (USA). The focus of this study was limited to two demographics: ethnic background and whether they lived on campus or off-campus.

3. Research methodology

A four-step approach was adopted to fulfil the objective of this study (see Figure 1). An extensive literature review was conducted to study various disaster-related factors such as the importance of disaster education, the impacts of disasters on educational institutions, and the importance of disaster risk reduction education. In the second step, a structured survey was developed based on various disaster-related parameters studied in the literature review. The survey was developed and distributed with the help of an online tool, Qualtrics. The invitations to participate were sent via email including a short description of the study. A total of 111 responses were collected, and in the third step, the collected data were analysed by performing descriptive and statistical analyses. As the collected data were in the 7 points Likert-scale format, the Kruskal Wallis test was performed to interpret the significance of students' perceptions based on two demographic characteristics (location and ethnicity). In the last step, results were interpreted and discussed in detail.

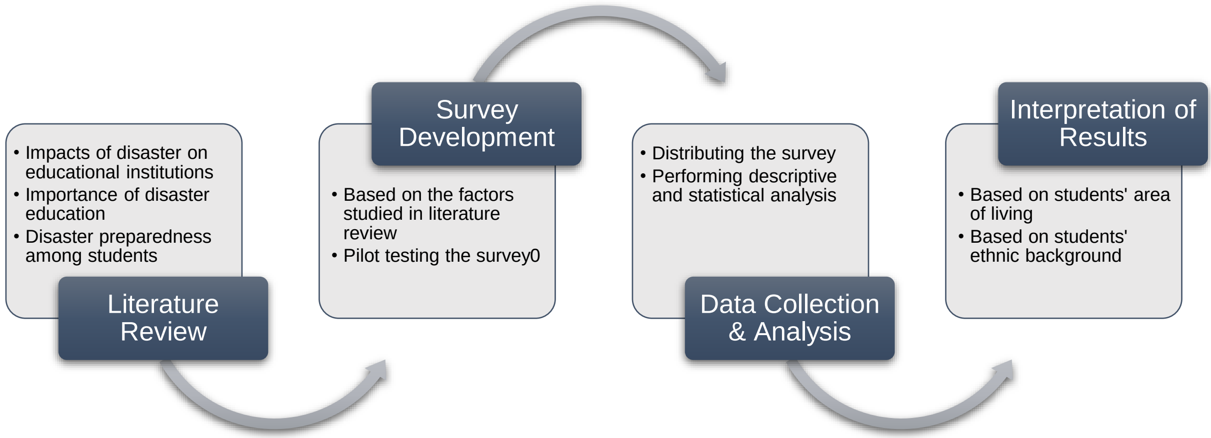

Figure 1. Research Methodology

Kruskal-Wallis test: The Kruskal Wallis test is a non-parametric test used to determine the difference between the observed average and the expected average of a data set. It is used to analyse data of two or more independent groups with an equal or different sample size that does not follow a normal distribution. It was adopted for this study as it is most suitable for analysing Likert scale data. The hypothesis developed for this study is shown in Table 1.

The equation used in the Kruskal Wallis test is provided below:

$$H = \frac{12}{N(N+1)} \sum_{i=1}^{a} \frac{R_i^2}{n_i} - 3(N-1) \quad (1)$$

Here, (R) indicates the rank of the individual group, (N) represents the total number of observations, (a) represents the number of groups (n_i) indicates the number of observations in group (i) [36].

Table 1. Hypotheses adopted for this study

Students' characteristics	Statistical test	Hypotheses
Students' Living On-Campus and Off-Campus	Kruskal-Wallis test	Null Hypothesis (H_0): Students living on campus and off-campus have the same perception regarding disaster preparedness and DRR education. Alternative Hypothesis (H_a): Students living on campus and off-campus have different perceptions regarding disaster preparedness and DRR education.
Asian and Non-Asian Students	Kruskal-Wallis test	Null Hypothesis (H_0): Asian and non-Asian students have the same perceptions regarding disaster preparedness and DRR education. Alternative Hypothesis (H_a): Asian and non-Asian students have different perceptions regarding disaster preparedness and DRR education.

4. Data collection and analysis

A comprehensive survey was developed based on the factors related to disaster education. The survey was developed and distributed with the help of an online data collection tool, Qualtrics. Pilot testing of the survey was conducted with the help of some doctoral students to check the clarity of questions before distributing it to the participants. The survey questionnaire was reviewed and approved by Institutional Review Board at the University of Texas at Arlington. The students enrolled at the University of Texas at Arlington and above the age of 18 years were chosen as the targeted population for this study. An invitation email was sent to the students with a brief description of the study. Electronic consent was obtained from the students at the beginning of the survey questionnaire. No compensation was provided to the students for participation in the study. A total of 111 responses were collected from students with different majors and levels of education. The survey questionnaire consisted of 45 questions in the form of Likert-scale and multiple-choice questions. The structure of the survey consisted of six sections with various questions regarding 1) demographics, 2) disaster experience, 3) disaster education, 4) emergency awareness, 5) university emergency procedures, and 6) implementation of disaster risk reduction (DRR) education, as shown in Figure 2.

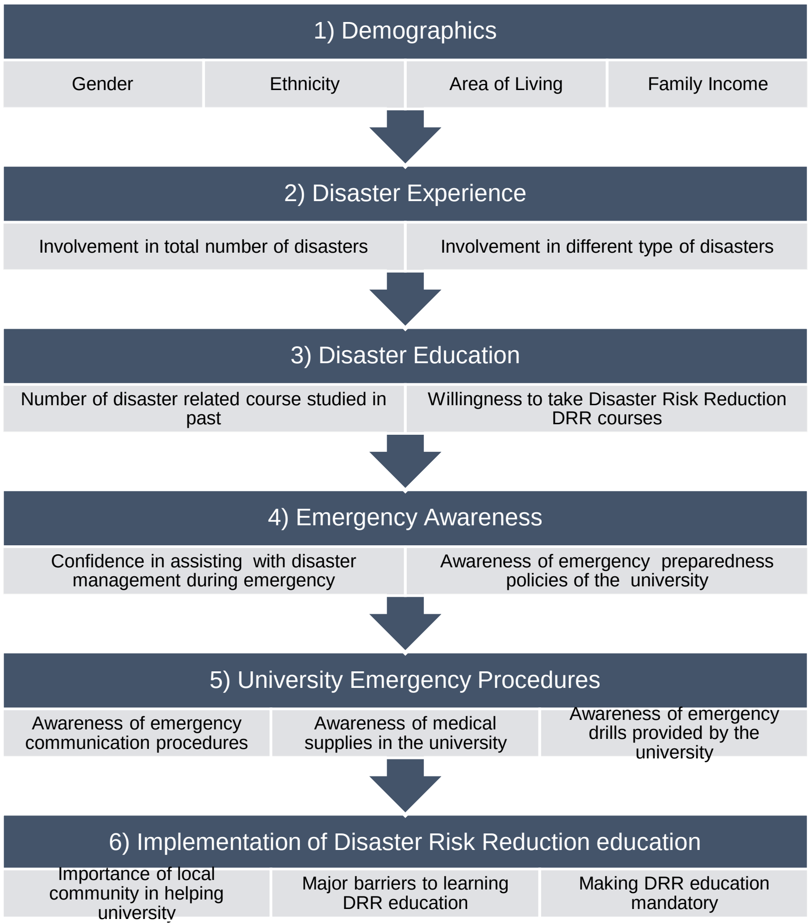

Figure 2. Structure of survey questionnaire

4.1. Descriptive analysis

The collected data revealed that of the 111 responses collected from the students, 78% of them were males, 22% females. Approximately 70% of the students lived off-campus and 30% lived on campus. Furthermore, analysing students' involvement in different types of disasters, it was found that the majority of the students had been involved in disasters such as earthquakes (25%), thunderstorms (23%), flooding (20%), tornadoes (13%), and hurricanes (5%), while almost half of them (45%) had not been involved in any type of disaster. An interesting finding suggested that the majority of the students' population (almost 74%) had not had any disaster-related education. A detailed descriptive analysis of the collected data is provided in Table 2.

Table 2. Demographic information of student participants in the survey

Demographic Characteristics	Number in Sample	Percentage in Sample
Gender		
Male	87	78%
Female	24	22%
Ethnicity		
Native American	0	0%
African American	7	7%
American Indian or Alaskan Native	0	0%
Asian	68	65%
Hispanic	12	11%
Native Hawaiian or Pacific Islander	0	0%

Other	18	17%
Level of Education		
Freshman	1	1%
Sophomore	6	5%
Junior	27	24%
Senior	5	5%
Masters	66	59%
Ph.D.	6	5%
Student's Area of Living		
Off Campus	78	70%
On-Campus	33	30%
Involvement in Disasters		
Hurricane	6	5%
Tornado	14	13%
Flooding	22	20%
Thunderstorm	25	23%
Earthquake	28	25%
Tsunami	3	3%
None	50	45%
Involvement in Number of Disasters		
0 – 1	69	63%
1 – 2	13	12%
2 – 3	16	15%
3 – 4	3	3%
4 – 5	2	2%
More than 5	7	6%
Disaster-related courses taken prior to university		
0 – 1	81	74%
1 – 2	22	20%
2 – 3	4	4%
3 – 4	1	1%
4 – 5	0	0%
More than 5	1	1%

4.2 Statistical analysis

To analyse the Likert scale data in the questionnaire, the Kruskal Wallis test was performed with the confidence level of 95% (P-Value ≤ 0.05) and 90% (P-Value ≤ 0.1). Table 3 indicates the P-Values based on the Kruskal Wallis test's results pertaining to the significance of students' perceptions of various types of disaster preparedness and disaster risk reduction (DRR) education parameters. A total of 22 parameters were tested based on two different demographic factors: 1) students living on campus and off-campus, and

2) Asian and non-Asian students. The results suggested that seven (7) variables tested significant based on where the students lived, and eight (8) variables tested significant based on ethnicity, as shown in Table 3.

Table 3. P-Values testing the significance of students' perceptions of disaster preparedness and DRR education

#	Variables	P-Values for Students living On-Campus & Off-Campus	P-Values for Asian & Non-Asian Students
1	Willingness to take DRR course	0.090**	0.804
2	Confidence to assist with disaster management during emergency	0.615	0.471
3	Confidence in providing basic first aid	0.534	0.230
4	Curriculum provides psychological first aid training	0.834	0.133
5	University has enough first aid boxes	0.280	0.002*
6	Importance of local communities to help university	0.763	0.406
7	Impact of severe natural disaster on student's life	0.084**	0.304
8	Students are responsible for their own safety	0.555	0.060**
9	Friends are responsible for students' safety	0.037*	0.037*
10	Parents are responsible for students' safety	0.084**	0.018*
11	University is responsible for students' safety	0.027*	0.018*
12	Government agencies are responsible for students' safety	0.403	0.137
13	Awareness of the emergency procedures at the university	0.450	0.124
14	Awareness of communication system provided by university during emergency	0.771	0.438
15	University has online database regarding disaster preparedness	0.542	0.505
16	Curriculum or disaster drill includes knowledge of disaster medicine	0.020*	0.021*
17	University buildings have disaster shelters	0.805	0.615
18	University includes students' guardians while providing disaster education	0.433	0.091**
19	Open to collaborating while handling a disaster	0.754	0.184
20	Importance of local communities on helping university to implement DRR courses	0.095**	0.551
21	DRR education should be made mandatory	0.017*	0.019*
22	Likelihood of giving a test based on DRR education	0.068**	0.047*

Note: * Indicates 95% Level of Confidence

** Indicates 90% Level of Confidence

5. Results and discussion

5.1 Analysis of students' perception of disaster preparedness and education: Students living on campus and off-campus

The results, obtained by performing the statistical analysis (Kruskal Wallis test), revealed that the students' perceptions of the impact of natural disasters on their lives were different whether they lived on campus or off-campus. The P-Values in Table 3 indicate that students living on-campus and students living off-campus also have very different perspectives of the roles that their friends, parents, and the university play in their safety during a disaster. They had similar opinions, however, on the role of governmental agencies in students' safety during a disaster. Based on their area of living, students have different perspectives of taking DRR courses and being tested on the content, as well as different perspectives on mandatory DRR education. Students who lived on-campus were more willing to take a DRR course than the students living off-campus, which might be because students living on-campus reside in university housing with very little access to essential supplies and no place for storage, which increases their vulnerability to a disaster [5]. Past research has indicated that students who perceive a higher risk of disasters tend to practice more disaster preparedness behaviour.

5.2 Analysis of students' perceptions of disaster preparedness and education: Asian & non-Asian students'

The P-Values in Table 3 suggest that the students' perceptions of their personal role and that of their friends, parents, and the university in a disaster differ, based on their ethnicity (Asian and non-Asian). However, irrespective of their ethnicity, students have similar perspectives on the responsibility of government agencies for the safety of students' during an emergency. Asian and non-Asian students' have different perspectives on mandatory DRR education in educational institutions. It was revealed that there is a significant difference in the perceptions of students of different ethnic backgrounds on disaster medical knowledge provided in the curriculum. Moreover, it was found that Asian and non-Asian students have a different level of awareness of first aid boxes provided by the university. It was observed that Asian students were more aware of the medical supplies provided by the university than the non-Asian students.

6. Conclusion

In conclusion, it was observed that DRR education is perceived significantly differently by students who live on-campus and students who live off-campus. The same difference exists, based on their area of living and ethnicity, between the students' perceptions regarding mandatory disaster risk reduction education. Among the Asian and non-Asian students, there was a significant difference in awareness regarding medical supplies provided by the university. This is an interesting finding, as many Asian students in the U.S. universities are international students who are unfamiliar with university emergency procedures and local emergency management services. Furthermore, it was also revealed that both the area of living and ethnic background of students affected their perspectives regarding the roles of their friends, parents, and university in students' safety during a disaster. Students had similar perspectives of the government's role in their safety, irrespective of the area of living or ethnicity. The findings of this study will help policymakers implement changes in existing disaster preparedness programs and will help faculty members and the academic staff to effectively develop and implement disaster preparedness courses and drills at the university, based on different characteristics of the students.

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An Analysis on Safety Risk Judgment Patterns Towards Computer Vision Based Construction Safety Management

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Abstract

Due to dynamic and constantly changing nature of construction projects, the highest accident and fatality rate makes the industry infamous in mitigating hazardous safety risks and protecting workers at jobsites. Despite of enormous efforts and serious attention by government agencies and professional bodies, current safety management still relies on traditional manual approach by auditing and supervising safety rule compliance which are infrequent, inefficient and prone to error. With the advent of new emerging technologies such as BIM, VR/AR, AI, computer vision, and big data analytics, various tech-based solutions to help manage and reduce site risks has been introduced during the last decade. Computer vision technology, in particular, has been most attractive to site safety monitoring by academics and construction startups around the globe. However, literature review has revealed that the vision-based researches are limited to object detection such as workers' PPEs and machines to help subsidize the manual approach prototypically. The purpose of this study is to propose a wide-range applicability of computer vision technologies by investigating safety risk patterns. In doing so, entire safety rules and clauses described in the Korea Occupational Safety and Health Agency (KOSHA) regulations of construction sector is reviewed and analyzed with safety experts. Four main safety risk judgment patterns were found and grouped for various vision technology applications. The remaining clauses was classified into two different types. It is expected that the findings of this study would provide an insight to researchers and developers in construction safety domain.

Keywords: KOSHA Rules, Computer Vision, Safety rule compliance, safety risk correlation pattern, risk recognition, safety monitoring

1. Introduction

Safety in construction remains a major issue. Despite various efforts to reduce the number of accidents and fatality in construction sites, accidents are still happening daily in the workplace. According to 26,570 records in the year 2016 from KOSHA, 29.3% of accident occurrences were from the construction sector [1]. These accidents, fatalities, injuries and near misses are costly which can be avoided by taking safety measures. Implementation of industry best practices and safety rules is one way to deal with construction safety [2]. Unfortunately, enforcement of regulations and best practices still relies on conventional safety procedures. Checking rule and best practices compliance to identify the potential hazards is a crucial step to effectively prevent accidents on a construction site [3]. Considering the conventional safety supervision, the safety manager has to physically visit the job site and visually observe every activity for potential hazards which is impossible and prone to error [4]. Traditional safety management-based risk detection and analysis are not sufficient to protect workers in construction job sites [5].

Many researchers have addressed the construction safety management issue recently by applying new technologies. Among the recent trend of technological research to enhance safety monitoring, computer vision holds immense potential [5,6]. To deal with the high fatality rates confronting the construction industry, there has been an advancement in computer vision-based safety monitoring research recently. The computer vision-based monitoring approach has the advantage of being able to systematically identify unsafe behavior and unsafe environments without affecting the productivity of workers in the field, with little additional cost to expand separate devices after automated monitoring system algorithms are deployed. Recently, many researchers considered computer vision application as a vital measure to deal with the construction safety management issue. However, most of these researches have limited narrow scope and consider some specific tasks only [6–8]. Hence, to ensure a safe working environment, KOSHA insight is inevitable to propose a comprehensive framework and check if the current state of the art advancement in computer vision technologies can adopt these rules in the construction site.

In order to propose a comprehensive KOSHA classification based image recognition technology approach for safety monitoring that should be feasible in practical use, it is necessary to deeply examine the KOSHA regulations for the extraction of information about all the construction entities that could lead to possible accidents. The KOSHA rules which show the positive relationship between the construction entities were grouped under Type-1: positive relation between objects, whereas the rules dealing with an inverse relationship between the entities were kept in Type-2: negative relation between objects. The Type-3: numerical judgment, categories the rules which show the numerical measures information for the safe operating procedure of an entity. On the contrary, the rules related to the establishment of risk zones were clustered in Type-4: determination of risk zones. Apart from that, the rest of the rules were classified under the category of "others" which includes the rules which can be covered by sensing or other technologies and some subjective rules which comes under the jurisdiction of management and administration. The articles related to management and administration for safety required at construction sites were excluded from the scope of this study.

2. Computer vision application in construction safety

Computer vision is an integrative field that deals with acquiring and processing digital images or videos to automate those tasks what the human visual system cannot perform. To automate the construction processes, several researchers have focused on computer vision technology for performance measurement, productivity analysis and safety monitoring [9]. In construction, many machine learning aided vision-based system has been developed to detect and track the construction entities (i.e. people, machinery and material), and recognize their unsafe behavior [6]. Despite the recent attraction and efforts of many researchers towards computer vision in construction safety, research being done in this domain is still premature to be applied practically. Concerning the KOSHA safety rules classification for effective implementation of image recognition technology in the real site, this paper reviews the concepts, techniques, and applications been done so far in construction safety and health.

3. Detection of unsafe acts based on correlation, numeric and risk area information

3.1. Positive correlation detection

The positive correlation could be the absence of a hard hat, failure to wear a safety harness while working on heights (person have a positive relationship with a hard hat and safety harness). To detect unsafe behaviour of a worker, Fang (2018) applied Faster-R-CNN to determine whether to wear or not, a protective helmet for job site workers [5]. To overcome fall accidents, another study from the same authors detects the safety harness and person while working at hights [6]. The previous efforts show the specific examples of recognizing construction entities and the positive relation between the entities. However, more insight is required to understand the comprehensive correlation structure among the construction entities advised in safety regulation by KOSHA.

3.2. Negative correlation detection

The negative correlation could be the risky actions having inverse relation with other construction entities (object/s) such as traversing structural members to take shortcuts, unsafe posture of humans to the ladder or scaffolding, the relation between electric wire and water, person and toxic material, etc. It was intended to identify the negative correlation of a worker to the given activity (leaning on handrails, dumping from height, climbing ladder) and determine if they have a hazard by depending on the body joints as parameters [10]. Likewise, to automatically recognize workers' unsafe behavior while using the ladder, Ding (2018) proposed a method of combining a convolution neural network (CNN) and long short-term memory (LSTM) to create a new hybrid deep learning model. Moreover, computer vision-based Mask-Region based Convolution Neural Network (Mask-RCNN) has been developed for detecting unsafe behaviour (the negative correlation between the person traversing and structural member) of individuals traversing the structural member in job site [7].

3.3. Object's numeric information extraction and detection

Visual monitoring of construction job sites needs numeric information (e.g. diameter, dimension checking, angle measurement, and weight) of the object for assessing several activities and ensure safe best practices. Many computer scientists focused on this domain considering some particular objects, yet, studies in this domain are still premature to be adopted practically in a construction site. In the manufacturing sector, a non-contact online approach was used to efficiently inspect, and measure the train wheel set's geometry based on optoelectronic measuring techniques employing a charged couple device camera[11]. Another study proposed multiple view images-based segmentation techniques with utilizing density formula to calculate steel bars weights [12]. To reduce the human input of manual measurement and automate the concrete workability test process, a 3D depth sensor (Kinect) based slump processing algorithm approach was proposed [13]. Considering the above example in the literature, the possibility of practical adoption of these techniques for the numerical measures to ensure safe operation of any tool or equipment in the real construction site is immense. To comprehend computer to detect unsafe behaviour based on the objects dimensions and specific numeric measure advised for safe operation, recognition of objects with additional spatial information (an object with numeric info) is requisite. The determine numeric information (angle of the ladder, dimensional information of object for calculating allowable weight for equipment or scaffolding, etc.) are then compared with specification and regulations to check the rule compliance and unsafe conditions.

3.4. Surrounding risk area recognition

This type of risk assessment recognizes sets of the risk zone and checks whether workers enter or leave the determined zone. As many construction worker's fatalities are related to struck-by events, for instance, workers on foot being in proximity to geo-referenced hazards or close to heavy equipment. To tackle these kinds of unsafe acts and conditions, one of the key considerations is to track the position of the resources [9]. Many previous studies attempted to automatically locate the real-time position of the construction entities using sensors technologies and computer vision techniques. However, computer vision-based tracking is getting popularity due to the advent of artificial intelligence aided vision technologies over sensor technologies such as non-contact, less cost and efforts. Vision-based tracking can generate a report of the temporal trajectory by assigning the consistent labels to the detected object [14]. Visual data were acquired from the readily available cameras in the heavy machinery and 3D position coordinates using a monocular camera to prevent the possible collision of workers and heavy equipment [15]. An Unmanned Aerial Vehicle (UAV) supported visual monitoring approach was proposed to tackle that struck-by hazards using YoloV3 and image rectification [16]. Similarly, a proactive construction hazard avoidance system that delivers hazards information through an augmented reality device is developed. The distance between the objects is calculated based on the spatial relation and the processed information that is safety level and distance are displayed using a wearable device (AR) [17]. The previous efforts depict significant contributions contemplating recent advancement in object tracking, however, due to the complex and dynamic environment of construction, object tracking is still challenging. One of the key limitations of the previous efforts is the limited application and narrow scope (i.e. human and specific equipment). To broaden the scope of computer vision-based tracking and risk recognition systems considering the risks and limited access zones, a deep analysis of regulations is needed.

4. Need for a safety rules classification structure

To enhance the construction safety management tasks, various technologies such as BIM-based safety planning, sensor and location tracking are being developed. However, the sensor, location-based technology applied to prior studies must be equipped with relevant devices in the worker's body or helmet, thereby reducing the efficiency of the work [17]. Also, devices are installed on a per-target basis, additional work is done to manage various components, and overspending is inevitable as the scope of control increases. On the contrary, the computer vision is getting popularity due to cost efficiency, does not need any attachments to the worker body and many efforts. Even though, currently, many researchers proposed very few computer vision-based systems with limited scope, as mentioned in the literature. To broaden the scope and develop a comprehensive computer vision-based risk recognition system, understanding of the safety monitoring expert knowledge such as industry best practices, accident cases, and safety regulations are mandatory. However, this study only focuses on the KOSHA regulations, specifically related to South Korea. This study aims to expand the scope of visual technology application for automatic safety rule checking during physical execution by exploring and classifying KOSHA rules. Therefore, this research developed a pattern-oriented classification of KOSHA rules that can employ a large scale of safety hazard recognition.

5. KOSHA legal analysis and classification

In 1953, labor standard law led the foundation for industrial safety and health policy in Korea. Thereafter in 1987, Korea Occupational Safety and Health Agency (KOSHA) was established with regards to the rapid development of industries in 1970 to 180. This research work used a logic-based mapping to interpret the safety rules from a human language such as KOSHA database to enhance technology advancement in machine learning. The name, type, and other properties were analysed and extracted from the rule. The rules were then classified into different groups based on the image recognition technology adoption nature. Rule translation typically has two aspects: (a) the condition or context where the rule applies and (b) the properties upon which the rule applies. The first step was identifying the target activity or object, for example, an activity such as foundation concrete work or a building element such as a rooftop. the second step was then checking whether the KOSHA rule related to this specific activity or element can adopt the state of art image recognition technologies or not.

Table 8 Analysis of KOSHA Regulations

Classification		Sub-level clause	Percentage
Application of Image Recognition Technology	Type-1: Positive relation between objects	214	25.9
	Type-2: Negative relation between objects	91	11
	Type-3: Numerical judgment	119	14.4
	Type-4: Determination of risk zones	52	6.3
Subtotal		476	57.6
Other	Rules covered by other technologies	106	12.8
	Clauses related to managerial and administrative issues	245	29.6
Total		827	100

The rules of KOSHA consist of 671 articles in 13 chapters, of which 277 are related to the construction industry. The 277 articles have then been categorized and broken down to the sub-category detail level. These 277 standards further contained 827 clauses that were thoroughly investigated and classified within this study. Articles that can adopt the visual judgment and measurement tools were then analyzed to classify statutes deemed necessary for the application of image recognition technology as shown in Table 2.

As a result, the KOSHA rules that were being considered applicable to the image recognition technology were noticed approximately 57% of the total articles, as depicted in Table 1. In addition, 29.6 percent of articles were not able to cope with the technologies. Among them, 12.8 percent were expected to be covered with other information and communication technologies (ICT). Thus, the remaining 43% of the rules that were unable to be adopted by IRT were categorized as "other" and were excluded from this research.

5.1. Type-1: Positive relation between objects

The positive relationship refers to two targets that must be presented together and are considered a hazard if one of them exist without the other one. Mainly, the positive relationship refers to determining whether a safe facility is installed and whether the protective gear is equipped or not. For example, in the site, while attempting welding activities fire extinguisher must exist near the welding area to prevent any hazard actions from occurring. For illustration, figure 1 shows some example of extracted rules from KOSHA for positive relation between the objects: (a) outriggers having positive relation with mobile scaffolding, (b) guardrails with mobile scaffolding, (c) stabilization base plate for scaffolding and (d) fire prevention shield while working with wielding.

Figure 13 Example of positive relation between the objects: (a) outriggers with mobile scaffolding, (b) guardrails with mobile scaffolding, (c) stabilization base plate for scaffolding (d) fire prevention shield with weilding machine

According to article 32 of KOSHA, the worker should wear protective gear in the following situations: 1. protection helmet; work in which there is a risk of falling or flying objects or falling workers. 2. Fall-protection built; working in a place at the likelihood of falling more than two meters in height or depth. 3. protection shoes; falling and landing on heavy objects, equipment or shocked by electric charges. 4. Googles; operations that may cause objects to fly. 5. Fire extinguisher; work where there is a possibility of sparks or objects flying during welding. 6. Electric shock preventing gloves; activities at a chance of electric shocks. 7. Heatproof clothing; operations that may cause burns due to high heat. 8. Dustproof mask; in the dusty weather or activities required putting on a dustproof mask as illustrated in Table 2.

Table 9 Example of a positive relationship between two objects

Location/activity/condition	Object A	Object B
In the job site	Worker	Helmet
Depth or height more than 2m	Worker	Hock (fall-protection belt)
In the job site	Worker	Shoes
Holding equipment	Worker	Googles
Risk of sparks or flying objects	Welding	Extinguisher
Cables or electric work	Wire, circuit box	Protection gloves
Welding	Fire, sparkling objects	Heatproof clothing
Dusty weather	Worker	Dustproof mask

5.2. Type-2: Negative relation between objects

In this case, two target objects should not be compatible with one another, and they are supposed to be a hazard and be determined as a direct risk factor, if present together. For instance, Type-2 focuses on electric shocks of electric machinery and appliances as mentioned in Article 302 of KOSHA (Ground of Electric Machinery and Instrument), Article 303 (Equipment of Electrical Machinery), Article 304 (short circuit breaker of Electrical Equipment). Figure 2 exemplified negative correlation between objects: (a) water with electric wire having negative relation, (b) explosive gas container having inverse relation with electric wires,

(c) ladder should not be used aerial lift platforms (d) awkward climbing action on scaffolding also shows unsafe behavior based negative correlation.

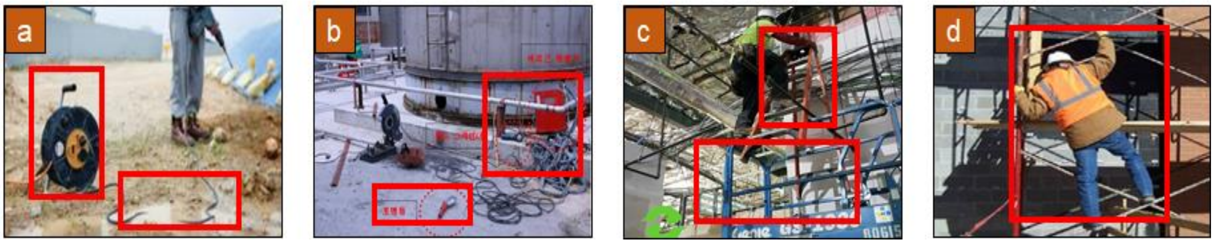

Figure 14 Example of negative relation between objects: (a) Water having negative relation with electric wire, (b) Explosive gas container having inverse relation with electric wires, (c) Ladder on aerial lift platform (d) Awkward climbing action on scaffolding

In the job site, liquids and water that can transmit electricity have a high danger factor when existing near or meet the electric installments. Therefore, electrical machines and appliances used in wet places are at risk of electric shock. It's advised to take preventive actions such as installing an electric leakage breaker. As a result, electricity transmitting liquids and machinery working on batteries or electric source appliances have a negative relationship with each other, and If the two targets coexist, they are perceived as a hazard as shown in Table 3.

Table 10 Example of negative relation between objects

Location/activity/condition	Object A	Object B
Near	Electric equipment	Inflammable substance
Near	Welding sparkles	Anti-falling net
Close to	Flammable liquid	Fire source
Under	Aerial lift platform	Ladder
Climbing action	Worker	Scaffolding/Ladder

The ladders using mobile scaffolding in the site is also considered an example of negative relationality. The article 68 (mobile scaffolding) of KOSHA restricts people from working with support or ladder on the work bed supported by mobile scaffolding. In the case of having a moving scaffolding recognizing a ladder installed above a moving scaffolding, it has a negative relationship and considered a hazard.

5.3. Type-3: Numerical judgment

Type-3 determines numeric information of a target, such as a length, spacing, and angle of the target object advised by the industry best practices and safety rules for the safe operation of the required tools and equipment. Failure to fulfil the required conformity, the system should raise alarm when measurements are outside the acceptable threshold. First, an example of installation intervals is a guard rail installed to prevent the falling risk. The temporary rail consists of rail handler, middle railing, and columns, which shall be installed at least 90 centimetres from the floor surface, and in case the rail handler height is more than 120-centimeter, then mid-bar should be installed. The gap between the rail handler and the floor surface should not exceed 60 cm in the cases illustrated above as shown in Figure 3. Next, scaffolding installation main bars should be horizontal/vertical, as mentioned in article 70 of KOSHA as shown in Figure 3. Other minor measurement standards related to scaffolding and machinery in different scenarios can be analysed and integrated within Type-3 as illustrated in Figure 3.

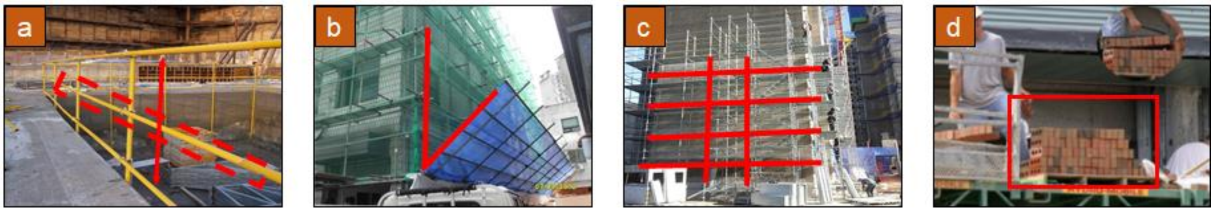

Figure 15 Example of Numerical judgment (Type-3): (a) Guardrails dimensions and specification for safe operation (b) Angle of safety net (c) horizontal and vertical distance and level checking (d) Load calculation of bricks on the scaffolding

5.4. Type-4: Determination of risk zones

As many construction worker's fatalities are related to struck-by events, Thus KOSHA advise many rules to make sure the safe working environment for construction worker. This type of risk assessment requires real time information to recognizes the controlled zone and checks whether workers enter to the determined zone. To tackle these kinds of unsafe acts and conditions, one of the key considerations is to track the position of the resources. For instance, lifting work using cranes where the load passing over the worker's head is prohibited, and the trace path of the cargo is considered controlled danger zone for workers, as shown in the Figure 4. Apart, it further includes prohibiting the workers from entering the loading area to prevent struck or collision with the unloading machines such as a forklift, etc, as illustrated in Figure 4.

Figure 16 Determination of risk zones:(a) worker entering to the proximity zone (b) risk zone under lifted material by crane (c) controlled zone around the opening in floor (d) controlled zone for the scaffolding work.

6. Discussion and conclusion

The purpose of this study is to propose a wide-range applicability of computer vision technologies by investigating safety risk patterns. In doing so, entire safety rules and clauses described in the Korea Occupational Safety and Health Agency (KOSHA) regulations of construction sector is thoroughly reviewed and analyzed with safety experts. Four main safety risk judgment patterns were found and grouped for various vision technology applications: Type-1: positive relation between objects, Type-2: negative relation between objects, Type-3: numerical judgment, and Type-4: determination of risk zones. The rest of the remaining clauses was classified into two different types - 'Clauses related to managerial and administrative issues' and 'Others'. Each safety risk pattern is matched with applicable computer vision technologies such as deep learning-based image recognition and processing algorithms. These findings of this study would provide an insight to researchers and developers in construction safety domain, though it is quite difficult and challenging to be realized at construction sites. The computer vision technology has a potential to greatly change current manual safety monitoring practices nonetheless and would help step towards global tech-based site management with other traditional management issues such as progress measurement, defect prevention, and so on.

7. Acknowledgements

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Analysis of Cost Performance Indicators in Reconstruction Projects: A Comparative Study of Low vs High Level Damages

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Abstract

With the increase in frequency and intensity of natural disasters, the number of transportation infrastructures needing reconstruction is also increasing. Insufficient financial resources and cost overruns are among the major limitations that affect the reconstruction works of the transportation infrastructure after a disaster; however, there are few resources to help practitioners monitor the cost of reconstruction and keep it within the allocated budget. This study aims to provide a comprehensive list of the critical factors that affect the reconstruction cost (CFRC) of transportation infrastructures after a disaster, and to categorize them, based on the level of damage incurred. A survey was conducted to determine the importance of 30 potential CFRCs, and the survey results were statistically analyzed. It was found that effective coordination plays a critical role in completing a project within the budget limitations, a slow decision-making process slows the reconstruction efforts and increases the probability of cost overruns, and the reconstruction cost of transportation infrastructures with a high level of damage are dependent on more factors than infrastructures with a low level of damage. For example, when the damage level is low, fewer disruptions to traffic are necessary during the reconstruction than if the damage level is high. When the damage level is high, the likelihood of more traffic disturbance is greater, which has the potential to create unforeseen costs and/or cost overruns. The outcome of this paper will be of value to the authorities who are responsible for controlling budget overruns during post-disaster reconstruction projects.

Keywords: maximum five keywords, in lower case, alphabetical order, separated by commas, finishing with full-stop

1. Introduction

Natural disasters are one of the major causes of losses and casualties worldwide [1, 2, 3], and hurricanes are among the most powerful and destructive disasters [4]. The destruction wreaked by Hurricane Katrina in 2005 was estimated at more than $160 billion [5], Hurricane Ike left massive destruction in its wake in 2005 [6], and Hurricane Harvey destroyed a considerable number of structures when it hit the southern part of Texas in 2017 [7].

Since the number of natural disasters, especially hurricanes, has increased over the last two decades [8, 9] limited financial resources have become a critical factor that seriously affects the success of post-hurricane reconstruction projects [10, 11, 12, 13]. Hidayat and Egbu [14] and Chang et al. [15] explained it by saying that inflated prices and/or shortages of laborers, materials, and equipment commonly occur after hurricanes and lead to cost overruns, schedule delays, and even failure of reconstruction projects. [16, 17, 18, 19]. Few studies have been conducted to estimate the cost and/or duration of post-hurricane reconstruction of transportation infrastructures to prevent cost overruns and time delays in projects, but the project's cost is usually considered an indicator of the duration of the construction phase [20, 21].

Reconstruction after a disaster comes with the notion of building back better, with resiliency against future disasters, which increases the reconstruction costs even more [22, 23]. One of the best strategies for completing a reconstruction project within budget is to identify the factors that affect its cost [24, 25]; however, few studies have investigated these factors and limited literature is available on the subject. In addition, not all disasters damage transportation infrastructures at the same level [26], which means that the resources and financial needs are different for the various levels of damage. For example, [13] found that floods damage transportation infrastructures more than fires or storms; therefore, the financial and resource outlay will be greater after a flood. Hence, it is necessary to investigate the factors that affect the cost of reconstruction based on the level of damage.

This research aims to fill the above-mentioned gaps by identifying and classifying the critical factors affecting reconstruction costs (CFRC) of transportation infrastructures after a disaster. To achieve the aim of this study, the following objectives were formulated: i) identify the potential CFRCs that affect the reconstruction cost, ii) determine the significant CFRCs that affect reconstruction cost, and iii) classify the CFRCs based on the level of damage. The outcome of this paper will be of value to the authorities who are responsible for controlling budget overruns during post-disaster reconstruction projects.

2. Literature review

In the last three decades, the number of natural disasters has increased significantly, and with that increase has come a strong disruption of the functioning of society, as serious human and environmental impacts are experienced when an affected community cannot cope with the loss of their resources [27, 28]. Natural disasters cause physical and psychological trauma to society and damage to the environment [25, 29]. Furthermore, the losses and damages experienced have not increased proportionally, as they increased from approximately $10 billion in 1975 to approximately $90 billion in 2009 [27].

The transportation sector experiences some of the greatest losses and damages from a disaster [27]; however, its reconstruction provides an often unrecognized advantage to the affected community, as several studies have shown that the reconstruction of the transportation sector accelerates the process of recovery in all of the affected areas [30]. It is a continuous procedure that needs to begin immediately after the disaster and often takes longer to complete than what was estimated [31, 32]. Multiple researchers and authors have espoused that cost overruns are one of the most serious issues and challenges that governments face in construction and reconstruction projects [33, 34, 35, 36] as a result of the complexity of the projects [37, 38].

Every post-hurricane reconstruction project is unique, and the differences can be those of safety and environmental issues or even the attitudes of the decision-makers [39, 40]. Multiple studies have been conducted to identify the root causes of post-disaster reconstruction projects' success and failure [41], and Table 1 depicts the causes of cost overruns and failure.

Table 1. Challenges creating cost overruns of the reconstruction of the transportation infrastructure after a disaster

Challenge	Previous Study
Finance and limitation of funds	[9]
Ineffective design	[22]
Inadequacy of resource procurement	[11]
Unavailability of human resources	[23]
Unavailability of material resources	[23]
Engineering mobilization	[24]
Inflation	[11]

3. Research methodology

3.1. Outline

A structured research framework was designed to fulfil the goals of this research. Figure 1 shows that a comprehensive review was performed of the existing literature to identify potential CFRCs affecting projects' costs. Over 200 journal articles, conference papers, dissertations, and research reports were identified from five main databases, Google Scholar, JSTOR, ProQuest, and Science Direct. More than 75% of all the articles were peer-reviewed journal articles. The articles were carefully reviewed, and the most relevant articles were included; the others were discarded.

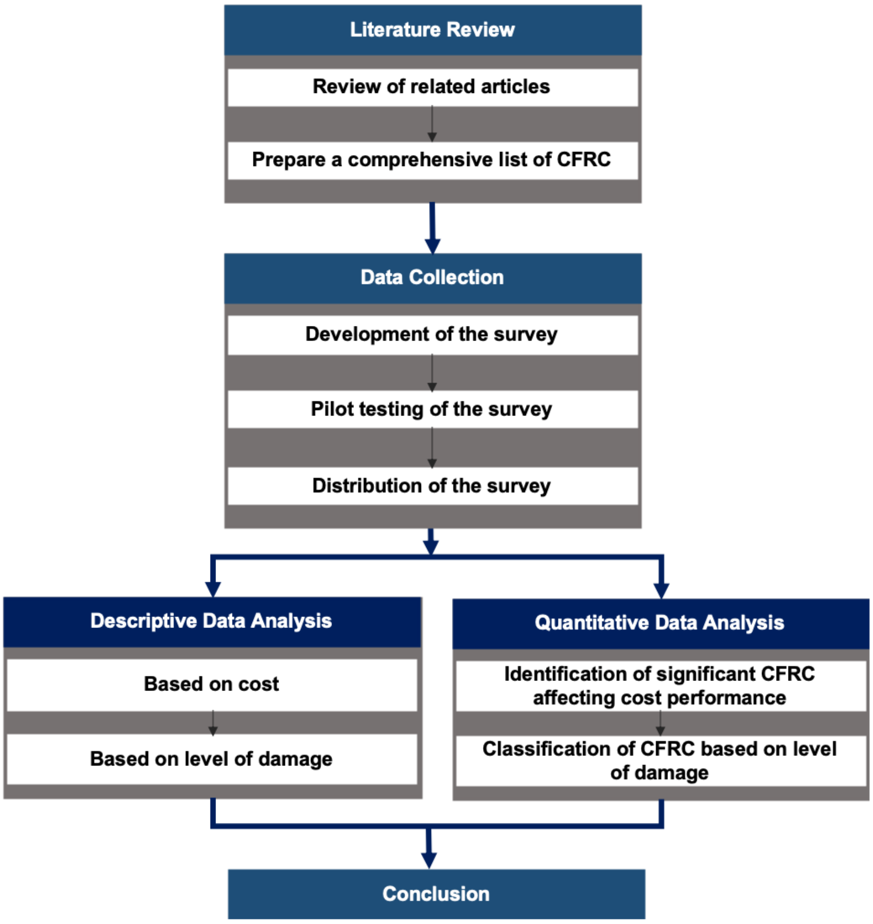


Fig. 1. Research methodology

Each CFRC was converted to a question of a survey that was pilot tested and distributed. The survey responses were analysed descriptively and quantitively and were discussed and interpreted to identify and classify the CFRCs that affect the cost of reconstruction after a disaster.

3.2. Statistical analysis methods

Various statistical tests were utilized, depending on the type of data that was collected from the survey. Table 2 summarizes the basic formal statistical methods that were used for the quantitative analysis in this study. The P-values that indicated the statistical significance of differences between the two targeted groups were generated through the relevant tests.

Table 2. Statistical analysis methods

Statistical Test	Assumptions
Two-sample *t*-test: This test was used for responses of a count or numerical value.	• The two groups follow a normal distribution. • Each project was independent from other projects.
Kruskal-Wallis: This test was used for Likert-scale questions (ordinal seven-point scale), where it could not be assumed that the data followed a normal distribution.	• The two groups follow an identically scaled distribution. • Each project was independent from other projects.
Chi-squared test: This test was used for survey questions with binary responses ("Yes" or "No"), testing whether the observed frequencies of "Yes" or "No" are equal for both targeted groups.	• Each project was independent from other projects.

4. Data collection

4.1. Potential PDR listing

A comprehensive literature review of scholarly articles was conducted for this study. A list of 30 potential CFRCs was prepared, based on the findings of the study and the authors' understanding and expertise. Table 3 shows the CFRCs that were considered for this study.

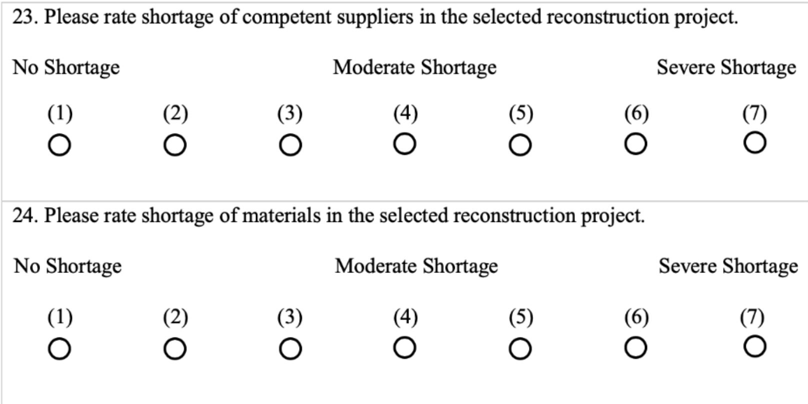
Table 3. List of potential CFRCs

#	List of CFRCs	#	List of CFRCs
CFRC1	Number of main/truck lines	CFRC16	Quality issues of materials
CFRC2	Total length	CFRC17	Quality issues of equipment
CFRC3	Level of complexity	CFRC18	Frequency level of logistics/ management issues
CFRC4	Distance from highly populated area	CFRC19	Quality of on-site inspection
CFRC5	Level of damage	CFRC20	Frequency of on-site inspection
CFRC6	Level of traffic disturbance	CFRC21	Information management
CFRC7	Shortage of experts	CFRC22	Pace of decision-making process
CFRC8	Shortage of field laborers	CFRC23	Implementation level of risk management
CFRC9	Productivity level of contractors	CFRC24	Coordination
CFRC10	Shortage of materials	CFRC25	Pace of workers' mobilization
CFRC11	PRT11. Shortage of equipment	CFRC26	Volume of debris
CFRC12	PRT12. Inflation of labor wages	CFRC27	Environmental/safety issues prior to executing the project
CFRC13	PRT13. Availability level of on-site infrastructure	CFRC28	Work suspension through execution of the project
CFRC14	PRT14. On-site accommodation level for staff	CFRC29	Regulatory requirements
CFRC15	PRT15. Shortage of suppliers	CFRC30	Availability of required temporary pathways

CFRC refers to critical factors affecting reconstruction cost of transportation infrastructure after a disaster.

4.2. Survey development

Based on the identified potential PRTs, a structured survey was developed, and each PRT became one question in the survey. The survey consisted of three main parts: i) respondent information, ii) area transportation network, and iii) project-based information. The survey consisted of 46 questions, and two samples of the questions are presented in Figure 2.


23. Please rate shortage of competent suppliers in the selected reconstruction project.

No Shortage | Moderate Shortage | Severe Shortage

(1) (2) (3) (4) (5) (6) (7)

24. Please rate shortage of materials in the selected reconstruction project.

No Shortage | Moderate Shortage | Severe Shortage

(1) (2) (3) (4) (5) (6) (7)

Fig. 2. Research methodology

4.3. Pilot testing

After the survey was developed, it was pilot tested to verify its suitability for the respondents. The pilot testing was performed among a limited number of respondents and was modified according to their comments. After that, the necessary approval for the survey was acquired and the survey was finalized.

4.4. Survey distribution and collection

A list of 500 potential respondents was prepared by the team. The list consisted of the name and contact information of the potential respondents who were either policymakers, project managers, or design and construction engineers, etc. Special attention was given to ensure that the respondents were working in different governmental and private agencies such as state transportation agencies, departments of transportation, the offices of cities, etc. They were contacted by email, and after three follow-up emails, 30 responses were collected.

5. Descriptive analysis

5.1. Analysis based on project cost

The descriptive data from the analyses associated with the baseline and actual budgets and schedules, as well as the rework costs corresponding to the 30 reconstruction projects, are provided in Table 4. As illustrated in this table, the means of the baseline and actual budgets were roughly $25 million and $35 million, respectively.

Table 4. Descriptive data analysis based on cost

		Minimum	Mean	Maximum	Standard Deviation
Cost	Baseline Budget	$300K	$22,930K	$100,000K	$33,200K
	Actual Cost	$500K	$36,540K	$150,000K	$53,110K

5.2. Analysis based on the level of damage

The respondents were asked to provide information about the damage level of the affective transportation infrastructures resulting from a hurricane in which they were involved. The results are shown in Figure 3.

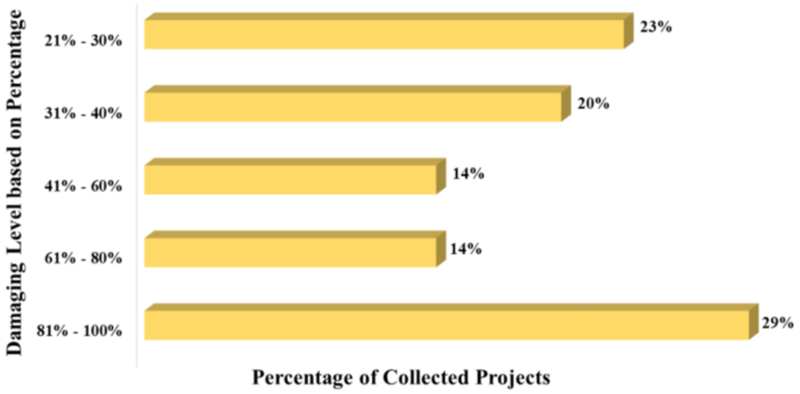


Fig. 3. Damage level of disasters based on the percentage

Figure 3 illustrates that about 45% of hurricanes damaged more than 60% of the transportation systems. In addition, roughly 35% of the transportation systems were damaged from 30% to 60%. As presented in Figure 5, the minimum damage level of transportation infrastructures was 21%.

6. Quantitative analysis

6.1. Significant CFRCs affecting the overall cost of reconstruction projects

The P-Values corresponding to the significant CFRCs affecting the cost performance of reconstruction projects are shown in Table 5.

Table 5. Significant CFRCs affecting cost performance

Category	List of CFRCs	*P*-Value
Physical Characteristics	CFRC1. Number of main/truck lines	0.051*
	CFRC2. Total length	0.049**
	CFRC3. Level of complexity	0.036**
	CFRC4. Distance from highly populated area	0.078*
Damaging Level	CFRC5. Level of damage	0.044**
	CFRC6. Level of traffic disturbance	0.196
Resource	CFRC7. Shortage of experts	0.011*
	CFRC8. Shortage of field laborers	0.054**
	CFRC9. Productivity level of contractors	0.069*
	CFRC10. Shortage of materials	0.077*
	CFRC11. Shortage of equipment	0.017**
	CFRC12. Inflation of labor wages	0.096*
	CFRC13. Availability level of on-site infrastructure	0.080*
	CFRC14. On-site accommodation level for staff	0.350
	CFRC15. Shortage of supplier	0.065*
Quality	CFRC16. Quality issues of materials	0.018**
	CFRC17. Quality issues of equipment	0.011**
Project Management	CFRC18. Frequency level of logistics/management issues	0.013**
	CFRC19. Quality of on-site inspection	0.072*
	CFRC20. Frequency of on-site inspection	0.422
	CFRC21. Information management	0.045*
	CFRC22. Pace of decision-making process	0.020**
	CFRC23. Implementation level of risk management	0.012**
	CFRC24. Coordination	0.046**
	CFRC25. Pace of workers' mobilization	0.258
Environment & Safety	CFRC26. Volume of debris	0.082*
	CFRC27. Environmental/safety issues prior to execution of the project	0.033**
	CFRC28. Work suspension through execution of the project	0.060*
Legal	CFRC29. Regulatory requirement	0.205
Local	CFRC30. Availability of required temporary pathways	0.163

*** denotes significant differences with 95% confidence*
** denotes significant differences with 90% confidence*

As there were three types of data (continuous, seven-point Likert scale, and binary) collected from the survey, the two-sample t-test, Kruskal-Wallis, and Chi-squared test were performed. As presented in Table 5, the 30 CFRCs identified by the literature were classified into eight categories: (1) physical characteristics, (2) damage level, (3) resources, (4) quality, (5) project management, (6) environment and safety, (7) legal, and (8) local. Table 5 presents that 24 out of 30 identified CFRCs were determined statistically significant for the cost performance of the targeted projects.

CFRC-3 (level of complexity), which belongs to the category of project characteristics, is an indicator that if a reconstruction project is complex, an increasing number of reworks is more probable due to errors made because of deficiencies in the laborers' knowledge and/or experience. Ultimately, these reworks might increase the cost of reconstruction. Since financial limitations are common after a disaster, the stated CFRC significantly decreases the cost performance.

Table 5 presents that low-quality materials (CFRC-16), belonging to the category of quality, and low quality of equipment (CFRC-17), belonging to the category of quality, lead to their replacement during the reconstruction process, which causes serious shortages in materials and equipment and increases the number and cost of overruns.

6.2. Classification of CFRCs affecting cost performance of low and high damage levels

The results of the P-Values of the CFRCs that affect the cost performance of infrastructures damaged at different levels is shown in Table 6. Twenty-six (26) CFRCs were determined statistically significant for highly damaged reconstruction projects and 19 CFRCs were recorded as statistically significant for low-level damaged reconstruction projects.

Table 6 indicates that when the damage is greater, more attention must be given to the factors that affect reconstruction cost. For example, when the level of damage is low, the level of complexity (CFRC 3) is less. and this CFRC does not affect the cost of reconstruction. However, when the level of damage is high, the complexity of the reconstruction is also probably high and creates the possibility of reworks and resulting overruns. Similarly, the level of traffic overruns (CFRC 6) is a significant factor for high-damage reconstruction costs but not a significant factor of low-damage reconstruction work.

Table 6. Significant CFRCs affecting cost performance of low and high damage transportation infrastructure

Category	List of CFRCs	*P*-Value	
		Highly Damaged	Low Level Damaged
Physical Characteristics	CFRC1. Number of main/truck lines	0.040**	0.022**
	CFRC2. Total length	0.025**	0.034**
	CFRC3. Level of complexity	0.068*	0.534
	CFRC4. Distance from highly populated area	0.056*	0.036*
Damage Level	CFRC6. Level of traffic disturbance	0.011**	0.397
Resource	CFRC7. Shortage of experts	0.001**	0.017**
	CFRC8. Shortage of field laborers	0.022**	0.075*
	CFRC9. Productivity level of contractors	0.078*	0.041**
	CFRC10. Shortage of materials	0.081*	0.082*
	CFRC11. Shortage of equipment	0.065*	0.037**

	CFRC12. Inflation of labor wages	0.055*	0.031**
	CFRC13. Availability level of on-site infrastructure	0.063*	0.061*
	CFRC14. On-site accommodation level for staff	0.325	0.197
	CFRC15. Shortage of suppliers	0.035**	0.487
Quality	CFRC16. Quality issues of materials	0.012**	0.059*
	CFRC17. Quality issues of equipment	0.062*	0.085*
Project Management	CFRC18. Frequency level of logistics/management issues	0.010**	0.063*
	CFRC19. Quality of on-site inspection	0.078*	0.021**
	CFRC20. Frequency of on-site inspection	0.085*	0.258
	CFRC21. Information management	0.058*	0.089*
	CFRC22. Pace of decision-making process	0.071*	0.073*
	CFRC23. Implementation level of risk management	0.008**	0.014**
	CFRC24. Coordination	0.001**	0.051*
	CFRC25. Pace of workers' mobilization	0.061*	0.357
Environment & Safety	CFRC26. Volume of debris	0.044**	0.526
	CFRC27. Environmental/safety issues prior to execution of the project	0.055*	0.070*
	CFRC28. Work suspension through execution of the project	0.091*	0.357
Legal	CFRC29. Regulatory requirement	0.258	0.278
Local	CFRC30. Availability of required temporary pathways	0.195	0.355

*** denotes significant differences with 95% confidence*
** denotes significant differences with 90% confidence*

7. Conclusion

The intensity and destructive nature of natural disasters are gradually and constantly increasing, and with them, the need for reconstruction of infrastructure, including transportation infrastructure, is also increasing. Keeping the reconstruction cost within budget is almost always a priority for practitioners, yet it is often difficult to do. This study identified the factors that contribute to the reconstruction cost of transportation infrastructure after a disaster. A survey was conducted that incorporated the identified factors, and the responses were descriptively and quantitatively analyzed. It was found that effective coordination plays a critical role in completing a project within the allocated budget. Additionally, it was found that a slow decision-making process commonly causes delays in the reconstruction that increase the probability of cost overruns. Moreover, the reconstruction of transportation infrastructures with a high level of damage depends on more factors than those with a low level of damage. The outcomes of this paper will be of value to authorities who are responsible for controlling budget overruns during a post-disaster reconstruction project.

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Challenges in Post-Disaster Housing Reconstruction: Analysis of Urban vs. Rural Communities

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Abstract

Reconstruction of safe and secure housing is commonly considered the most effective means of returning rural and urban communities affected by disasters to pre-disaster living conditions. In addition, the reconstruction process and the degree of its success greatly impacts the community's ability to work through the next disaster. The various challenges that the reconstruction process encounters have been identified, investigated, and analyzed in this study. After reviewing 177 articles in detail, approximately 30% of which pertained to reconstruction of houses after earthquakes, 54 challenges were identified and placed into four categories: general, physical, social, and economic. About 30% of the reviewed articles were studied the challenges of housing reconstruction after earthquake. In addition, the journal of Disaster received the highest frequency (37) among the reviewed papers in which the challenges of housing reconstruction after disaster in urban and rural communities were studied. This study succinctly assists decision-makers and project managers allocate needed resources effectively and improve the performance of post-disaster reconstruction of housing in both rural and urban areas.

Keywords: post-disaster recovery, housing, reconstruction, rural, communities

1. Introduction

Considerable damages that governments cannot prevent often occur from natural disasters [1, 2, 3]. Different parts of the world have been faced recently with numerous natural disasters that have caused substantial losses [4, 5]. For example, when Hurricane Harvey occurred in the southern part of Texas in 2017, it destroyed a considerable number of buildings and houses and displaced residents. This type of destruction is common in both rural and urban areas, and often leads to displacing residents permanently [6, 7].

Multiple studies have been conducted to optimize the post-disaster reconstruction of housing in urban and rural communities and to maximize the outcomes of those efforts [1, 5, and 8]. Even so, few researchers have analyzed the rural and urban challenges simultaneously, which is the goal of this study.

A thorough review of 177 scholarly papers provided the background for investigating the challenges associated with post-disaster reconstruction of housing and formulating the following objectives: (1) identify the challenges, (2) categorize the identified challenges, (3) calculate the frequency that the challenges occur, and (4) rank the challenges based on the frequency of them. The findings of this study can help practitioners assess the challenges associated with post-disaster reconstruction of housing in both urban and rural communities so that they can allocate their resources properly.

2. Research methodology

More than 300 journal articles, conference papers, and research reports published from 2000 to 2019 were studied. More than two-thirds of them were journal papers, and the others were research reports, conference proceedings and dissertations. A four-step methodology was adopted for this study, as presented in Figure 1. Five major databases, including Google Scholar, Science Direct, Compendex, Inspec, and ProQuest were used to collect the articles, and the essential information, like the name of the journal, the disaster type, and the challenges related to post-disaster recovery were presented. As shown in Figure 1, the challenges were categorized, then their frequencies and ranks were calculated.

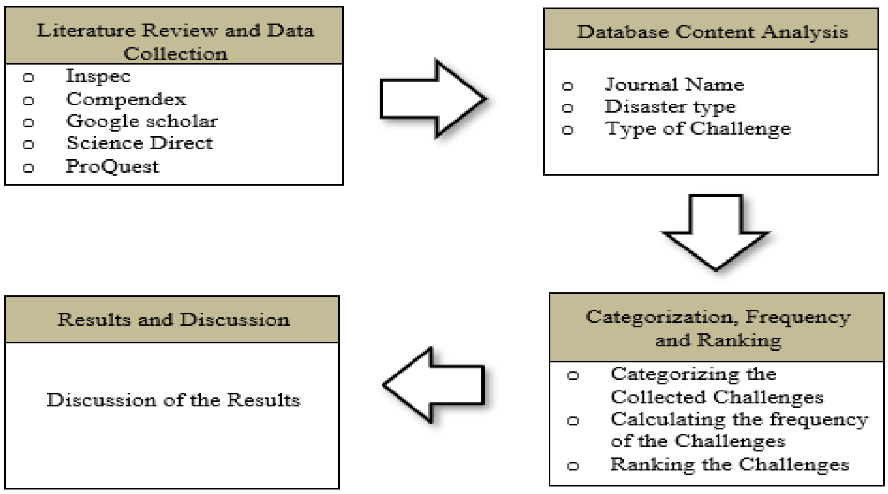

Figure 1. Research methodology

2.2. Journal name

For this study, 177 related journal articles issued by well- established publishers from the years 2000 to 2020 were carefully reviewed to identify the challenges associated with post-disaster reconstruction of housing in both urban and rural communities, and a list of them, with their frequencies and percentages, is presented in Table 1. The first five journals listed published 69 percent of the articles. The Disasters journal, which is published by the Overseas Development Institute, ranked first and was the source of 21% of the total number of the papers. The International Journal of Project Management, which is published in collaboration with the Association for Project Management and the International Project Management Association, ranked second with 16%.

Table 1. Frequency and percentage of reviewed articles based on journals

Journal Name	Frequency	Percentage
Disasters	37	21
International Journal of Project Management	28	16
Communication	22	12
International Journal of Strategic Property Management	19	11
International Journal of Disaster Resilience in the Built Environment	15	9
Journal of Contingencies and Crisis Management	10	6
Journal of Architecture	7	4
Administration & Society	6	3
Computer-aided Civil and Infrastructure Engineering	4	2
Journal of Geographical Sciences	4	2
Eastern Geographical Review	3	2
Habitat International	2	1
Journal of Management in Engineering	2	1
Other journals	18	10
Total	177	100

2.3. Disaster type

The types of disasters were grouped according to various considerations. Some disasters, such as earthquakes, have a sudden impact on society [9], while others like droughts and storms impact the community very slowly [10]. Figure 2 shows the distribution of papers based on disaster type. As shown in Figure 2, about 30% of the articles studied the post-disaster reconstruction of housing after earthquakes.

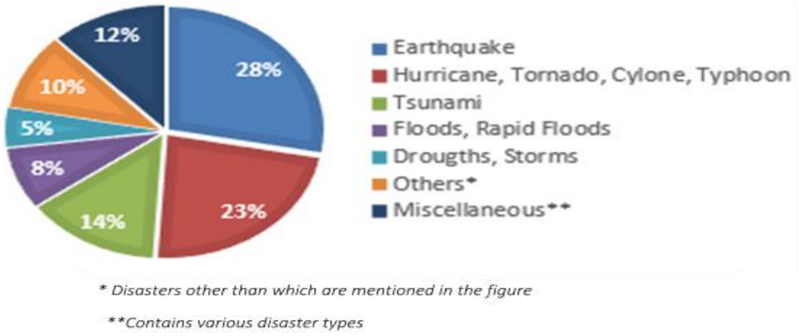

Figure 2. Distribution of papers according to the disaster types

3. Post-disaster reconstruction of housing in urban and rural areas

Post-disaster reconstruction of housing in rural and urban areas presents challenges that are specific to each area. Inspired by the studies conducted by Yilmaz et al. [11] and Alipour et al. [12], the authors of the present review categorized the challenges identified through the existing literature into four main categories: general, economic, social, and physical.

3.1. General challenges

The general challenges are presented in Table 2 and were classified into six main categories: (1) resources, (2) planning and management, (3) land values, (4) occupancy and interaction, and (5) population, and (6) occupation. The frequency of the challenges in each category was counted, and the categories were ranked. As illustrated in Table 2, the challenges belonging to the resource category received the highest frequency (55) and were recorded as the first rank. The challenges belonging to the planning and management category received the second highest frequency (32).

Gur [13] and Arslan [14] believed that the size of the population in the affected area plays a crucial role in the length of time required to complete the housing reconstruction. Since urban areas are usually more populated than rural areas, the reconstruction would be expected to take longer in them [15]. Effective management is another important element associated with housing reconstruction after a disaster [16]. According to the studies conducted by Alipour et al. [12], it is easier to establish effective communication and coordination among those in a rural area because rural communities commonly follow their local leaders, while those in urban communities want to know every detail of the process, making the controlling and management of them complicated [17].

In 2013, Tafti and Tomlinson conducted a study in which it was concluded that the affected families/individuals who own the houses that are destroyed are more willing to participate actively in the process of reconstruction. Accordingly, as rural people are usually homeowners and live in their houses, they are active in the reconstruction process. On the contrary, some of the people in the urban areas are tenants and often do not fully participate in the reconstruction.

Table 2. List of general challenges and their categories, frequencies, and ranking

Category	Challenge	Previous studies	Frequency	Ranking
Resources	• Availability of public facilities • Accessibility to resources • Competing demand for resources • Scarcity of resources	[18, 19, 20, 21, 22, 23]	55	1
Planning and Management	• Institutional capacity for planning and regulation • Inadequate planning • Inadequate operational management related to post disaster recovery • Effective management	[12, 21, 24, 25, 26, 27]	32	2
Land issues	• Land Values • Shortage of land for relocation	[23, 28, 29, 30]	21	3
Occupancy and Interaction	• Ownership status • Type of occupancy • Interaction between neighbors	[13, 30]	16	4
Population	• Level of expectations • Number of population	[13, 14, 31, 32]	5	5
Occupation	• Farming Habits	[18, 23]	2	6

Boen and Jigyasu [23] found that farming habits are a major challenge in rural areas. The farmers they studied, who were relocated from their native place during a natural disaster, were unable to cope with their new environment, as it required changing their farming habits. The land provided to them for farming might not grow the varieties of crops that they were accustomed to growing, and it was sometimes located far from where they were staying. This caused the farmers to abandon the place they were relocated to and return to their native places to rebuild their houses.

3.1. Social challenges

The social challenges associated with post-disaster reconstruction of housing in urban and rural communities were identified by conducting a comprehensive review, and the results are shown in Table 3. The challenges were classified into five main categories: (1) literacy, (2) culture, (3) lifestyle, (4) community, and (5) government services. The frequency of the social challenges belonging to each category that were cited in the existing literature was counted and the categories were ranked.

As indicated in Table 3, one of the critical challenges associated with post-disaster reconstruction of housing is effectively involving the community in the process [33, 34] In 2010, Jha et al. [35] explained that affected people in rural areas participate actively in the process because they know and trust each other and the responsible organizations, and the advertising is very easy, as it consists mostly of just talking to one another. Conversely, the structure of an urban area is usually complicated, and it is difficult to encourage and/or convince the urbanites to participate [36].

Table 3. List of social challenges and their categories, frequencies, and ranking

Category	Challenge	Previous studies	Frequency	Rank
Literacy	• Education level • Level of public awareness	[26, 37, 38]	24	1
Culture	• Cultural disparities after relocation • Level of required privacy	[39, 40, 41, 42, 43, 44, 45]	19	2
Lifestyle	• Poverty, Inequality, and unemployment • Capability of self-settlement • Level of healthcare • Loss of livelihood • Using of modern technology	[23, 33, 46, 47, 48, 49, 50]	15	3
Participation and Mobilization	•Public participation •Insufficient time allowed for community mobilization	[14, 21, 25, 33, 40, 51]	14	4
Government Services	•Local social capital •Availability of social services	[42, 52]	10	5

As presented in Table 3, Peng et al. [47] stated that a community's capabilities play a significant role in the length of time needed to complete housing reconstruction after a disaster. The people in rural communities are usually capable of self-settlement and work hard to expedite the reconstruction process, while urban people are more dependent on governments and other responsible organizations doing it for them.

Table 3 indicates that community participation is one of the major challenges. After any disaster, it is very common that the affected people are ignored in the process of decision-making [51]. The lack of public participation overshadows the real demand of the affected people [33, 53].

3.2. Economic challenges

The challenges associated with economics and finance were identified through the existing literature and are presented in Table 4, which shows that the economic challenges were classified into three categories: financial resources, management, and the local economic level. The frequency of the challenges belonging to each of the categories was calculated and ranked.

Table 4. List of economic challenges and their categories, frequencies, and ranking

Category	Challenge	Previous Studies	Frequency	Rank
Financial Resources	• Availability of financial resources • Lack of funding • Extraordinary financial requirements	[54, 55, 56, 57, 58, 59, 60]	41	1
Management	• Availability of multiple source procurement • Availability of economic monitoring • Local economic engagement • Financial management	[19, 37, 43, 58, 61, 62]	14	3
Local Economic Level	• Affordability of essential needs • Income level • Local economic level	[38, 52, 63]	12	5

As indicated in Table 4, the income level of the affected people is a major challenge to housing reconstruction after a disaster [38]. As rural people commonly have a low/limited level of income from occupations such as fishing and agriculture, they cannot afford their essential needs through a post-disaster time [63]. Governments and responsible organizations have to face these economic challenges by distributing and/or investing available funding throughout the process of housing reconstruction.

3.3. Physical challenges

The physical challenges associated with housing reconstruction in both rural and urban areas after a disaster were determined from the existing literature and are shown in Table 5. The challenges were classified into six categories: (1) quality, (2) construction team, (3) design, (4) transportation, (5) safety, and (6) nature of the land. The frequency of the physical challenges was calculated, and then the related ranking was counted.

Table 5 indicates that the sizes of the houses and the number of rooms in them is very important for completing post-disaster reconstruction [38, 64]. In 2010, Onder et al. [33] conducted a study in which they demonstrated that the duration of post-disaster reconstruction in the urban areas may be longer than in rural areas because the houses and rooms in urban areas are usually larger.

Table 5. List of physical challenges and their categories, frequencies, and ranking

Category	Challenge	Previous Studies	Frequency	Rank
Quality	• Quality of construction • Quality of materials	[42, 65, 66]	30	1
Construction Team	• Absence of proper technical assistance • Inexperienced construction management team	[23, 25, 43, 67]	22	2
Design	• Size of houses and rooms • Complexity of design • New or improved building codes	[38, 42, 68, 69,70]	16	3
Transportation	• Availability of transportation services • Distance to city center and other services	[31, 37, 52, 71]	12	4
Safety	• Health and safety management issues • Environmental risk • Exposure to hazardous materials	[21, 54, 68, 72, 73]	11	5

Nature of Land	• Complex urban landscape • Geological nature of resettlement site • Remoteness and geography	[72, 74, 75]	4	6

Gok [69] and Gok et al. [70] believed than complex designs make housing reconstruction difficult and more subject to multiple issues. Because the designs of urban houses are usually more complex than those of rural houses, their reconstruction can be complicated and more subject to schedule delays and cost overruns [76]

As indicated in Table 5, one of the major challenges to reconstruction is the quality and scale of the work [77], which is often far beyond the capacity of the accessible inspectors. After a disaster, the normal regulations, design requirements, and permits are suspended in order to speed up the construction [78] This leads to inspectors with heavy workloads and results in poor inspections [66]. In one case in Indonesia, the poor quality of the housing constructed by a nongovernmental organization was unacceptable to the communities, and about 300 houses were destroyed [65].

4. Conclusion

In this study, 177 articles were thoroughly reviewed to identify the challenges associated with post-disaster reconstruction of housing in urban and rural areas. The challenges were classified into general, social, economic, and physical categories. The frequency of the reviewed journals was then calculated, and their ranking was counted. The results revealed that there are remarkable differences between policies of post-disaster reconstruction of rural housing and urban housing. Additionally, effectively communicating with and coordinating the activities of people in a rural area is easier than it is with people in an urban area. The results also demonstrated that affected families/individuals who own the houses that were destroyed are more willing to participate actively in the process of reconstruction. Accordingly, as rural people are usually homeowners and live in their own houses, they are more active in the reconstruction process. On the contrary, some of the urban people in the affected areas are tenants, rather than homeowners, and they often do not fully participate in the reconstruction process. This study will help project managers allocate resources effectively and enhance the outcomes of post-disaster reconstruction of housing in both rural and urban areas.

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Critical Construction Work Items for Sustainable Hospitals

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Abstract

Currently, the Chilean public health infrastructure presents significant advances in the implementation of sustainable design criteria, with the incorporation of these criteria in the architecture and speciality projects. However, it is possible to observe that during the construction phase of the project there are no standardized verification processes of the project guidelines in these aspects, which could affect the sustainable life cycle of these buildings. Errors in the execution of critical health infrastructure items have various consequences during their operation, such as excessive corrective maintenance, increased in public spending for additional energy requirements from the systems, or discomfort of building occupants (overheating or over-cooling problems). Besides, the technical inspection of public works in Chile focuses mainly on the administrative fulfilment of construction contracts rather than on the verification of the technical aspects of projects. This problem establishes the need to analyze the critical items that must be verified on-site to ensure that the sustainability criteria delivered during the design stage are executed correctly, allowing a sustainable operation of these buildings over time. Then, this research focused on determining what the critical items and activities that should be reviewed on-site, as well as on detecting the possible weaknesses of the project review process are. A survey to professionals involved in the design, construction and inspection of hospital infrastructure was applied. The results were analyzed using the AHP methodology, showing as critical items the thermal envelope (20%) and the thermal and ventilation installations (17%). At the activity level, there was no significant consensus on the most relevant to the review process. There are also differences in the vision of engineers and architects regarding some issues. Finally, the need to have technical regulations that provide procedures and control standards for each item, system and installation from early design phases was identified.

Keywords: public health infrastructure, sustainability, sustainable buildings

1. Introduction

Currently, the public health infrastructure presents essential advances in determining sustainability design criteria, which are reflected in the development of architecture and speciality projects. The incorporation of these criteria arises in the mid-2000s, due to the State's drive to include energy efficiency in public infrastructure as a response to international commitments regarding climate change [1]. However, it is possible to observe that during the construction phase of the public health infrastructure, there are no standardized verification processes of the project guidelines regarding sustainability, which could affect the sustainable life cycle of these buildings. Mistakes in the execution of critical items in the health infrastructure have various consequences during the operation of a building, from excessive corrective maintenance and increased public spending for extra energy, to environmental discomfort for the people who use the building (overheating or over-cooling problems). [2]

For their part, Technical Inspection of public works in Chile focuses on the administrative compliance of construction contracts rather than on the verification of the technical aspects of the projects. A study by the Office of the Comptroller General of the Republic [3] indicates that the most relevant observation in public health work contracts is the failure to comply with technical aspects. In contrast, other academic studies verify that the flaws in the design processes are the main factor that affects the problems that are triggered in the works [4]. This problem reflects the need to have protocols and construction standards incorporated from the beginning, at the design stage and accompanied by a technical inspection of work focused on the correct functionality of the characteristics of the systems and facilities in hospital establishments. The research focuses on a survey carried out on professionals who participate in the design, construction and supervision of hospital works. The results are analyzed with the AHP methodology to rank the critical items and the critical activities and also detect the possible weaknesses that these professionals observe in their work.

2. Methodology

The present study has been divided into two stages. In the first stage, a summary and analysis of the context of hospital establishments in Chile are presented, to understand how they manage the design, tender and construction phases, deepening in the processes related to the technical inspection of works. This stage ends with the presentation of the minimum design requirements needed for energy efficiency and sustainability in operation in Hospitals. This information is the basis for identifying the critical items that need to be reviewed in the execution stage of hospital centres in Chile. In the second stage, the critical items are selected through a survey applied to different experts in the area. The results were analyzed using a multi-criteria prioritization method (AHP).

3. MINSAL's role in public health building

The Chilean Ministry of Health (MINSAL) has within its functions to set the policies and regulations for investment in infrastructure and equipment of the public establishments that make up the healthcare networks [5]. For such purposes, the Under secretariat of Assistance Networks oversees regulating and supervising the operation of health networks through the design of policies, regulations, plans and programs for their coordination and articulation. Within this undersecretary, a division manages the resources available to finance initiatives in infrastructure and health equipment. Each project or action must comply with all the regulatory requirements that emanate from the MINSAL regarding sanitary provisions, quality of care and user satisfaction. In this sense, MINSAL is responsible for generating investment plans in health infrastructure, as well as the criteria and guidelines with which the designs, construction and operation of new health facilities, will be developed.

4. Hospital establishments

Hospitals correspond to closed care establishments, which provide health benefits in a continuous care regime (24 hours) and which must have organized resources of infrastructure, equipment, and personnel necessary for their permanent operation. Hospitals provide comprehensive, general, and/or specialized care, aimed at providing health benefits for the recovery, rehabilitation and palliative care of sick people and are empowered to admit patients with bed occupancy. Currently, hospital establishments are configured with an ambulatory care area attached (medical consultations, procedure rooms, therapeutic, diagnostic support units, and emergency) and complementary to closed care where hospitalizations are mainly located. In Chile, hospitals are highly relevant to meet the health care needs of the population. However, the national health infrastructure is in a deficit situation, which is evidenced by the lack of hospital beds by the number of inhabitants. This situation has generated, in the last decade, the development of investment plans in hospital infrastructure that allow strengthening the existing healthcare network. Despite the efforts made, the latest diagnosis carried out in 2018 indicates that 80% of hospitals still fail to comply with the current infrastructure quality standard, due to the age of their buildings and 63% of facilities have a structure before the 80s [6].

4.1. Design and execution process of hospital works

The development of Health projects is carried out through public bidding under different types of contract and work. This type of contract generates a close collaboration between the public sector (Ministry of Health), manager of the initiatives, and the private sector (Consulting, Architecture, Engineering and Construction Companies) in the planning, programming, preparation of preliminary projects and development of the projects, both low and high level of medical and technological complexity of establishments. The plans go through the following stages from the investment idea to the operation:

- Hospital Pre-investment Study: it defines the number of atributes that the establishment will offer, the number and size of the facilities, the management model, human resources, medical equipment, and financial sustainability. Besides, during this stage, the site is selected.
- Design: the Pre-project sub-stage is carried out, in which architecture is defined at a basic level of development as well as the design criteria of the corresponding specialities. Also, the Project sub-stage is carried out, where the design of architecture and specialities is developed at a level suitable for execution. Products include detailed engineering and planimetry, technical specifications and BIM modelling.
- Execution: During this stage, the designated construction company executes the works according to the approved in the design, planimetry and technical specifications of architecture and specialities and the provisions of the contract.

4.2. Technical inspection of public hospitals

In Chile, there is no detailed procedure for the inspection of hospital works. Although there is a Technical Works Inspection Manual [7], its scope is aimed at the inspection of social housing and its items, extending overtime to paving projects and green areas [3].

Thus, a study on observations and recommendations in the execution of public works contracts carried out by the Comptroller General of the Republic between 2012 and 2015, showed that a large part of these observations is directly related to the role of the technical inspection of works, highlighting non-compliance with technical regulations (27%). Compliance with technical regulations groups together all the relevant observations associated with breaches of both the technical bases, be they technical specifications, plans and/or memories of structural calculation, as well as existing regulations applicable to the contract, such as the Chilean INN Standards, the Roads Manual of the MOP, the General Law of Urbanism and Constructions, and its ordinance, and in the case of health, special regulations for hospital infrastructure buildings such as the Basic Technical Standards for Closed and Open Care [3]. The same study shows that 51% of the works observed have a relationship with health establishments. On the other hand, Moscoso [3] indicates that public hospital projects, generated inside the traditional contracting system, do not include the technical inspector in early design stages, which is why two main problems arise. First, activities are generated that do not add value. Since the technical inspector is hired or assigned at the start of the work, he must invest time in studying the project and all the administrative documents that are part of the work. Second, the contribution and experience that the technical inspector can deliver in the early stages of the project, where any modification has a minor impact on its costs, is wasted.

Another study on Technical Inspection of Works indicated that above the typical problems that construction works present, there are a significant number of facts and situations that give rise to conflicts and doubts, not always attributable to a wrong decision by the owner or poor management of the contractor. These conflicts usually have their origin in some of the following causes: projects that do not have an adequate level of detail, which prevents defining with precision and objectivity, the requirements and standards that must be verified by the technical inspector; the parent projects do not have efficient coordination among themselves or with the specialities; the roles and responsibilities that the different agents of the constructive process must assume to varying stages of the projects are not appreciated; analysis and evaluations, essential for adequate and timely decision-making, must be based on uncoordinated and unreliable records; and the indetermination, omissions and errors that the administrative bases of the contracts present, give rise to a significant number of conflicts in the relationship between the parties.

4.3. Sustainable construction in public hospitals

Since the mid-2000s, the Chilean Ministry of Health has incorporated sustainability criteria in the designs of health facilities. The first efforts around sustainability are focused on energy efficiency, establishing envelope specifications (walls and windows) with better thermal behaviour. It reduces energy demands for the thermal conditioning of the enclosures, as well as the incorporation of more efficient active systems (air conditioning and lighting systems). Since 2010, the Chilean government the planning of new infrastructure because of the earthquake of February 27 of that same year. This reconstruction focused on a series of establishments with structural damage in the areas affected by the earthquake. Currently, the concept of sustainability has been attempted to incorporate in the designs of health establishments in a comprehensive way, recognizing the social, economic, and cultural fields.

The sustainability attributes of hospital establishments, addressed during the design, need to be audited and finally operated in the way they were projected. In this way, the initial sustainable objectives will be achieved. The proper functioning of the systems and facilities is relevant, by scheduling the correct management of maintenance and operation of these throughout the useful life of the building. Following the above, the main critical items that must be audited during the execution of a hospital project should be at least: Envelope; Acoustic Insulation; Finishing; Sanitary Facilities; Lighting and Electrical Installations; Thermal and Ventilation Installations; Non-Conventional Renewable Energy Systems, Landscaping and Waste Management.

5. Multi-Criteria Analytic Hierarchy Process (AHP) methodology

In this process, a weight (wi) is calculated for each alternative, making a two-by-two comparison of all the criteria. The method that has been chosen is the Analytic Hierarchy Process (AHP) of Saaty [8] due to its high popularity to determine the prioritization in varied problems such as politics, social aspects, personal desires, education, industry or engineering [9]. The AHP uses an underlying scale with values from 1 to 9 to rate the relative preferences of the two elements, being 9 an extremely preferable preference and 1 a neutral preference between the two pairs. With these values, a square matrix [A] is obtained that contains paired comparisons of alternatives or criteria.

A is said to be a matrix of paired comparisons of n alternatives if a_{ij} is the measure of the preference of the alternative in row i when compared to the alternative in column j. When i = j, the value of a_{ij} will be equal to 1 since the alternative is being compared with itself. Then, to determine whether or not a consistency level is "reasonable," we need to develop a quantifiable measure for the comparison matrix Anxn (where n is the number of alternatives to be compared). It is known that if matrix A is perfectly consistent, it produces a normalized matrix Nnxn of elements w_{ij} (for i, j = 1, 2, ..., n), such that all columns are identical, that is, $w_{12} = w_{13} = ... = w_{1n} = w_1$; $w_{21} = w_{23} = ... = w_{2n} = w_2$; $w_{n1} = w_{n2} = ... = w_{nn} = w_n$.

It is then concluded that the corresponding comparison matrix A can be determined from N, dividing the elements of column i by wi (which is the inverse process of determining N from A). This is how the consistency ratio (CR = CI/RCI) is calculated. This ratio or quotient is designed such that values exceeding 0.20 are a sign of inconsistent judgments. CR values of 0.10 or less are a sign of a reasonable level of consistency in paired comparisons. In contrast, values between 0.10 to 0.20 are moderately consistent since in the value judgment, some alternatives have the same degree of importance for the evaluator. In these cases, the decision-maker is likely to want to reconsider and modify the original values of the matrix of paired comparisons. For its part, the CI value is the consistency index of the matrix A = (λmax – n) / (n-1), where n is the number of alternatives and λmax is obtained by calculating the vector column A and then adding its elements. RCI is the random consistency index of A = 1.98 (n-2)/n, with n being the number of alternatives.

6. Analysis of responses

To obtain a hierarchy of the items (E: Envelope; AI: Acoustic Insulation; F: Finishing; SF: Sanitary Facilities; LEI: Lighting and Electrical Installations; TVI: Thermal and Ventilation Installations; REn: Non-Conventional Renewable Energy Systems, L: Landscaping and WM: Waste Management) that must be inspected on a hospital to ensure the sustainability of the building in operation, experts from the design and technical inspection of health establishments were surveyed. The group of experts was selected considering experience in the design and monitoring of health projects of at least 5 years, and direct involvement in the technical inspection of works in establishments currently under construction. The professionals consulted were 9 architects and 7 engineers with experience in design and monitoring of hospital establishment projects, as well as 10 technical inspectors with direct experience in technical inspection of public hospital establishments in execution.

Regarding the hierarchy of the items to be audited during construction to meet sustainability requirements in the operation stage, preference of 20% is observed for the envelope, followed by Thermal and Ventilation Installations with 17% and then Finishings and Non-Conventional Renewable Energy Systems with 13%, hence the consistency was 0.20. Finally, the three least voted elements were Landscaping, Acoustic Insulation and Waste Management with 7%, 6% and 5% (Table 1).

Table 1: Hierarchy of each item to be audited in the construction stage to ensure that the occupation/exploitation of the building complies with sustainable standards - Source: Own Elaboration

Hierarchy	E>TVI>F=REn>LEI>SF>L>AI>WM								
Construction ítem	E	AI	F	SF	LEI	TVI	REn	L	WM	*w*
E	1	4	3	3	3	3	2	1	2	20
AI	¼	1	¼	½	¼	¼	¼	4	1	6
F	⅓	4	1	7	¼	⅓	⅓	3	3	13
SF	⅓	2	1/7	1	⅓	1	1	3	4	10
LEI	⅓	4	4	3	1	⅓	⅓	1	2	11
TVI	⅓	4	3	1	3	1	3	3	3	17
REn	½	4	3	1	3	⅓	1	1	4	13
L	1	¼	⅓	⅓	1	⅓	1	1	1	7
WM	½	1	⅓	¼	½	⅓	¼	1	1	5
λmax	11.47	CI	0.31	RCI	1.54	CR	0.20			

Nomenclature
E: Envelope; AI: Acoustic Insulation; F: Finishing; SF: Sanitary Facilities: LEI: Lighting and Electrical Installations; TVI: Thermal and Ventilation Installations; REn: Non-Conventional Renewable Energy Systems, L: Landscaping and WM: Waste Management

The responses regarding prioritization of the audited activities in the envelope (the item with the highest priority) were separated into two groups. The first group was the suggestions made by the architects and, the second group was the items suggested by engineers and technical inspectors (see Fig. 1), which explains the significant difference in terms of the priorities indicated by each group.

For the group of architects, the priority in the 3 most voted activities was Roofing insulation (25%), thermal enclosure insulation (15%) and Windows (14%). In the envelope activities audit, the 3 most voted activities by the group of engineers and technical inspectors were thermal enclosure insulation (26%), Vapor and Humidity Barrier (16%) and Ventilated Floors Insulation or Roofing insulation (15%). Thermal bridge sun protection windows

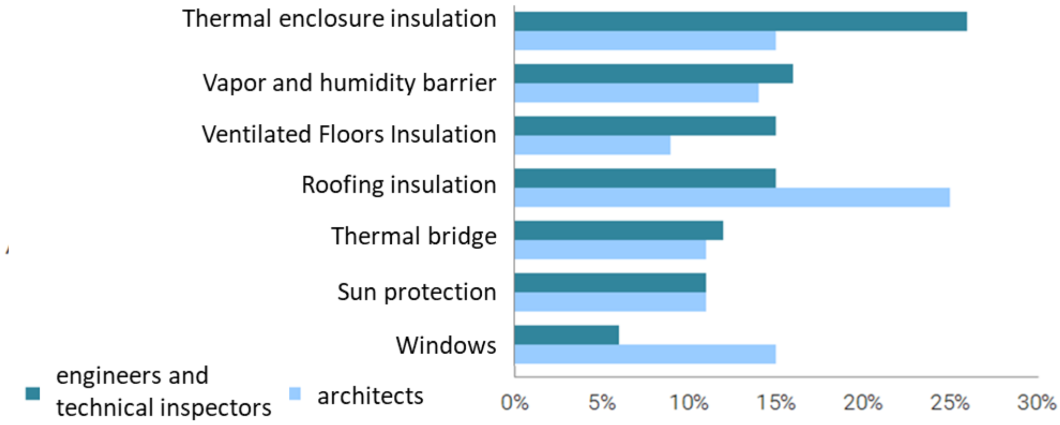

Fig. 1: Prioritization of professional regarding the activities of the enveloping item - Own elaboration

7. Conclusion

MINSAL is currently developing an extensive investment plan in health infrastructure, which considers the construction of 75 new hospitals for the country. Thus, it poses a significant challenge for the health sector to build this new infrastructure under sustainability parameters and to maintain it properly during its operation. Depending on the type of execution contract, the flow of information between the different phases may be hindered, because diverse teams carry out the design, construction and audits in each of them. Besides, These audits are developed in an independent way and without the proper follow-up. Due to the complexity that characterizes health facilities, continuous verification processes are required at all stages to ensure the operation of the projected systems and facilities and, therefore, established sustainability requirements.

On the other hand, the process of surveying experts and then identify through the AHP methodology their opinion regarding critical items to be inspected in hospital works allowed verifying the relevance of each critical element. It was found that the items that should be of most significant concern were the Thermal Envelope (20%), and the Thermal Installations and Ventilation (17%). The answers to the surveys also show the need for technical regulations in Chile that provide procedures and standards for the inspection of systems and facilities. It is necessary to develop coordinated and better quality projects from the design phase. The contribution of a specialized professional at the early stages of the design is also recognized.

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Designing Sustainable Gabion Houses for Haiti Using Local Resources

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Abstract

Many concrete masonry unit (CMU) block homes have been constructed recently in Thoman, Haiti using volunteer labor under the supervision of But God Ministries. The average cost of construction is $5,000 per home and is dependent on availability and willingness of volunteer labor. Thoman's landscape is covered in loose rocks, largely due to dried up river beds. A sustainable home design which utilizes this abundantly available resource could drive down construction cost and reduce the need for volunteer labor. Gabion walls are wirework containers filled with rock or rubble. Though they are typically used in the construction of dams and retaining walls, they have successfully been used to construct other various structures including structural foundations (Liu, 2012), commercial construction (Conti, 2016) and residential applications in developing countries (Potangaroa, 2013). This research includes the physical construction of an L-shaped wall to determine the effectiveness and feasibility of constructing gabion homes in Thoman, Haiti. The physical wall model consists of a 2-foot wide by 6-inch deep concrete foundation, 8-foot tall wall cages of 10-gauge concrete reinforcing mesh with 6-inch by 6-inch openings, No. 1 aggregate wall infill, and stucco finish on both sides. The total length of wall is 16-feet, with one 10-foot leg and one 6-foot leg. Scaled models of three different roof structures were constructed and analyzed to determine which material systems would best serve the intended purpose for the gabion home design. The roof systems tested include wood frame, angle iron frame, and PVC frame, each of which was topped with corrugated metal roof panels. Two methods were tested for airflow which include corrugated plastic panels and mesh screens. The research findings suggest that chicken wire should be added to the proposed design to serve as a liner for the gabion baskets. The added wire helps secure smaller river rock and provides additional surface area for stucco adherence. The recommended cement to sand mixture for stucco was found to be 1:1. The angle iron framed roof proved to be the most effective of the three roof systems tested because of its availability, strength, and durability. Finally, the mesh screens were chosen to be the most effective roof ventilation method as it was shown to provide more airflow through the structure. Future research should analyze the strength and lifecycle of the final proposed design and evaluate alternate roof systems.

Keywords: gabion, rubble, house, sustainability

1. Introduction

The January 12, 2010 Haiti earthquake destroyed almost 20% of the buildings in Port-au-Prince and killed nearly 250,000 people. While the earthquake is not categorized as "great" from seismic standards, its damages rank it as one of the deadliest earthquakes of the 21st Century [1]. The reasoning for such extensive damage from this earthquake stems from the fact that Haiti is the poorest country in the Americas and a majority of homes are self-constructed and not built to any seismic codes [2]. An estimated 89% of the fatalities in Haiti resulted from faulty building construction, such as the use of masonry without any reinforced steel [2]. Evidence suggests that the earthquake would not have been so devastating if proper construction techniques had been applied. For example, the U.S. Embassy in Haiti was constructed with concrete walls and only suffered minor damages [2].

Thoman, Haiti is a rural village just 50 miles east of Port-au-Prince. Currently, CMU block housing is the predominant type of house being built by volunteers with But God Ministries. The average cost to build CMU block house is roughly $5,000 and volunteers typically travel down to Thoman to build it. There is a strong need for this research because Thoman's landscape is covered in loose rocks that would be the perfect natural resource for a gabion wall house. Gabion walls are wirework containers filled with rock or rubble and are typically used in the construction of retaining walls. A sustainable, repeatable house design that utilizes the loose rock abundantly available in Thoman could drastically decrease the cost to construct homes for Thoman residents and minimize the dependency on American volunteers to build houses in the region.

2. Literature review

2.1. Introduction

A gabion is a wire cage filled with rocks or rubble and is typically used in the construction of retaining walls for erosion control. The cages can be vertically continuous or shorter and stacked on top of each other to form a wall [3]. Gabions can vary in thickness depending on their intended use and the cages can either have a polygonal net or a rectangular net. The idea of modifying the design of traditional gabions to expand their applications beyond retaining walls is not a new one. Gabions have previously been used in structural foundations, commercial construction, and residential construction in developing countries.

2.2. Sustainable housing and construction

Sustainable housing offers both environmental and financial benefits that are supported in research, both quantitatively and qualitatively. Some of these benefits include better construction materials available for construction, savings that outweighed the cost of buying sustainable appliances vs. unsustainable appliances current cost, a better payback period in regards to sustainable techniques, and the ability for sustainable housing to be built under controlled costs [4]. Many of the characteristics that gabion cages have make them very good options for sustainable housing in developing countries. They are durable, require no power tools for modification, utilize natural resources, and they can be built using an unskilled labor force. When it comes to sustainability, the steel of the gabion cages is expensive in terms of the energy used in its production and recycling processes, but the material itself can be recycled many times.

2.3 Previous work

Previous research shows that the use of gabion cages has been explored for various construction uses in underdeveloped areas, including the places listed below. Interviews were conducted with a representative involved in construction for each individual location to ascertain best practices and lessons learned.

- Nepal – Rubble from destroyed buildings was used to fill cages and rebuild structures after earthquakes [5].
- Grande Goav, Haiti – River rock from dried up river beds was used to fill cages and construct houses after the 2010 earthquake [6].
- Lilavois, Haiti - Crushed rubble was used to fill cages and construct houses as part of disaster response after earthquake devestation [7].
- Port-au-Prince, Haiti – Researchers at Kennesaw State University developed a gabion house design and built a prototype on campus then implemented the design in Port-au-Prince [8].

Although great information was gleaned from all three of the interviews listed above, the research conducted at Kennesaw State University [8] produced a detailed design that simply needed refinement to adapt the structure for use in Thoman.

2.4 Design considerations

With there being no form of electricity in rural villages of Haiti to combat hot climate in the warmer months, it is imperative that the gabion house be designed in a way that promotes natural airflow. This aspect of the design will be a collaboration between the roof and the walls of the house. Key openings that facilitate airflow need to be established on the walls and openings to promote circulation as well as improve air quality and indoor air temperature. Previous research analyzed the natural ventilation quality of a traditional Malay house by measuring temperature, humidity, and wind speed of the house [9]. The results stated that the indoor temperature and relative humidity was lower than the outdoors, indicating that having maximum openings on the walls of the house leads to high air intakes and puts an emphasis on cross air ventilation.

Aside from openings, there are novel ways for roof designs to promote ventilation. A previous study focused on the effect of solar chimneys inclination rate on air ventilation rates [10]. This study measured exit air velocity at increasing inclination angles and determined that the optimal angle is between 45 and 75 degrees. Another discovery was that air reached deeper into the interior room as the inclination angle increased. While a solar chimney would be an effective way to promote ventilation, the scope of this research limits the amount of available resources and including a solar chimney in the design of the gabion house is impractical.

3. Research methodology

A methodology was formulated based on the knowledge gained from the literature review. The published research on gabion houses and the interviews conducted were used to formulate a basic gabion house designs and 3 basic roof designs for testing. The research proceeded in the following steps.

- Create basic design drawings of gabion house
- Construct gabion wall prototype
- Construct 3 roof prototypes for comparison

SketchUp was the primary tool used to create design drawings. While there is an abundance of online design software available, many products require the user to purchase a license. The fact that SketchUp is free is important since the future users of the drawings will include non-profit organizations and volunteer organizations. Additionally, the design itself was simplistic, so complex programs like Revit were not necessary for this project. The preliminary design is shown in Figure 1, below.

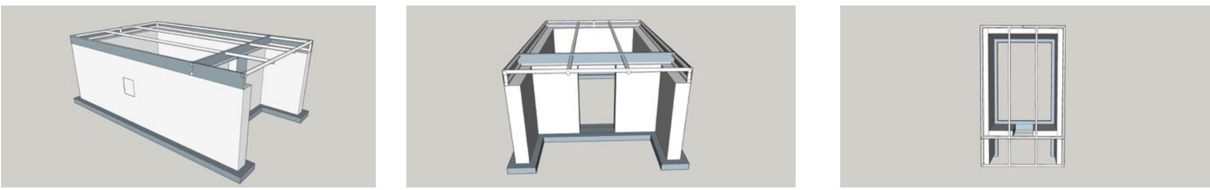

Figure 1: Sketchup model of Gabion House

The physical construction of a portion of the gabion house was completed at the McWhorter School of Building Science (BSCI) field lab on Auburn University's campus. Different fill materials and methods were compared and the design's foundation system was analyzed. A corner of the proposed design (L-shaped wall) was constructed. Construction of an L-shaped wall rather than a full-scale model allowed a reduced cost and complexity while providing a sufficiently detailed analysis of the proposed wall design.

Three roof prototypes were also constructed at Auburn University's BSCI field lab. The first roof model analyzed was a wooden roof frame which was chosen for its simple design. The concern for this model is that wood is not readily available in Haiti, so it may be difficult to implement this system in the village of Thoman. The second model tested was a single-slope PVC pipe frame which was chosen for its ease of construction. The third roof prototype built was an angle iron roof frame due to its perceived strength and material longevity.

4. Results and discussion

4.1 Foundation

The extensive interview with Fatih Oncul at Kennesaw State University [8] was the strongest influence on the design and construction of the foundation for the L-shaped wall. The wall's final foundation design was 6-inches wider than the wall on each side, making its total width 2-ft with a depth of approximately 6-inches. The concrete mix consisted of 1 part Portland cement, 2 parts sand, 3 parts aggregate, and water. To mimic the resources that would be available in Thoman, Haiti, the concrete was mixed with a shovel with a wheelbarrow by hand and poured into the footing. As the concrete was poured, two j-hooks of #4 rebar were placed on the 10-foot wall and one was placed along the 6-foot wall. A level was also used to periodically check if the foundation was level between the rebar reference points.

4.2 Wall cages

The cages used for wall framing were constructed by hand with wire cutters and pliers from a 5-ft x 150-ft roll of 10-gauge concrete reinforcing mesh with 6-inch x 6-inch openings. Two 6-ft tall cages were constructed for the L-shaped wall; one was 10-ft in length and the other was 5-ft in length. Both cages had cross bracing every 1-ft which created 1-ft x 1-ft columns. In order to assemble the cages, the wall panels were cut to their appropriate dimensions with 3 inches of wire left on all sides so they could be bent around to secure the pieces together. For the 10-ft wall, two panels, 5-ft each in length, had to be connected together by laying a 1-ft width panel over the seam of the two 5-ft panels and then bending the wires around to connect them. Before assembling the panels together, chicken wire was placed on the interiors of the panels to prevent smaller rock from spilling out of the cage openings. Additionally, tie wire was placed on both ends of the L-shaped wall. It was zig-zagged down from the top of the cage and provided the wall with additional lateral strength. The tie wire was also used to connect the two separate pieces of the L-shaped wall; tie wire was wrapped around the interior and exterior connection points of the two wall segments. Figure 2 provides visual representation of the gabion walls gages resting on the hand-mixed concrete foundations.

Figure 2: Foundation & Wall Cages

4.3 Cage fill and stucco

The gabion wall cages were filled with #1 aggregate from Martin Marietta Quarry in Auburn, AL. This aggregate was selected to mimic the approximate size range of river rock near Thoman, Haiti. The aggregate size ranged from as small as a golf ball to as large as a softball. Previous research utilized concrete rubble to fill the gabion baskets [8]. It was noted that the river rock in Thoman are much more dense than the aforementioned concrete rubble. To prevent bulges in the gabion wall baskets due to this extra weight from the river rock infill as opposed to concrete rubble, only every other column was filled with rock initially.

While attempting to fill only every other column with the aggregate, it was discovered that chicken wire needed to be placed against the cross-bracings to prevent the rocks from spilling into the adjacent columns. The rocks spilled through the opening which resulted in a slower fill process and every column ended up being filled at least 3 feet high. Through some trial and error, the most efficient fill process was filling a bucket with river rock and then dumping them into a cage column, but additional chicken wire on the cross bracings would significantly accelerate the process in the future.

The design included a concrete stucco on both sides of the wall to strengthen the structure and promote water resistance. A 50/50 mixture of Portland cement and sand with water proved to be the best consistency of mix to stucco the cages. The mixture adhered easily to the structure and eliminating gravel from the mix gave it a more refined finish. Only part of the L-shaped wall was covered in stucco due to budget limitations of the research, however, the full design provides a fully-stuccoed finish on all surfaces. Additionally, construction of the mock-up wall revealed that in order for the entire house to be stuccoed, all of the cages must be filled with river rock or a material other than chicken wire must be used to allow the stucco to fully adhere to the structure. Figure 3 shows the rock-filled wall cages as well as the partial stucco application.

Figure 3: Filled Wall Cages

4.4 Windows

The inclusion of a window into this wall was simpler than originally anticipated. The design called for two 2-ft x 2-ft square windows to allow ventilation and natural air flow through the proposed structure. To test constructability of this design, a window was incorporated into the L-shaped wall. In order to prevent sagging of the top of the window, five pieces of #4 rebar were laid across the opening and extended further than the window's width on either side. The space above the window opening was filled with river rock. Figure 4 shows the window frame details.

Figure 4: Window Opening

4.5 Roof

Each of the three roof prototypes constructed were built at a ¼ scale. The first roof model constructed was a wood-framed structure built at a 1 in 12 slope. After the wooden frame was complete, a simple metal roofing panel was attached to the top. Corrugated plastic panels with ventilation holes were added to the sides of the frame to complete this prototype. The total cost of materials for the wood-framed prototype was $48.92.

The angle iron roof consisted of a single-sloped roof with a slope of 1 in 12. The structure was made entirely of angle iron with an overhang of 8.75-inches on the front and back end of the roof and 13-inches on either side. The lengths of overhang with this design were flexible measurements in order to adjust for error during construction and to minimize waste. A metal roofing panel was added to the top. Although no gable ventilation was provided, the proposed ventilation for this model consists of corrugated plastic, similar to the wood-framed model. The total cost of materials for the angle iron-framed prototype was $278.04.

The basic design of the PVC pipe roof frame is similar to the wood and angle iron systems. The PVC pipes were pieced together with connectors and adhered with all-purpose cement. A simple metal roofing panel was attached to the top of the PVC frame while meshing was added to the sides to provide ventilation. The total cost of materials for the PVC pipe-framed prototype was $133.65.

Figure 5 shows the completed frames for each of the three roof prototypes built. Though the wood-framed prototype was the least expensive and simplest to construct, the availability of wood in Thoman is limited and the susceptibility of the material to rot is troublesome. The PVC pipe-framed prototype proved to have limited strength and was more complex to construct than the wood frame. Although the angle iron-framed prototype was the most expensive of the three, its inherent strength and durability make it a viable choice for the final recommended design.

Figure 5: Iron, PVC, and Wood Roof Prototypes

6. Conclusions and recommendations

The research presented herein indicates that a gabion house is a legitimate alternative to the current CMU block houses being built in Thoman, Haiti. The feasibility of the gabion design is dependent on future tests to determine is the cages are strong enough to support the river rock that is found in Haiti. If the cages can be completely filled with the local Thoman river rock without bulging or breaking, then the gabion house model could prove to be a better financial option than the CMU block houses currently being built in the region.

After constructing multiple scaled roof models with different materials, angle iron is the recommended roofing material because if its availability, strength, and durability. While wood would typically be the first choice because if its simplicity, workability, and economy, its lack of availability in Haiti makes it less desirable for this application. PVC was very easy to assemble, but the strength of the material and connections is lacking compared to angle iron or wood. One of the disadvantages to angle iron, as discussed in chapter 4, was the difficulty that came with welding. For the roof system to be assembled onsite, welding equipment and experience welders would need to be present in Haiti.

Two options were tested for airflow: mesh screening and clear plastic corrugated paneling. The mesh screening is the recommended for this application as it was found to provide the most airflow which will lower the indoor thermal temperature in the Haitian houses which typically do not have Heating, Ventilation, and Air Conditioning (HVAC) systems.

Future research should consist of quantitative experiments to analyze the exact strength and life cycle of the materials and design proposed herein. Additionally, qualitative experiments should be conducted to determine the ease of implementation of the proposed wall and roof designs within the community in Thoman, Haiti. This future research should assess the availability of welders and angle iron in Thoman to determine the feasibility of using the proposed roof design. Finally, future research should include a detailed construction cost analysis of the proposed design as compared to other methods currently used in the region of Thoman.

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Digital Fabrication of Contemporary Structures in Architectural Design Optimization

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Abstract

Trends in contemporary architecture are constantly changing the quality of engineering solutions through broadly understood optimization. The designers, as never before, are facing the possibility to adjust the material and manufacturing technology to desired aesthetic outcomes, by not only the material usage but also the self-organization of the optimization of the structure. The development of modern computational software and the ability to modeling structural forms in non-Euclidean geometry while using algorithms lead designers to new fields of designing and constructing. Parameterization of modeling tools and processes caused an increase in interest in bionic and biomimetic inspirations. It is expressed by imitation of the structure and behavior of living organisms. Such actions enabled the implementation of ideas as *forms follow energy* and *forms follow forces*. Analysis of the morphology of structural forms as well as generative modeling based on logical patterns taken from Nature are one of the contemporary tools of designing. Nowadays, the development of building technologies is strongly supported by digital techniques of manufacturing building elements, which has a significant impact on the architectural detail shaping. Geometrically complex forms are generated as non-modular elements; due to the rapid growth of digital fabrication (components with different shapes are made individually - cut out by CNC machine tools, printed, cast). with outstanding precision). A vital element of new technologies development is the search for new materials and the improvement of manufacturing methods at the same time. The article presents new tools and methods for the optimization of structural elements on selected examples.

Keywords: Architectural Design Optimization, digital fabrication, fabrication, generative design

1. Introduction

Trends in contemporary architecture are constantly changing the quality of engineering solutions through the broadly understood optimization process. The designers, as never before, are facing the possibility to adjust the material and manufacturing technology to desired aesthetic outcomes [1]. The information technologies drastically changed the designing process giving the ability to optimize not only the material usage but also the self-organization of the structures [2]. In the process of evolutionary design, which is a part of Architectural Design Optimization, the main focus is not only on the architectural design phase but also on optimizing the construction and object management phases. The 21-century is characterized in Sustainable Development, which stresses that, among others, the AEC sector should reduce energy consumption and greenhouse gas emission. The optimization of the designing process in AEC is still inefficient because each discipline is optimizing its part of the project without a global overview of the whole undertaking [2] [3]. Implementing artificial intelligence (AI) into the designing process accelerated cooperation in the AEC sector since the case studies are still conducted on prototypes of small scale instead of professional practice systems [4].

In contemporary interdisciplinary designing, there is a noticeable approach in prototyping in architectural scale. The ability to create a complex geometry of free-form buildings requires not only the knowledge of designing software (CAD) but also understanding of the manufacturing conditions and restrictions (CAM). Contemporary prototyping requires designers to develop an idea to ready product methodology of working and fully understanding material properties. The *form follows material* statement is nowadays an essential factor of fabrication. The advancing digitalization of designing and fabrication tools faces a slow change in designing awareness. For the first time in history, designers face no strict regimes while using specific construction technologies. Digital fabrication helps to achieve a unique architecture with standard materials such as steel or concrete [5]. In the middle of the 20th-century (1947), Mies van der Rohe referring to a minimalist style, said a maxim '*Less is more*.' This time in architectural design is characterized by the awareness of cost and time reduction achieved by mass production of identical elements. Especially visible in engineering sectors such as car fabrication and assembling of unified elements were factors economic prosperity. In the construction industry, the catalogs of ready-made, available at a place in warehouse building parts become available to quick assembly. Available now, the revolution of choices [6] exposes designers to limitless possibilities of materials, technology, manufacturing. New materials and technics of assembly are being invented. No longer, the cost optimization is connected with unified, identical structural or architectural elements. The Post-Fordism era thanks to the access to digital fabrication and rapid prototyping, allows designing with not seen before precision. Access to digital fabrication in the interdisciplinary designing, where architects, structural designers, material engineers can design a new methodology of creating unique solutions, based on the needs of the building, not on the available or unified materials and their geometries. The best example can be here the brick, which has a standardized dimension in comparison to the 3d printed clay element adjusted to the exact needs of the project.

Nowadays, the development of building technologies is strongly supported by digital techniques of manufacturing building elements, which has a significant impact on the shaping of architectural details. Geometrically complex forms are generated as non-modular elements; due to the rapid growth of conventional fabrication (individual components are made individually - cut out by CNC machine tools, printed, cast). The new language was needed, which does not use traditional technical drawing. An example can be *file-to-factory,* the communication between humans and machines in prototyping. This method, instead of leading the designing process, adapt out results to available technology [7]. The main advantage of this type of rapid prototyping is the ability to sustain the perfect outcomes-the the final product of each individual element. No more the repetitive, utilized elements guarantee the exact manufacture dimensions. As an example of different methods of manufacturing technologies using the same material, which can be a clay is formative and additive digital fabrications. By forming materials, robots or drones are used to assemble brick following a predesigned pattern, while in 3D printing, a clay is printed in layers in order to obtain the required shape [8].

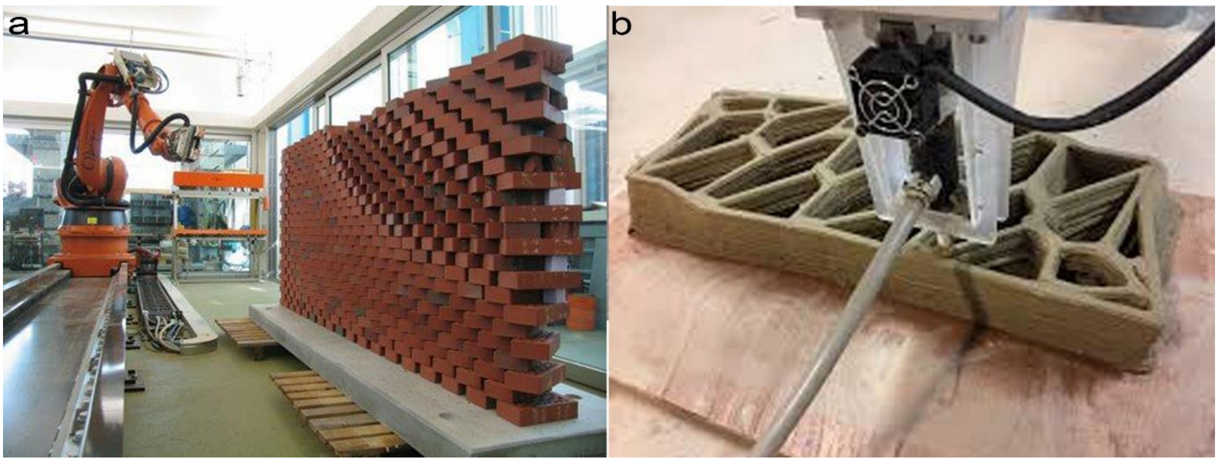

Fig. 1. Examples of fabrication methods using different approach using clay material: (a) Structural Oscillations, Installation at the 11th Venice Architectural Biennale, by Gramazio &Kohler Research, ETH Zurich, (b) 3D printing execution [8]

2. Literature review

The complexity of contemporary designs, lead to the '*more is different*' statement [9]. The role of the designers in the creative designing practice changed, from designing exact geometries, based on available element cross-sections, to controlling the process of designing rules. It is visible in the new sustainable fabrication methods, like FiDU (ger. *Freie Innen Druck Umformung)*, which stands for Free Inner Pressure Forming. This method allows receiving lightweight structures with a high-stress capacity, as well as the size of the file needed in file-to-factor manufacture technology.

Development of modern computational software and the ability to modeling structural forms in non-Euclidean geometry while using algorithms lead designers to new fields of designing and constructing. Parameterization of modeling tools and processes caused an increase in interest in bionics and biomimetics. It is expressed by imitation of the structure and behavior of living organisms. Such actions enabled the implementation of ideas as *forms follow energy* and *forms follow forces*. Analysis of the morphology of structural forms as well as generative modeling based on logical patterns taken from Nature are one of the contemporary tools of rational design. Not only in the context of minimizing material usage but what is more important, in the self-organization of structural elements to attain force equilibrium in structures.

The interrelation between shape, material, and behavior of structures found in Nature becomes a base of new methods of optimization. Biomimetic inspirations are the main factor of the designing process, where the properties of selected materials, structural behavior as well as manufacturing technologies influence the early stage of designing and, therefore, the structural optimization process [10] [11]. The integration of tools that help to optimize the construction process under human-machine collaboration is continuously invented [12]. An example of an interdisciplinary tool where material properties are one of the main factors of optimizing the final architectural form is a Material-based Integrated Computational Design Model (MICD-m), where parametric modeling environment was used [13]. The ability to create a new method of fabrication and the understanding of the material which designers use nowadays lead to the creation of a new language and a platform of communication, which goes far beyond the complexity of the form [14] to synthesis and sustainable performance in order to achieve the minimization of costs and the consumption of natural resources [15].

3. Discussion

A vital element of manufacturing development is the search for new materials and the improvement of technologies such as digital machines supporting manufacturing processes. The control of the CAD-CAM prototyping is based on multicriteria optimization [16]. It also helps in incorporating variable parameters into the design, such as structure modeling, shapes, fabrication method, material properties, but also material and structure behavior, lightning, heat, humidity, or air movement [17]. The most significant factor of digital fabrication and prototyping is the availability of fabrication solutions, as well as the supervising of the assembling process and correcting errors (if any occurs during fabrication).

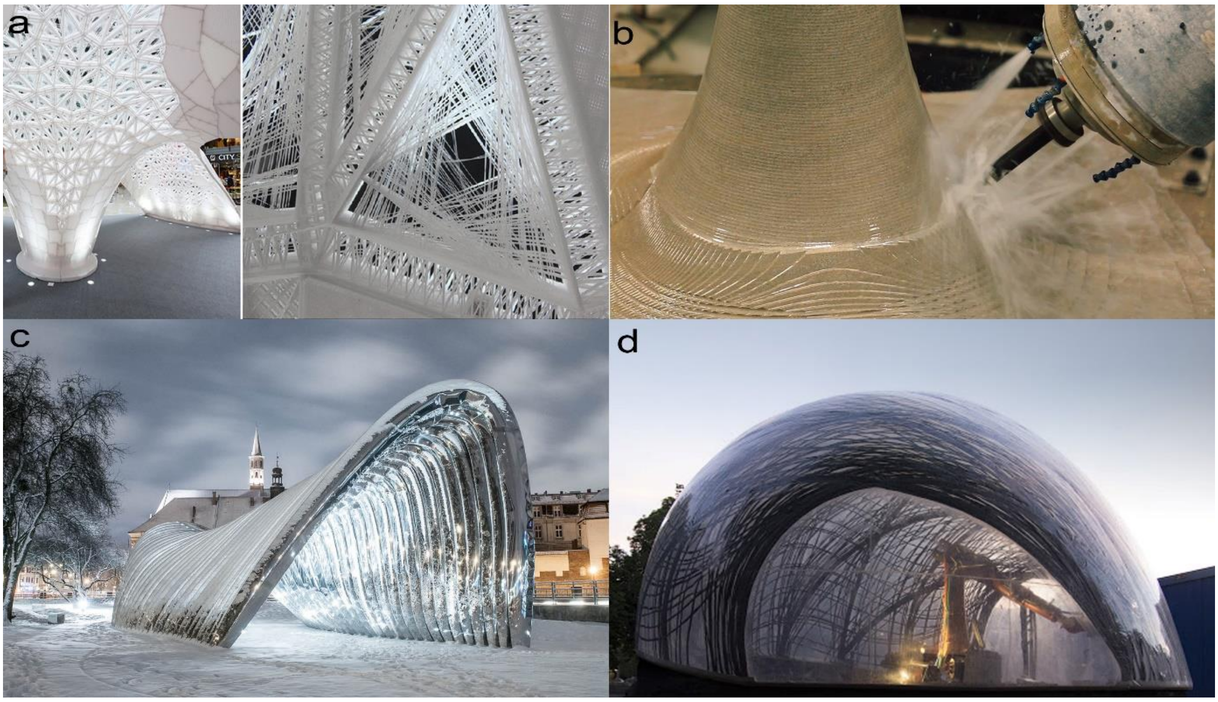

Fig. 2. Basic methods of fabrication in small scale object: (a)additive technology- the Vulcano Pavilion, (b)subtraction technology-The Autodesk Pavilion, (c)formative technology- Nawa Pavilion, (d) formative technology-ICD-ITKE Research Pavilion

The turn from NC(Numerical Control) to CNC(Computer Numerical Control) devices improved the prototyping and fabrication development. The two main methods of fabrication are Subtraction and Addition. In the first method, robots, lasers, streams of water, or plasma as we as more traditional tools as cutting blades might be used. Basing of the available type of the machine, 2D, and 3D objects of architectural scale can be obtained. However, these machines are limited to the cutting area or machine arm length. Up to 21-century in additive methods, only small scale objects could be made. The leading technology of additive methods is 3D printing. Currently, massive scale concrete printers are available to print, for example, a concrete building element, such as beams, trusses, as well as whole buildings. The most basic printing materials are plastic, clay, concrete, or steel. The significant area of research is based on the new bio-engineering material, such as biodegradable timber composites or technologies of 3D bioprinting. The combination of those which use machines to assembly the undertake without human interaction. In this method, robots, as well as drones or any other computer-controlled tools, can be used. This method is by far one of the most challenging for designers, not only they have to design the geometry(CAD), precisely understand the materials and machines properties (CAM), but also set the exact algorithm for assembling. This method is mostly accompanied by generative design as well as computational methods of manufacturing, give designers illusory feeling that they replace his thought process. In fact, by following his algorithmic instructions, they are indicators of the quality of designers' knowledge and creativity [18] [19]. In this sense, digital fabrication, in combination with generative design, can be considered as a synthesis of logic thinking, knowledge, which combines technical and human needs solutions and what is the essential freedom of design [20].

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Establishment of a Framework to Measure Disaster Preparedness: Development of Strategies to Enhance Disaster Preparedness Activities

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Abstract

Despite disasters being extremely disruptive to campus life and affecting students both mentally and physically, college students are one of the most overlooked sub-groups in the community following a disaster. It is, therefore, crucial for disaster risk reduction (DRR) to be implemented in universities, where disaster preparedness, response, and mitigation strategies and programs are still lacking even though disaster awareness has increased. This study aims to investigate disaster awareness and preparedness of university students and develop a framework within which to measure the level of their disaster preparedness. To fulfill the objective of this study, a comprehensive literature review was conducted to understand how knowledgeable and prepared students are for disasters. The review provided the basis for the development of a comprehensive survey that was distributed through an online platform. After two follow-ups, 111 survey responses were collected and analyzed, both qualitatively and quantitatively. Based on the analysis, a framework was developed, linking the characteristics of students with different levels of DRR education. It was found that the students' perspectives of the responsibility of friends, parents, and university and/or government agencies to provide for their safety during a disaster are formed by personal characteristics (male or female, graduate or undergraduate, educated or uneducated about disaster preparedness, etc.). It was also observed that graduate and undergraduate students have significantly different opinions about the adequacy of the first aid boxes at their university, and students with prior disaster preparedness education believe that it is important for local communities to help educational systems implement DRR courses. The opinions of students with prior disaster preparedness education differ significantly from those without disaster preparedness education on whether DRR education should be mandatory. The findings of this study will contribute to the US educational system to effectively develop and implement DRR courses and will guide policymakers in their assessment of the universities' emergency preparedness policies.

Keywords: disaster-preparedness education, disaster preparedness framework, students' disaster preparedness

1. Introduction

The Federal Emergency Management Agency (FEMA) [1] defines a disaster as an occurrence that has resulted in property damage, deaths, and/or injuries to a community. Every year, US cities are hit by more than 100 disasters that cause extensive deaths, destruction of property [2, 3, 4], and billions of dollars of economic losses [5]. In the period of 25 years from 1990 to 2015, the economic losses from natural disasters totalled approximately 700 trillion dollars [6]. Hurricane Sandy in New York (2012) and Hurricane

Harvey in Houston (2017) are recent examples of natural disasters, each responsible for the loss of approximately 100 lives [5, 7].

Natural disasters are responsible for causing physical damages [8, 9], creating social and psychological disorders in society [10, 11, 12], and damaging the environment [13]. By way of illustration, the 1991 Northridge disaster led to the disruption of critical highways at four different locations in the Los Angeles Metropolitan Area, upsetting the movement of people and causing an estimated economic loss of 1 million dollars per day. The economic losses from Hurricane Katrina in New Orleans and Hurricane Rita in the area surrounding the Gulf of Mexico were $1845 billion and $120 billion. Furthermore, the annual frequency of natural disasters has increased significantly worldwide [13, 14]. However, the losses and damages have not increased in proportion as in the period between 1975 to 2009 the losses increased from approximately $10 billion to $90 billion.

Disasters such as hurricanes, earthquakes, floods, etc. can disrupt campus life, interrupt classes, damage school buildings, and leave students in an emergency crisis [15]. According to Hoffmann and Muttarak [16], disaster risk reduction (DRR) plays an important role in achieving sustainable development [17]. Universities are beginning to recognize the importance of disaster preparedness and the risks associated with the lack of it, and students are also becoming aware of its importance through experience, the media, and awareness seminars conducted by various organizations [18]. Despite this, however, disaster preparedness, response, and mitigation strategies are still lacking in universities and schools. Tanner and Doberstein [19] stated that students are more vulnerable to a disaster than the general population because of their lack of knowledge, yet few educational institutions recognize the importance of educating their students about proper disaster preparedness [20]. Development of a DRR curriculum for students requires knowing and understanding the factors that affect students' DRR preparation; however, few studies have addressed this issue [21].

This study aims to investigate the disaster awareness and preparedness of university students and develop a framework within which to measure the students' preparedness. To begin this study, a comprehensive literature review was conducted to understand the factors that affect DRR education in universities. Based on the review, a survey was developed and distributed to students to collect their opinions about the identified factors. The findings of this study will assist both faculty members and other academic staff in updating the existing programs, enhancing the disaster preparedness of students, addressing the potential challenges in advancing knowledge, and reducing costly and deadly damages.

2. Literature review

2.1. Impacts of disasters on educational institutions

According to the Centre of Epidemiology of Disasters (CRED) International Disaster Database, the damages caused by natural disasters from 2003 to 2013 added up to 1.5 trillion US dollars. The economic losses from 2016-2017 were approximately 200 billion [22]. These statistics give a cursory view of the monetary damages that are caused by natural disasters overall, but overlook the fact that this includes damages to universities. Loma Prieta Earthquake (1989), Hurricane Andrew (1992), Northridge Earthquake (1992), Colorado State University Flooding (1997), Hurricane Georges (1998), and Hurricane Floyd (1999) are some of the catastrophic events that damaged academic buildings and forced schools to close because of no water and/or electricity [15]. Disasters can affect universities in numerous ways, such as the loss of administrative and research data; damage to libraries; spoiling specimens in laboratories; vitiating computer and communication systems; wrecking buildings; and injuring students, faculty, and staff members; etc. [15].

2.2. Current trends in disaster preparedness education

Tanner and Doberstein, [19] found that students are more vulnerable to disasters than other community groups and are the most ignored in the planning for emergency preparedness. Similar results were found by [23] while assessing tornado preparedness of non-student tenants, student tenants, and non-student homeowners. They learned that students were the least prepared group for disasters due to their lack of knowledge and low level of disaster preparedness. Research by Tan et al. [24] conducted in China revealed that less than half of the university students had been exposed to disaster rescue skills. A later study in Indonesia by [6] found that the lack of willingness among teachers to motivate students to study resulted in the schools not teaching DRR courses that would stimulate a low level of disaster preparedness. A survey by Tan et al. [24], conducted to assess the knowledge of primary rescue skills used in emergencies, suggested that cardiopulmonary resuscitation (CPR) was the least desired and the most studied and practiced skill.

2.3. Importance of disaster risk reduction education and skills

The risks of disasters can be significantly reduced when students have the appropriate hazard awareness, education, and rescue skills [25, 26] that they can put into practice during an actual disaster [27,28]. Survival techniques should be taught or overseen by experts, as it is the most difficult part of disaster education and involves a certain amount of practical training [24]. Universities that have medical and/or nursing departments have an advantage, as they have professionals and equipment that can train the students and effectively implement disaster-related courses [29]. This preparedness helps the students by i) preparing them mentally for the occurrence of a disaster, ii) encouraging them to collaborate with emergency management practitioners, iii) increasing their confidence in handling emergencies, iv) providing them with an understanding of the physical and psychological consequences of disasters, and v) creating an awareness of the importance of personal safety [30]. The quality of DRR preparedness depends on the will and creativity of the teacher [31], and cooperation and consultation among teachers can help to successfully implement DRR education. Teachers who are more experienced in disaster education should be appreciated and treated as role models to encourage other teachers to follow their examples [32].

2.4. Challenges to developing and delivering disaster preparedness courses

Previous studies have shown that developing comprehensive safety plans and effective communication between the different stakeholders in a university is difficult [33]. Implementation of a disaster preparedness course requires a collaborative effort on the part of all of the stakeholders, and the executive staff of the university should partner up with the local emergency management agencies to improve disaster preparedness for both students and local communities [34]. The government agencies' main course of action is usually to meet with various stakeholder groups and assist them with rehabilitation [6]. They predominantly focus on the community in general, and the university students are not given much consideration. Disaster response and recovery programs have been successful only in agencies and educational institutions that have strengthened their relationships with the community and provided practical training [33].

Developing practical DRR courses also depends on the financial capacity of the schools [6]. Lack of knowledge is not the main problem; knowing how to circumvent the obstacles to teaching and learning the appropriate skills is. According to Amri et al. [31] a large proportion of teachers believe that training will make it easy for them to provide DRR education in the classroom. Furthermore, [6] stated that combining science and technology with practical training will help students learn important disaster-related skills that have the potential to reduce disaster risk-related losses. Spiekermann et al. [35] summed it up well by stating that the two major difficulties that are faced by those dealing with disasters are the lack of resources to put knowledge into practice, and the dearth of a continuous source of knowledge that enables policymakers to make effective decisions.

The literature review revealed how little information is available about students' preparedness and the difficulties they face during disasters. Hence there is a lot of evidence to substantiate the need for including disaster management courses at the university level. As students become acquainted with the dos and don'ts of actions to be taken in the midst of or at the end of a natural calamity, they feel more confident in their own ability to cope and can help prepare their family members and friends address the challenges effectively. It is, therefore, important that the level of awareness among students in university be analyzed and tools be developed to help them plan appropriate post-disaster management activities.

3. Research methodology

The four-step methodology depicted in Figure 1 was undertaken to fulfill the objectives of this research. The first step consisted of an extensive literature review of research papers and journal articles to gain a general idea of the existing knowledge on the following issues: Impacts of disasters on educational institutions, current trends in disaster preparedness education, importance of disaster risk reduction (DRR) education and skills, and challenges to developing and implementing DRR courses. The second step was to develop a survey questionnaire, based on the factors studied in the literature review, to gain knowledge of university students' perceptions of disaster education and university emergency policies. After pilot testing the survey, it was distributed anonymously among students who were above 18 years old. The third step was the analysis of the data. A descriptive analysis of the data, followed by a statistical analysis was conducted. As most of the questions in the survey were 7 point Likert scale type questions, the Kruskal-Wallis test was used to determine and analyze the differences in perception of the students on DRR education and their university's emergency policies, based on their level of education and gender. The same test was used to analyze whether there was a difference in the opinion of students with and without disaster-related education. After all of the input, the results of the statistical test were interpreted.

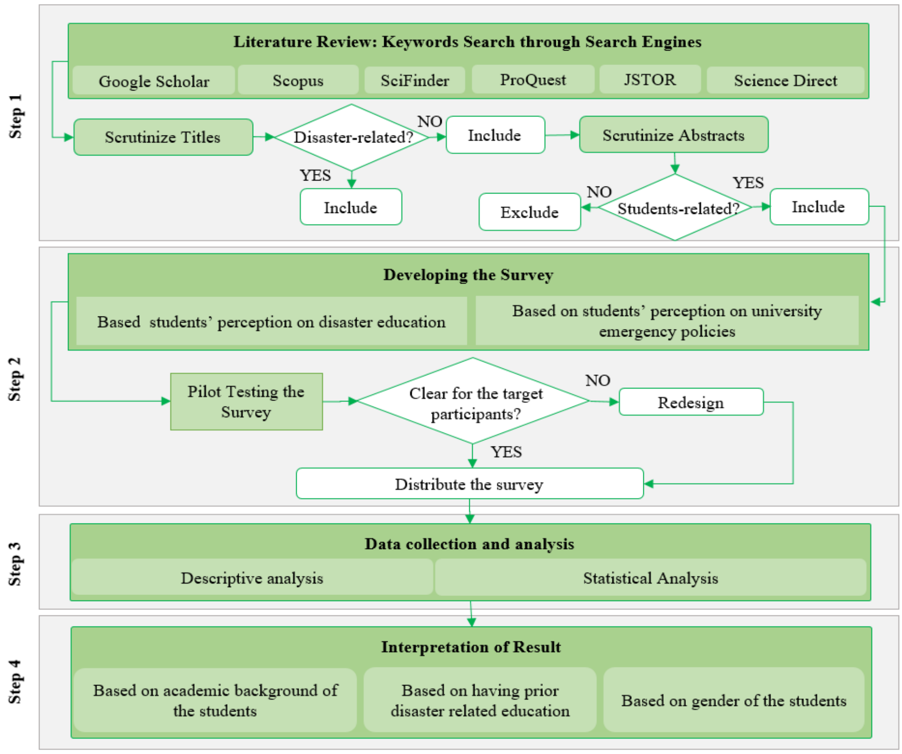


Fig. 1. Research methodology

The Kruskal-Wallis test determines the difference between the actual observed average and the expected average of a data set and is most effective when the data set does not follow a normal distribution. It was selected for this study as it was best suited for the Likert-scale test. The hypothesis developed for this study is shown in Table 1.

Table 1. Hypotheses adopted for this study

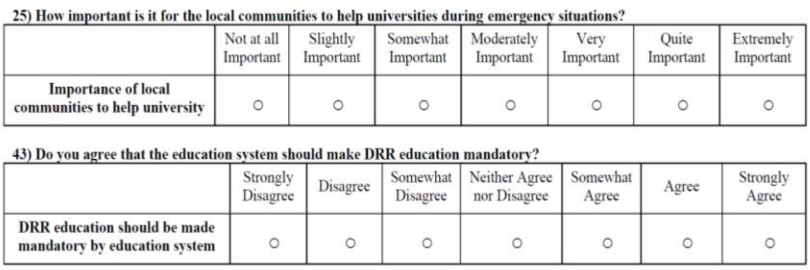
Students characteristics	Statistical test	Hypotheses
Graduate and undergraduate students	Kruskal-Wallis test	Null Hypothesis (H_0): Graduate and undergraduate students have the same perception of DRR education. Alternative Hypothesis (H_a): Graduate and undergraduate students have a different perception of DRR education.
Students with prior DRR education and without prior DRR educations	Kruskal-Wallis test	Null Hypothesis (H_0): Students with prior DRR education and without prior DRR education have the same perception towards DRR education. Alternative Hypothesis (H_a): Students with prior DRR education and without prior DRR education have different perceptions towards DRR education.
Female students and male students	Kruskal-Wallis test	Null Hypothesis (H_0): Female and male students have the same perception towards DRR education. Alternative Hypothesis (H_a): Female and male students have different perceptions of DRR education.

The Kruskal-Wallis test uses the equation (1). Here, R represents the rank of the individual group, n_i represents the number of observations in group I, N represent the total number of observations, and a represents the number of groups [36].

$$H = \frac{12}{N(N+1)} \sum_{i=1}^{a} \frac{R_i^2}{n_i} - 3(N-1) \tag{1}$$

4. Survey development

A structured survey was developed based on the information gained from the literature review about the importance, awareness, and impacts of DRR on students. An online survey was developed, using an online survey assessment tool, "Qualtrics." Figure 2 shows some sample questions that were used in the survey. An invitation email with the details of the study was sent to the students with the help of the faculty, and an electronic informed consent was provided. Students were not compensated for their participation in any way. The survey was developed based on six parameters relating to disaster risk reduction education in universities: (1) demographics, (2) disaster experience, (3) disaster risk reduction education, (4) emergency awareness, (5) emergency drills at universities, and (6) implementation of DRR courses. The survey consisted of 25 multiple choice questions, 19 rating scale questions, and 1 open-ended question.



25) How important is it for the local communities to help universities during emergency situations?

	Not at all Important	Slightly Important	Somewhat Important	Moderately Important	Very Important	Quite Important	Extremely Important
Importance of local communities to help university	○	○	○	○	○	○	○

43) Do you agree that the education system should make DRR education mandatory?

	Strongly Disagree	Disagree	Somewhat Disagree	Neither Agree nor Disagree	Somewhat Agree	Agree	Strongly Agree
DRR education should be made mandatory by education system	○	○	○	○	○	○	○

Fig. 2. Sample questions in the survey

The first section of the survey consisted of demographic questions such as gender, year of birth, major, current year of education, racial or ethnic heritage, mode of transportation for travelling to the university, whether they live off-campus or on-campus, etc. The second section of the survey consisted of questions about the types and number of disasters the participants had been involved in. The third section of the survey was multiple choice questions about the number of disaster-related courses taught in universities and what form of disaster education (practical or theoretical) is better. The fifth section of the survey consisted of rating-scale type questions pertaining to the student's awareness of university procedures and emergency supplies available at the university. The sixth section of the survey consisted of questions about barriers to learning DRR and the importance of local agencies helping universities implement it. All of the rating scale type of questions in the survey were based on the Likert-scale. The population of this study was students who were older than 18 years. Before the survey was distributed, it was pilot tested to ensure the clarity of the questions.

5. Data collection and analysis

5.1. Descriptive analysis

A total of 111 students from a variety of majors and with different levels of education responded to the survey. Undergraduate students constituted 35 percent of the total, and graduate students constituted 65 percent. The majority of them (74 percent) had not received any education related to disasters, while 26 percent of them had some amount of disaster-related education. A detailed descriptive analysis of the survey participants is shown in Table 2.

Table 2: Descriptive analysis of the student participants in the survey

Demographic Characteristics	Number in Sample	Percentage in Sample
Gender		
Male	87	78%
Female	24	22%
Ethnicity		
Native American	0	0%
African American	7	7%
American Indian or Alaskan Native	0	0%
Asian	68	65%
Hispanic	12	11%
Native Hawaiian or Pacific Islander	0	0%
Other	18	17%
Level of education		
Freshman	1	1%
Sophomore	6	5%
Junior	27	24%
Senior	5	5%
Masters	66	60%
Ph.D.	6	5%
Mode of transportation to university		
Walking	59	53%
Personal Vehicle	8	7%
Campus Transit Service	2	2%
Public Transport	42	38%
Time to reach university		
Less than 10 Minutes	35	32%
10 - 20 Minutes	36	32%
20 - 30 Minutes	21	19%
30 - 60 Minutes	18	16%
More than an Hour	1	1%
Student's living in the area		
Off - Campus	78	70%
On - Campus	33	30%

Demographic Characteristics	Number in Sample	Percentage in Sample
Age Range		
Under 25 Years Old	68	61%
Between 25 and 29 Years	43	39%
Above 29Years Old	11	10%
Annual family income		
Less than $15,000	16	16%
$15,000 to $30,000	28	28%
$30,000 to $60,000	18	18%
$60,000 to $100,000	28	28%
More than $100,000	9	9%
Involvement in disaster		
Hurricane	6	5%
Tornadoes	14	13%
Flooding	22	20%
Thunderstorm	25	23%
Earthquakes	28	25%
Tsunami	3	3%
None	50	45%
Involvement in the number of disasters		
0 - 1	69	63%
1-2	13	12%
2-3	16	15%
3-4	3	3%
4-5	2	2%
More than 5	7	6%
Disaster-related courses taken during pre-university education		
0 - 1	81	74%
1 – 2	22	20%
2 – 3	4	4%
3 – 4	1	1%
4 – 5	0	0%
More than 5	1	1%

5.2. Statistical analysis

Table 3 lists the results of the Kruskal Wallis test on the students' perceptions, based on their level of education, disaster-related education, and gender. Based on the P values in Table 3, 5 of the 11 variables were found to be significant for undergraduate and graduate students. For students with and without disaster-related education, 4 variables were found to be significant. Three variables were found to be significant based on gender.

Table 3: P-Values testing the significance of students' perception of the university's emergency policies and disaster risk reduction (DRR) education

#	Variables	P-Values for undergraduate and graduate students	P-Values for students with and without disaster-related education	P-Values for male and female students
1	Curriculum provides psychological first aid training	0.373	0.097**	0.08**
2	University has enough first aid boxes	0.000*	0.710	0.580
3	Importance of local communities to help university	0.344	0.005*	0.173
4	Friends are responsible for students' safety	0.128	0.614	0.062**
5	Parents are responsible for students' safety	0.914	0.053*	0.305
6	University is responsible for students' safety	0.035*	0.677	0.022*
7	Government Agencies are responsible for students' safety	0.003*	0.708	0.120
8	Awareness of the emergency procedures in the university	0.002*	0.532	0.873
9	Awareness of communication system provided by the university during emergency	0.035*	0.905	0.802
10	Importance of local communities on helping the university to implement DRR courses	0.823	0.048*	0.407
11	DRR education should be made mandatory	0.250	0.049*	0.035*

Note: "*" Indicates 95% Level of Confidence and "**" Indicates 90% Level of Confidence

6. Interpretation of the result

6.1. Analysis of undergraduate and graduate students' perception of the university's emergency procedures

From the Kruskal-Wallis test (Table 3) it is evident that graduate students and undergraduate students have different perceptions of the sufficiency of the first aid boxes. They also possess different levels of awareness of the emergency communication and procedures provided by the university. Although they have similar perspectives of the roles of friends and parents in providing safety during a disaster, they have very different perspectives of the roles of universities and government agencies. Both undergraduate and graduate students, however, believe that DRR education should be mandatory in educational institutions.

6.2. Analysis of students' perceptions of disaster-related education: students with and without disaster-related education

The P-values in Table 3 indicate that students who have had DRR education have a different view of adding psychological first aid services to the disaster curriculum than the students who have not had any DRR education. Their perceptions of the roles of their parents in providing safety in the midst of a disaster also differ. All of the students, however, believe that friends, universities, and governmental agencies have similar roles to play in student safety during disasters. Their opinions about the importance of local communities helping universities implement DRR courses also differ according to whether they have had the benefit of prior DRR education, as do their views of mandatory DRR education.

6.3. Analysis of students' perceptions of the disaster-related activities: male and female students

The P-values in Table 3 indicate that male and female students have significantly different opinions about adding psychological first aid to the disaster curriculum. They have similar views of government agencies' role in their safety during a disaster, but different views of the university's role in their safety and whether DRR education should be mandatory in educational institutions.

7. Proposed framework

Based on the above discussion, a conceptual framework, shown in Figure 3, was developed to understand the characteristics of the students that affect the disaster preparation of an institution. Three characteristics of students were linked with the disaster preparedness factors of an institution: level of education, prior DRR education, and gender. Figure 3 shows that all three characteristics affect their perception of the responsibility of friends, parents, and university and government agencies during a disaster, yet only their level of education affects their awareness of emergency communication and procedures provided by the university while recovering from the disaster. Prior DRR education impacts the perception of the students regarding the importance of local communities helping implement DRR, and both having prior DRR education and the gender of the students affect their opinion as to whether DRR education should be mandatory at educational institutions.

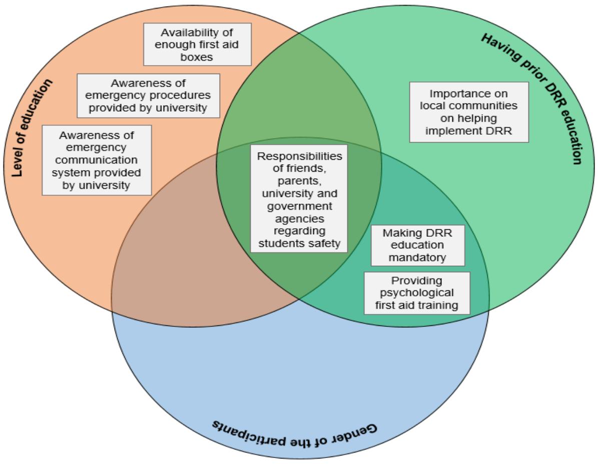


Fig. 3. Conceptual framework linking characteristics of students with factors of DRR education

8. Conclusion

Universities serve as important educational and research centers; hence it is vital that they implement disaster risk reduction education. With that in mind, this research developed a framework to show the relationship of the characteristics of students with different factors of DRR education, and it was found that the characteristics make a notable difference. For example, having had DRR education does not impact the students' awareness of the emergency communication provided by the university, but the level of education does. Irrespective of the level of education, graduate and undergraduate students have similar opinions about whether DRR education should be mandatory; however, students with prior DRR education and male students with or without prior DRR education have a significantly different opinion about mandatory DRR education mandatory than students without DRR education and female students with or without DRR education. The findings of this study will assist both faculty members and other academic staff in updating existing programs, enhancing the disaster preparedness of students based on their characteristics, addressing potentially challenging advancements in knowledge, and reducing costly and deadly damages.

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Health and Safety Challenges on South African Regional Public Sector Projects

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Abstract

The South African construction industry has a poor health and safety (H&S) record, and continues to be noted for H&S non-compliance, injuries, and fatalities.

The aim of the study reported on was to evolve a strategy to mitigate H&S non-compliance, injuries including fatalities, design originated hazards, and recurring H&S problems experienced on a provincial Department of Public Works' (DPW) projects.

The study adopted a quantitative approach and focused on seven school construction projects, and included, inter alia, construction project managers (CPMs) based in the provincial DPWs' project management department that were involved with the projects. The CPMs were surveyed using a self-administered questionnaire.

The study determined that inadequate H&S knowledge and awareness, inadequate H&S management and supervision on site, inadequate worker participation, inadequate H&S training, inadequate designer 'report', negligence, unsafe acts and conditions, H&S non-compliance, inadequate Safe Operating Procedures (SOPs) and Safe Working Procedures (SWPs), inadequate commitment of various project stakeholders, ignorance, and poor client H&S leadership are the primary causes of H&S non-compliance, injuries including fatalities, design originated hazards, and recurring H&S problems.

Recommendations include: H&S must be included as a project value; H&S must be integrated within the Department's internal project systems from project inception to project close out, and all stakeholders' H&S competencies must be enhanced.

Keywords: clients, health and safety, practices, value

1. Introduction

The considerable number of accidents, fatalities, and other injuries that occur in the South African construction industry are highlighted in the 'Construction Health & Safety Status & Recommendations' report [1]. The report cited the high-level of non-compliance with H&S legislative requirements, which is indicative of a deficiency of effective management and supervision of H&S on construction sites as well as planning from the inception / conception of projects within the context of project management. The report also cited a lack of sufficiently skilled, experienced, and knowledgeable persons to manage H&S on construction sites.

Given the differing interpretation of project management globally, it is important to define it within the context of South Africa, namely: "Construction project management is the management of projects within the built environment from conception to completion, including management of related professional services, and the construction project manager is the one point of responsibility in this regard." [2] Therefore, construction project managers (CPMs) coordinate and manage design delivery, manage the procurement process, integrate the design, procurement, and construction processes, and monitor the construction process.

The Construction Regulations, which constitute the primary regulations in terms of managing H&S in the South African construction industry, allocate a range of H&S responsibilities to clients, designers, quantity surveyors, principal contractors, and contractors [3]. Given the definition of construction project management and the requirements arising from the Construction Regulations, CPMs must ensure that H&S is integrated into the six stages of projects. Furthermore, integration implies that CPMs must ensure that H&S is a 'value' during projects.

Given the status of H&S in South African construction, the requirements of H&S legislation, the functions of CPMs, and the status of H&S on a provincial Department of Public Works' (DPW) projects, a study was conducted among the department's CPMs, the objectives being to determine the:

- extent to which a range of thirteen factors contribute to recurring H&S problems in construction;
- respondents self-rating of their knowledge regarding eight project management of H&S aspects;
- extent to which sixteen factors contribute to design originated hazards;
- extent to which ten factors contribute to exposure to hazards on construction sites, and
- frequency at which twenty-four factors are the cause of construction accidents.

2. Review of the literature

2.1. Compliance and non-compliance

The Department of Labour inspectorate conducted inspections throughout South Africa in August 2007 [1]. 52.5% of the contractors were found to be non-compliant with the Occupational Health & Safety Act and the Construction Regulations on the 1 415 construction sites visited. Of the 1 388 notices issued by inspectors, 86 (6%) were improvement notices, 1 015 (73%) were contravention, and 287 (21%) were prohibition. These findings indicate contractors in general are not complying, and underscore the rationale for client responsibility for construction H&S in terms of the Construction Regulations, and the need for CPMs to integrate construction H&S into the six stages of projects.

2.2. Health and safety legislation

In terms of the South African Construction Regulations [3], clients are required to, inter alia, prepare an H&S specification based on their baseline risk assessment (BRA), which is then provided to designers. Designers in turn are required to, inter alia: consider the H&S specification; submit a report to the client before tender stage that includes all the relevant H&S information about the design that may affect the pricing of the work, the geotechnical-science aspects, and the loading that the structure is designed to withstand; inform the client of any known or anticipated dangers or hazards relating to the construction work, and make available all relevant information required for the safe execution of the work upon being designed or when the design is changed; modify the design or make use of substitute materials where the design necessitates the use of dangerous procedures or materials hazardous to H&S, and consider hazards relating to subsequent maintenance of the structure and make provision in the design for that work to be performed to minimise the risk. To mitigate design originated hazards, requires hazard identification and risk assessment (HIRA) and appropriate responses, which process should be structured and documented.

Thereafter, clients must include the H&S specification in the tender documentation, which in theory should have been revised to include any relevant H&S information included in the designer report. Thereafter, they must, inter alia: ensure that potential principal contractors (PCs) have made provision for the cost of H&S in their tenders; ensure that the PC to be appointed has the necessary competencies and resources; ensure that every PC is registered for workers' compensation insurance cover and in good standing; discuss and negotiate with the PC the contents of the PC's H&S plan and thereafter approve it; take reasonable steps to ensure that each contractor's H&S plan is implemented and maintained; ensure that periodic H&S audits and documentation verification are conducted at agreed intervals, but at least once every 30 days; ensure that the H&S file is kept and maintained by the PC, and appoint a competent person in writing as an agent when a construction work permit is required. To mitigate design originated hazards, requires HIRA and appropriate responses, which process should be structured and documented.

2.3. The role of project managers

The Australian Federal Safety Commissioner's best practice client H&S principles emphasise, inter alia, the inclusion of H&S as an integral aspect of project management, and that H&S should be afforded status equal to that afforded cost, quality, and time [4].

A previous study conducted among CPMs in South Africa determined that they frequently consider / refer to H&S on fourteen occasions, as opposed to infrequently. However, they do so more frequently during the downstream and midstream stages than the upstream stages of projects. Downstream occasions include site inspections / discussions, site meetings, and site handover; and midstream occasions include preparing project documentation, evaluating tenders, pre-tender meeting, and pre-qualifying contractors. Furthermore, they consider / refer to sixteen design related aspects frequently as opposed to infrequently - method of fixing, position of components, specification, type of structural frame, and site location predominate [5].

2.4. Contributing factors in accidents

A study conducted by Haslam, Hide, Gibb, Gyi, Pavitt, Atkinson, & Duff [6] reviewed 100 accidents.

The first category includes 'immediate accident circumstances and shaping factors'. Problems arising from workers, which includes all site-based personnel, or the work team, especially worker actions or behaviour and worker capabilities, were judged to have been involved in over 70% of the accidents. Workplace factors, most notably poor housekeeping and problems with the site layout and space availability, were considered to have contributed 49% of the accident studies. Local hazards on site were a feature in many of the 100 accidents reviewed. Shortcomings with equipment, including personal protective equipment (PPE), were identified in 56% of the incidents. Deficiencies with the suitability and condition of materials, including packaging, featured in 27% of incidents.

The second category are 'originating influences', in which case inadequacies with risk management were considered to have been present in 94% of the accidents. In terms of 'construction design and processes', Haslam et al. state that the elimination or reduction of risks through design or alternative methods of construction is highly desirable. In terms of 'project management', a clear influence from problems with project management was identified in only a quarter of the accident studies, although this is likely to have been because the precise effects are difficult to corroborate. In terms of 'risk management' deficiencies related thereto were identified in most of the 100 accidents studied. Acci- dents invariably involve an inadequately controlled risk, which is indicative of a management failing. In terms of 'client and economic influences', there was limited direct evidence of the influence of client requirements or the economic climate on the accidents studied, although they undoubtedly do affect construction H&S. In terms of 'H&S education and training', the explanations from the accident study interviews and focus groups for construction workers engaging in unsafe acts were three-fold: H&S being overlooked in the context of heavy workloads and other priorities; taking shortcuts to save effort and time, and inaccurate perception of risk. Underlying each of these are inadequate H&S knowledge, which indicates deficiencies with H&S education and training. A further issue is the inadequacy of university construction-related courses in terms of H&S education.

3. Research

3.1. Research method and sample stratum

The study adopted a quantitative approach and focused on seven school construction projects, and included, inter alia, forty construction project managers (CPMs) based in the provincial DPWs' project management department that were involved with the projects. The CPMs were surveyed using a self-administered questionnaire. The questionnaire consisted of eleven questions, six of which were closed-ended, and five open-ended. The six closed-ended questions were five- or six-point Likert scale-type questions. A further seven questions were included in an addendum, which were closed-ended and were five- or six-point Likert scale-type questions. Thirty-nine responses were received and included in the analysis of the data, which equates to a response rate of 97.5%. The analysis of the data entailed the computation of descriptive statistics in the form of frequencies and a measure of central tendency in the form of a mean score (MS).

3.2. Research findings

97.4% of respondents have worked for their current employer > 1 year, 58.9% for > 5 years, and 25.6% > 10 years. The mean length of time respondents had worked for their current employer is 9.6 years. 100% of respondents have worked in construction for > 1 year, 71.8% for > 5 years, and 41% > 10 years. The mean length of time respondents had worked in construction is 13.7 years. Therefore, the respondents can be deemed experienced, which contributes to the reliability of the findings.

56.4% of respondents were '≤ 40' years of age, and 43.5% were > 40 years. Per definition relative to workers, people > 40 years of age are 'older workers'. The mean age was 40 years. 33.3% of respondents were female, and 66.7% were male. In terms of qualifications, 84.6% of the respondents have a National Diploma or higher qualification.

Table 1 indicates the extent to which factors contribute to recurring H&S problems in construction in terms of percentage responses to a scale of 1 (minor) to 5 (major), and a MS ranging between 1.00 and 5.00.

It is notable that all the MSs are above the midpoint score of 3.00, which indicates that in general the respondents can be deemed to perceive the factors contribute to recurring H&S problems in construction to more of a major than a minor extent. It is notable that no factors' MSs are > 4.20 ≤ 5.00 – between a near major to major / major extent.

All the MSs are > 3.40 ≤ 4.20, which indicates the respondents perceive the factors contribute to recurring H&S problems in construction between some extent to a near major extent / near major extent.

'Poor client H&S leadership' is the only factor that has a MS > 3.80 ≤ 4.20, which falls within the upper part of the range. This is notable as it is client related, and the Construction Regulations schedule a range of requirements for clients. This is followed by 'inadequate construction H&S planning', which indicates the role of sound construction management in the form of planning. This in turn is followed by 'insufficient H&S skills', 'inadequate construction management commitment to H&S', 'inadequate financial provision for H&S in the BoQ', 'inadequate construction manager H&S knowledge', 'inadequate construction manager H&S experience', 'inadequate construction management involvement in H&S', and 'inadequate construction management participation in H&S', which are all H&S related. These findings highlight the importance of construction management involvement and participation in H&S in addition to construction management commitment to H&S. 'Non-integration of H&S into projects during the planning stages', 'inadequate design for construction H&S', and 'insufficient H&S communication amongst stakeholders' amplify the multi-stakeholder nature of H&S. Last ranked 'inadequate top management support' yet again amplifies the importance of management.

Table 1. Extent to which factors contribute to recurring H&S problems in construction.

Factor	Response (%)						MS	Rank
	Un-sure	Minor…………………..............Major						
		1	2	3	4	5		
Poor client H&S leadership	7.7	2.6	10.3	17.9	30.8	30.8	3.83	1
Inadequate construction H&S planning	5.1	5.1	10.3	23.1	23.1	33.3	3.73	2
Insufficient H&S skills	0.0	5.1	10.3	30.8	17.9	35.9	3.69	3
Inadequate construction management commitment to H&S	0.0	5.3	2.6	28.9	44.7	18.4	3.68	4
Inadequate financial provision for H&S in the BoQ	0.0	7.7	15.4	12.8	30.8	33.3	3.67	5
Inadequate construction manager H&S knowledge	0.0	5.1	10.3	28.2	25.6	30.8	3.67	6
Inadequate construction manager H&S experience	0.0	10.3	5.1	23.1	33.3	28.2	3.64	7
Inadequate construction management involvement in H&S	0.0	5.3	7.9	26.3	42.1	18.4	3.61	8
Inadequate construction management participation in H&S	0.0	5.3	5.3	31.6	42.1	15.8	3.58	9
Non-integration of H&S into projects during the planning stages	2.6	10.3	7.7	25.9	23.1	30.8	3.58	10
Inadequate design for construction H&S	2.6	7.7	2.6	38.5	25.6	23.1	3.55	11
Insufficient H&S communication amongst stakeholders	7.9	5.3	5.3	39.5	18.4	23.7	3.54	12
Inadequate top management support	5.1	5.1	17.9	20.5	23.1	28.2	3.54	13

Table 2 indicates the respondents' rating of their knowledge regarding various project management of H&S aspects in terms of percentage responses to a scale of 1 (limited) to 5 (extensive), and a MS ranging between 1.00 and 5.00.

It is notable that all the MSs are below the midpoint score of 3.00, which indicates that in general the respondent's rate their knowledge regarding various project management of H&S aspects as below average.

7 / 8 (87.5%) MSs are > 2.60 ≤ 3.40, which indicates the respondents rate their knowledge regarding various project management of H&S aspects aspects as below average to average / average. 'Identifying design originated hazards' is ranked first, followed closely by 'risk management, 'constructability reviews', 'implementing H&S systems at client level', 'baseline risk assessment (BRA)', 'project managing construction H&S', and 'designing for construction H&S'. All eights aspects are important in terms of project managing construction H&S, and it is notable that given the function of the respondents, the latter is ranked sixth.

The MS of last ranked 'design hazard identification and risk assessments (HIRAs)' is > 1.80 ≤ 2.60, which indicates that the respondents rate their knowledge regarding this aspect as limited to below average / below average. This is notable as design HIRAs are a key intervention in terms of 'designing for construction H&S'.

Table 2. Respondents rating of their knowledge regarding various project management of H&S aspects.

Aspect	Response (%)						MS	Rank
	Un-sure	Limited……………………....Extensive						
		1	2	3	4	5		
Identifying design originated hazards	2.6	13.2	23.7	21.1	34.2	5.3	2.95	1
Risk management	0.0	18.9	10.8	35.1	32.4	2.7	2.89	2
Constructability reviews	8.6	8.6	25.7	31.4	22.9	2.9	2.84	3
Implementing H&S systems at client level	2.7	13.5	16.2	45.9	18.9	2.7	2.81	4
Baseline Risk Assessment (BRA)	10.5	13.2	18.4	36.8	15.8	5.3	2.79	5
Project managing construction H&S	0.0	13.5	29.7	35.1	13.5	8.1	2.73	6
Designing for construction H&S	7.9	10.5	28.9	34.2	13.2	5.3	2.71	7
Design HIRAs	7.9	15.8	36.8	21.1	15.8	2.6	2.49	8

Table 3 indicates the extent to which factors contribute to design originated hazards in terms of percentage responses to a scale of 1 (minor) to 5 (major), and a MS ranging between 1.00 and 5.00.

It is notable that all the MSs are above the midpoint score of 3.00, which indicates that in general the respondents can be deemed to perceive the factors contribute to design originated hazards to more of a major than a minor extent.

It is notable that the top ranked factor 'inadequate H&S consultants' construction expertise in terms of the management of H&S' has a MS > 4.20 ≤ 5.00, which indicates it is deemed to contribute between a near major extent to a major / major extent to design originated hazards.

13 / 16 (81.3%) MSs are > 3.40 ≤ 4.20, which indicates that the factors are deemed to make between a contribution to a near major / near major contribution to design originated hazards. The MSs of the factors ranked second to seventh fall within the upper part of the range, namely > 3.80 ≤ 4.20. These include 'inadequate departmental H&S personnel's construction expertise in terms of the management of H&S', 'inadequate designer report', 'inadequate H&S consultants' H&S knowledge of construction activities', 'failure to appoint CHSA at Stage 1', inadequate design HIRAs', and 'project design and inputs are incomplete when construction commences'.

The factors ranked fifteenth and sixteenth have MSs > 2.60 ≤ 3.40, which indicates that they are deemed to make between a near minor contribution to contribution / contribution to design originated hazards - 'inadequate top management H&S knowledge of construction activities', and 'client initiated variations'.

Table 3. Extent to which factors contribute to design originated hazards.

Factor	Response (%)						MS	Rank
	Un-sure	Minor……………………..............Major						
		1	2	3	4	5		
Inadequate H&S consultants' construction expertise in terms of the management of H&S	10.5	2.6	2.6	13.2	21.1	50.0	4.26	1
Inadequate departmental H&S personnel's construction expertise in terms of the management of H&S	7.9	2.6	7.9	15.8	23.7	42.1	4.03	2
Inadequate designer report	10.8	2.7	5.4	24.3	21.6	35.1	3.91	3
Inadequate H&S consultants' H&S knowledge of construction activities	10.3	5.1	2.6	28.2	15.4	38.5	3.89	4
Failure to appoint CHSA at Stage 1	10.5	5.3	5.3	18.4	26.3	34.2	3.88	5
Inadequate design HIRAs	15.4	0.0	5.1	30.8	20.5	28.2	3.85	6
Project design and inputs are incomplete when construction commences	5.1	2.6	7.7	30.8	15.4	38.5	3.84	7
Inadequate designers' H&S knowledge of construction activities	10.3	2.6	7.7	17.9	38.5	23.1	3.80	8
Inadequate reference to H&S at design stage	5.4	2.7	5.4	35.1	16.2	35.1	3.80	9
Inadequate Departmental H&S personnel's H&S knowledge of construction activities	7.7	2.6	12.8	25.6	12.8	38.5	3.78	10
Inadequate designers' construction expertise in terms of the management of H&S expertise	7.9	5.3	7.9	23.7	21.1	34.2	3.77	11
Designer initiated variations	7.7	5.1	7.7	25.6	30.8	23.1	3.64	12
Alterations in scope	7.7	5.1	10.3	30.8	15.4	30.8	3.61	13
Inadequate top management construction expertise in terms of the management of H&S	7.9	10.5	10.5	23.7	21.1	26.3	3.46	14
Inadequate top management H&S knowledge of construction activities	10.3	5.1	15.4	33.3	15.4	20.5	3.34	15
Client initiated variations	7.7	2.6	20.5	33.3	17.9	17.9	3.31	16

Table 4 indicates the extent to which factors contribute to exposure to hazards on construction sites in terms of percentage repsonses to a scale of 1 (minor) to 5 (major), and a MS ranging between 1.00 and 5.00.

It is notable that all the MSs are above the midpoint score of 3.00, which indicates that in general the respondents can be deemed to perceive all factors contribute to exposure to hazards on construction sites.

It is notable that no MSs are > 4.20 ≤ 5.00 – aspects contribute between a near major to major / major extent to exposure to hazards on construction sites.

However, all the MSs are > 3.40 ≤ 4.20, which indicates the aspects contribute between some extent to a near major / near major extent. The aspects ranked in the top five, and which are within a range of 0.05, are ‘inadequate awareness’, ‘inadequate training’, ‘inadequate H&S management’, ‘inadequate H&S supervision’, and ‘inadequate H&S expertise’. These are followed by ‘inadequate H&S knowledge’, ‘inadequate H&S culture’, ‘inadequate PPE programmes’, ‘inadequate H&S experience’, and ‘inadequate health promotion’.

Table 4. Extent to which factors contribute to exposure to hazards on construction sites.

Factor	Response (%)						MS	Rank
	Un-sure	Minor………………….............Major						
		1	2	3	4	5		
Inadequate awareness	0.0	0.0	7.7	33.3	38.5	20.5	3.72	1
Inadequate training	0.0	0.0	15.4	28.2	25.6	30.8	3.72	2
Inadequate H&S management	0.0	0.0	12.8	25.6	41.0	20.5	3.69	3
Inadequate H&S supervision	0.0	2.6	10.3	30.8	28.2	28.2	3.69	4
Inadequate H&S expertise	0.0	0.0	7.7	41.0	28.2	23.1	3.67	5
Inadequate H&S knowledge	0.0	2.6	12.8	35.9	17.9	30.8	3.62	6
Inadequate H&S culture	0.0	5.3	7.9	36.8	23.7	26.3	3.58	7
Inadequate PPE programmes	0.0	0.0	20.5	28.2	25.6	25.6	3.56	8
Inadequate H&S experience	0.0	2.6	12.8	41.0	17.9	25.6	3.51	9
Inadequate health promotion	0.0	2.6	15.4	38.5	20.5	23.1	3.46	10

Table 5 presents the frequency at which factors are the cause of construction accidents in terms of percentage responses to a frequency range never to always, and MSs ranging between 1.00 and 5.00.

It is notable that 20 / 24 (83.3%) MSs are > 3.00, which indicates that in general, respondents can be deemed to perceive these factors are frequently the cause of construction accidents, as opposed to infrequently.

It is notable that none of the causes’ MSs falls within the range > 4.20 ≤ 5.00 – between often to always / always.

12 / 24 (50.0%) MSs are > 3.40 ≤ 4.20, which indicates the factors can be deemed to be the causes of accidents between sometimes to often / often - ‘employee negligence’ is ranked first, followed by ‘unsafe acts’; ‘unskilled workers’; ‘unsafe conditions’, ‘non-compliance with H&S’, ‘inadequate H&S training’; ‘poor working platforms’, ‘inadequate worker participation’, ‘poor housekeeping’, ‘non-compliance to SOPs’, ‘non-compliance to SWPs’, and ‘inadequate monitoring of construction activities relative to the H&S plan’.

The remaining 12 / 24 (50.0%) MSs are > 2.60 ≤ 3.40, which indicates the factors can be deemed to be the causes of accidents between rarely to sometimes / sometimes. 8 / 12 (66.7%) of the factors’ MSs fall within the upper part of the range, namely > 3.00 ≤ 3.40 - ‘inadequate PPE’, ‘inadequate H&S management’, ‘inadequate risk management’, ‘inadequate H&S supervision’, ‘inadequate maintenance of plant and equipment’, ‘inadequate monitoring of construction activities relative to design HIRAs (by designers & construction project manager/principal agent)’, ‘inadequate design HIRAs’, and ‘inadequate construction HIRAs’. The remaining 4 / 12 (33.3%) factors’ MSs fall within the lower part of the range > 2.60 ≤ 3.00 - ‘inadequate baseline risk assessment’, ‘poor site layout’, ‘work factors’, and ‘extreme temperatures’.

Table 5. Frequency at which factors are the cause of construction accidents.

Factor	Response (%)						MS	Rank
	Unsure	Never	Rarely	Some-times	Often	Always		
Employee negligence	0.0	2.6	2.6	20.5	46.2	28.2	3.95	1
Unsafe acts	0.0	5.1	5.1	20.5	43.6	25.6	3.79	2
Unskilled workers	2.8	5.6	11.1	25.0	30.6	25.0	3.60	3
Unsafe conditions	0.0	5.1	12.8	33.3	15.4	33.3	3.59	4
Non-compliance with H&S regulations	5.1	2.6	5.1	41.0	30.8	15.4	3.54	5
Inadequate H&S training	0.0	7.7	12.8	15.4	46.2	17.9	3.54	6
Poor working platforms	0.0	5.1	7.7	35.9	33.3	17.9	3.51	7
Inadequate worker participation	2.6	5.1	7.7	30.8	41.0	12.8	3.50	8
Poor housekeeping	2.6	5.1	5.1	38.5	38.5	10.3	3.45	9
Non-compliance to SOPs	7.9	2.6	7.9	36.8	36.8	7.9	3.43	10
Non-compliance to SWPs	8.1	2.7	2.7	51.4	24.3	10.8	3.41	11
Inadequate monitoring of construction activities relative to the H&S plan	5.1	0.0	15.4	35.9	33.3	10.3	3.41	12
Inadequate PPE	2.6	5.1	17.9	28.2	25.6	20.5	3.39	13
Inadequate H&S management	2.7	2.7	18.9	29.7	29.7	16.2	3.39	14
Inadequate risk management (in general)	17.9	5.1	15.4	25.6	25.6	10.3	3.25	15
Inadequate H&S supervision	2.6	5.3	15.8	42.1	23.7	10.5	3.19	16
Inadequate maintenance of plant and equipment	2.6	5.3	23.7	34.2	15.8	18.4	3.19	17
Inadequate monitoring of construction activities relative to design HIRAs (by designers & construction project manager/principal agent)	10.5	2.6	21.1	34.2	21.1	10.5	3.18	18
Inadequate design HIRAs	20.5	5.1	7.7	46.2	20.5	0.0	3.03	19
Inadequate construction HIRAs	20.5	5.1	15.4	33.3	23.1	2.6	3.03	20
Inadequate Baseline Risk Assessment	17.9	5.1	23.1	28.2	17.9	7.7	3.00	21
Poor site layout	0.0	2.6	28.2	46.2	23.1	0.0	2.90	22
Work factors	0.0	7.9	28.9	34.2	23.7	5.3	2.89	23
Extreme temperatures	0.0	10.3	38.5	30.8	12.8	7.7	2.69	24

4. Conclusions

Given the extent to which a range of thirteen factors contribute to recurring H&S problems in construction, it can be concluded that: H&S problems recur; clients, designers, and contractors contribute thereto, and contractor-related factors include general planning and a range of H&S-related issues. The latter include inadequate management commitment, support, and involvement, financial provision, knowledge, skills, and experience. Given the latter, construction management have a major role to play in the mitigation of recurring H&S problems. Furthermore, a multi-stakeholder approach underscored by a multi-faceted contractor approach is required to mitigate recurring H&S problems.

Given that respondents rated their knowledge regarding eight project management of H&S aspects as below average, it can be concluded that: their tertiary built environment education is inadequate; they are lacking in terms of related continuing professional development (CPD), and there is limited understanding and appreciation of 'designing for construction H&S'.

Given the extent to which sixteen factors contribute to design originated hazards, it can be concluded that: clients, and designers contribute thereto; designers' tertiary built environment education is inadequate; designers are lacking in terms of related CPD, and there is limited understanding and appreciation of 'designing for construction H&S'.

Given the extent to which ten factors contribute to exposure to hazards on construction sites, it can be concluded that hazards have their origin in a range of stakeholders, and a range of contractor-related inadequacies contribute thereto.

Given the frequency at which twenty-four factors are the cause of construction accidents, it can be concluded that a range of stakeholders are the origin of the causes, however, the management of contractors has a predominating role to play, especially in terms of H&S training and worker participation in H&S.

5. Recommendations

H&S awareness should be maintained at industry, industry sector, organisation, and project level among all stakeholders. Furthermore, H&S should be a value on all projects, which implies that it is addressed from Stage 1, included in the project charter, addressed during CPMs' meetings with clients, designers, QSs, and contractors, and during project progress meetings. The management of all stakeholders should be committed to H&S, become involved therein, and support H&S endeavours.

CPMs should adopt a multi-stakeholder approach in terms of the project management of H&S throughout all six stages of projects to mitigate recurring H&S problems, and ideally, should evolve an integrated multi-stakeholder project H&S plan. HIRA should be a hallmark of projects commencing with the client BRA, complemented by design HIRA, and followed by construction HIRA. Planning by all stakeholders in general is important to ensure that H&S is integrated into the design, procurement, and construction processes.

Construction H&S should be embedded in all tertiary built environment education, and professional association and / or statutory council accreditation panels should assess the status quo. Professional association and statutory councils should promote, and preferably, deliver H&S-related CPD.

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Impact of Family Income on Public's Disaster Preparedness and Adoption of DRR Courses

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Abstract

When disasters occur, they affect a community's educational institutions, yet students are still one of the most ignored groups of people when it comes to disaster preparedness. Demographic characteristics highly determine and influence the effects of a disaster; hence, when preparing for it, the students' demographic information should be considered. Little research exists in the literature that addresses the impacts of such characteristics on students' preparedness. Therefore, this study aims to identify the impacts of demographic information related to family income on students' perceptions of disaster preparedness and disaster risk reduction (DRR) education. To fulfill this goal, a survey was conducted, and 111 responses were collected. Statistical analysis revealed a several intriguing conclusions. It was found that all of the students, irrespective of their family income, realize the necessity of DRR education and are willing to take the course if it is offered. Family income comes into play, however, when the resources of the DRR courses are discussed. Students with different family incomes have different perceptions regarding phycological first aid training and knowledge of disaster medicine included in DRR courses. It was found that family income has a significant impact on students' awareness regarding emergency procedures and communication systems offered by the university, as well as on students' confidence in assisting the university with disaster management during a disaster. This study will help educational institutions and practitioners develop DRR resources that will be best suited for the students with certain demographic characteristics.

Keywords: disaster preparedness, family income, students' perception of DRR education

1. Introduction

Factors like global warming, population density, and climate change are contributing to a continuous increase in the intensity and frequency of natural disasters [1,2,3]. With their unexpectedness and unthinkable destructive powers, they cause physical as well as psychological damages to the public and the environment [4, 5, 6, 7, 8, 9]. From 2016 to 2017, the monetary value of damages due to natural disasters was approximately $200 billion worldwide [10, 11, 12, 13], and in 2018, 355 people died as a result of a natural disaster in the United States [14]. To reduce these damages, all three phases of a disaster timeline must be prepared for: pre-disaster phase, disaster-impact phase, and post-disaster phase [15, 16, 17, 18]. The pre-disaster phase mainly focuses on the preparedness of the community and people [19]. When people are not prepared to face a disaster, its impact increases several folds [20, 21]. When victims are unable to establish contact with their close family while they are suffering from the disaster, it increases their mental distress [22, 23, 24]. In 2003, after understanding the importance of preparedness, the Federal Emergency Management Agency (FEMA) established a campaign called "Ready," which they update periodically [22, 25]. During the last update in 2019, they provided preparedness resources for kids, teens, families, educators, and organizations. Like this program, however, current research on disaster preparedness did not recognize the importance of preparedness for students, even though they are one of the most vulnerable groups when a disaster-affected area contains an educational institution.

Students are more vulnerable to disasters than the general population [26], as they lack basic preparedness knowledge [27]. In addition to suffering from physical injuries, they also endure emotional and behavioural disorders from which it takes a long time to recover. It is, therefore, important to establish the Disaster Risk Reduction (DRR) curriculum in educational institutions [28]. The students' demographics and the factors that affect their preparedness are important to such a curriculum, but the effects of some of the demographic factors are still unclear [29, 30].

This study aims to investigate the effects of the demographic factor, family income, on the students' disaster preparedness by fulfilling the following objectives: (i) performing a thorough literature review on disaster preparedness and students' perception of it, (ii) identifying the variables that determine the effects of family income on students' perception of disaster preparedness, and (iii) identifying the effects of family income on students' perception of DRR education and disaster preparedness. The findings of this study will help academic staff and practitioners take the steps necessary to better prepare the students for a disaster.

2. Literature review

2.1. Effects of disaster on students and educational institutions

Education quality of a society has a great impact on its economic level [31]; hence careful care should be devoted to ensuring that educational institutions are fully functional at their best quality level [32, 33]. Disasters can affect students in many ways. Jaradat et al. [34] claimed that disasters can affect universities by destroying the buildings and injuring the students, faculty, and staff, in addition to destroying the research data, laboratory samples, library resources, etc. Sometimes, disasters have long-term effects on educational institutions by damaging their water supplies and electricity [34]. Yet, students are not given their due compared to other groups of affected people. Mulilis et al. [35] found that students' level of preparedness is very low, as they don't have the proper knowledge and skills, partially due to their lack of interest [36], but also because teachers are not motivated to effectively teach disaster risk reduction courses [37]. Even though it is important to have a certain level of awareness regarding disasters [38], the awareness is not equivalent to being prepared. Being prepared also requires being able to successfully implement rescue practices during a disaster [39, 40].

2.2. Effect of demographic factors in disaster preparedness

Disaster preparedness can substantially reduce the negative impacts of disasters, and demographic factors often modify the preparedness of an individual [30]. Many researchers have studied the relationship between demographic factors and disaster preparedness. For example, Kim and Zakour [41] found that people from a community in which there is a strong bond among the residents tend to be better prepared for a disaster. Donner and Lavariega-Montforti [42] found that gender, education, and ethnicity do not necessarily have a direct connection with preparedness, but previous experience and income do. Yao [43] conducted a study of 349 participants to determine the influence of demographic factors on disaster preparedness and found that age and education level have little connection with the level of preparedness of the individual. Kaser et al [44] found that the demographic characteristics of an individual determine his/her preparedness for effective communication during a disaster.

2.3. Effect of income on disaster preparedness

Research shows that disaster preparedness is dependent on personal and family income. Kim and Zakour [41] established a direct relationship between income and available resources required for disaster preparedness. Doner and Lavariega-Montforti [42] found that those with higher income levels tend to store emergency supplies and/or build a shelter, which increases their level of emergency preparedness. However, their research, based on a community, did not conclude whether family income plays a role in the preparedness of the students. Gilhooly [45] found that people from low-income families often struggle with emergency preparedness. Above discussion emphasize the need to look into the relationship between family income and students' disaster preparedness.

2.4. Disaster preparedness and students

Donner and Lavariega-Montforti [42] found that older adults are more prepared than younger people to face a disaster. Young people attending schools and universities are the most vulnerable, as they are there for a significant portion of the day, without a legal guardian's supervision. Tan et al. [36] found that more than 70% of students desire DRR courses and would be willing to take them, as they lack confidence in their ability to survive a disaster. Unfortunately, government agencies mainly focus on disaster preparedness and rehabilitation at the community level and pay very little attention to students' preparedness [37].

The literature review signifies that even though there is a fair amount of research on the influence of demographic factors on disaster preparedness and students' preparedness, there is a dearth of information on how the demographic characteristics affect students' disaster preparedness. Studies that focus on the influence of family income on disaster preparedness of the students' are even rarer. Hence, the goal of this study is to investigate the impacts of family income on students' disaster preparedness.

3. Research methodology

This research followed the five-step methodology shown in Figure 1. The first step focused on conducting a thorough literature review to help the authors understand the current condition of the literature regarding students' disaster preparedness and to identify a list of variables for use in performing a statistical analysis. In the second step, questions for each variable, along with demographic questions, were developed for the survey. After that, the survey was pilot tested and modified based on the responses to make it more appropriate for the participants. After collecting the survey responses, descriptive and quantitative analyses were conducted.

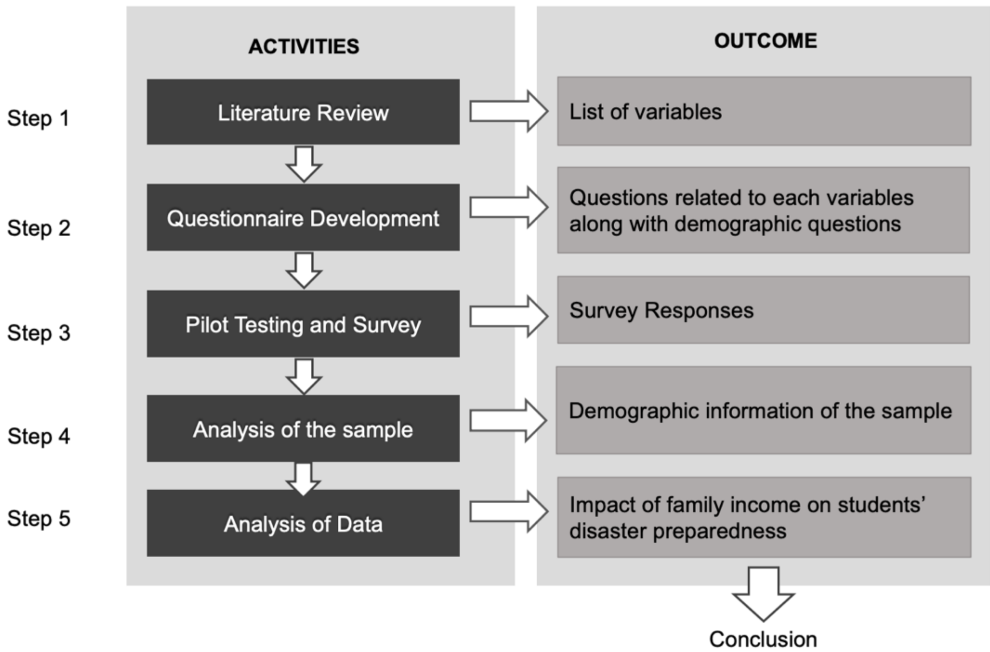

Fig. 1. Research methodology

As most of the questions in the survey followed a seven-point Likert scale, this study used the Kruskal-Wallis test to determine the differences in the way that students perceived the variables of disaster preparedness. SPSS software was used to perform the tests, and for greater precision, both 90% and 95% levels of confidence were considered. Table 1 shows the hypotheses developed for this study.

Table 1. Adopted hypotheses for the study.

Demographic characteristic of students	Statistical test	Hypotheses
Low and high family income	Kruskal-Wallis test	Null hypothesis (H_o): students with low family income and students with high family income have the same perception of DRR education Alternate hypothesis (H_a): students with low family income and students with high family income have different perception of DRR education

4. List of variables

Based on the literature review, a list was made of the variables that identify the level of preparedness of students (Table 2). The variables were arranged into five categories.

Table 2. P-Values testing the significance of students' perception of disaster preparedness and Disaster Risk Reduction (DRR) education.

Category	#	Variables
DRR education	1	DRR education should be made mandatory
	2	Willingness to take DRR course
	3	Likelihood of giving a test based on DRR education
	4	Curriculum provides psychological first aid training
	5	Curriculum or disaster drill include knowledge regarding disaster medicine
University resources	6	University has online database regarding disaster preparedness
	7	University has enough first aid boxes
	8	University buildings have disaster shelter
	9	University include student's guardian while providing disaster education
Community help	10	Importance of local communities on helping university to implement DRR courses
	11	Importance of local communities to help university
Awareness and experience	12	Open to collaborate while handling a disaster
	13	Confidence to assist with disaster management during emergency
	14	Confidence in providing basic first aid
	15	Impact of severe natural disaster on student's life
	16	Awareness of the emergency procedures in the university
	17	Awareness of communication system provided by university during emergency
Safety responsibility	18	Students are responsible for their own safety
	19	Friends are responsible for students' safety
	20	Parents are responsible for students' safety
	21	University is responsible for students' safety
	22	Government Agencies are responsible for students' safety

The first category is related to DRR education and includes the variables that indicate the requirement of DRR education and the students' perspectives towards the DRR curriculum. The second category is the university resources, which examines students' knowledge about the university's disaster-related supplies. The third category is the community assistance, which includes the variables that help understand students' perspectives regarding the community's role in the university's disaster preparedness. The fourth category is awareness and experience, which examines students' perspectives of their personal disaster awareness and experience. The fifth category is safety responsibility, which focuses on the students' beliefs about who is responsible for their safety during a disaster.

5. Survey development

Questions for each variable were prepared, using a seven-point Likert scale option. Demographic questions consisted of gender, year of birth, ethnicity, family income, etc. Figure 2 shows a couple sample questions of the survey.

Choose best suited option based on you understanding

How important it is for the local entities to help universities to implement DRR courses?	Not at all Important	Slightly Important	Somewhat Important	Moderately Important	Very Important	Quite Important	Extremely Important
	O	O	O	O	O	O	O

Do you agree that university should include guardian while providing disaster preparedness education?	Strongly disagree	Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Agree	Strongly Agree
	O	O	O	O	O	O	O

Fig. 2. Sample of the survey

The survey was pilot-tested and modified accordingly to make it appropriate for the intended participants.

6. Demographic information of the sample

The survey responses were analyzed and organized to portray the demographic information of the participants (Table 3). The majority of the participants were young Asians, under 25 years old. Only 11% of the participants were older than 29. The annual family income of 16% of the participants was less than $15,000, and 9% of the total participants had an annual family income greater than $100,000.

Table 3. Demographic information of the survey.

Category	Division	Number in sample	Percentage in sample
Ethnicity	Native American	0	0%
	African American	7	7%
	Asian	68	65%
	Hispanic	12	11%
	Other	18	17%
Age range	Under 25 years old	68	61%
	Between 25 to 29 years	43	39%
	Above 29 years old	11	10%
Annual family income	Less than $15,000	16	16%
	$15,000 to $30,000	28	28%
	$30,000 to $60,000	18	18%
	$60,000 to $100,000	28	28%
	More than $100,000	9	9%

7. Analysis of the students' perception of disaster preparedness and DRR education based on family income

Table 4 shows the results of the Kruskal-Wallis test for students with a low family income and a high family income. These values are important to understanding students' perceptions of their preparation to handle a disaster and whether the perceptions were influenced by their family income.

Table 4. Kruskal-Wallis test result for the students with low and high family income

Category	#	Variables	P-Values for Students with Low and High Family Income
DRR education	1	DRR education should be made mandatory	0.308
	2	Willingness to take DRR course	0.688
	3	Likelihood of giving a test based on DRR education	0.717
	4	Curriculum provides psychological first aid training	0.079*
	5	Curriculum or disaster drill include knowledge regarding disaster medicine	0.102*
University resources	6	University has online database regarding disaster preparedness	0.213
	7	University has enough first aid boxes	0.033**
	8	University buildings have disaster shelter	0.136
	9	University include student's guardian while providing disaster education	0.427
Community help	10	Importance of local communities on helping university to implement DRR courses	0.640
	11	Importance of local communities to help university	0.153
Awareness and experience	12	Open to collaborate while handling a disaster	0.120
	13	Confidence to assist with disaster management during emergency	0.030**
	14	Confidence in providing basic first aid	0.837
	15	Impact of severe natural disaster on student's life	0.188
	16	Awareness of the emergency procedures in the university	0.051*
	17	Awareness of communication system provided by university during emergency	0.086*
Safety responsibility	18	Students are responsible for their own safety	0.624
	19	Friends are responsible for students' safety	0.133
	20	Parents are responsible for students' safety	0.617
	21	University is responsible for students' safety	0.444
	22	Government Agencies are responsible for students' safety	0.146

Note: "*" Indicates 90% Level of Confidence and "**" Indicates 95% Level of Confidence

8. Interpretation of the result based on Kruskal-Wallis test

8.1. DRR education

The majority of the students, irrespective of their family income, believe that DRR education should be mandatory and are willing to take the course when it is offered by their institution. They are also willing to take a test that will assess their understanding of DRR. This shows that even though they are young, they are concerned about their preparedness to face a disaster. Not all of the students are satisfied with the design of the curriculum of the DRR education, however. Students from low- and high-income families have different perceptions of the psychological training and knowledge of medicine that the curriculum offers.

8.2. University resources

The majority of students, regardless of their family income, have the same perception of most of the disaster preparedness resources that the university offers. They believe that a university should have an online disaster database and a disaster shelter, and that the university should include their guardians in their efforts to better prepare the students for a disaster. However, students from low-income families and students from high-income families have different perspectives regarding the number of available first aid boxes.

8.3. Community help

Irrespective of the differences in the demographic characteristics of the students, all of them believe that it is impossible for them to have a satisfactory level of disaster preparedness without the community collaborating with the university. They also believe that the community can play a vital role in helping the institution implement DRR courses.

8.4. Awareness and experience

Family income doesn't necessarily impact the students' willingness to collaborate while handling a disastrous situation and providing basic first aid. Irrespective of their demographic characteristic, they believe that a disaster's impact on them can be severe; however, family income affects confidence and awareness levels. For example, students from low- and high-income families have different levels of awareness regarding the university's emergency procedures and communication system for handling a disaster.

8.5. Safety responsibility

From Table 4 it is evident that family income does not necessarily impact the students' perceptions regarding who is responsible for the safety of the students, themselves, friends, parents, university, and government agencies, during a disaster.

9. Interpretation of the result: based on box plots

To understand the effects that family income has on students' perceptions regarding disaster preparedness, a box plot for the variable "confidence to assist with disaster management during an emergency," with p-value 0.030 (Table 4) was drawn (Figure 3). It is evident from the figure that the students from the high-income families are more confident in rendering assistance during emergencies than those from low-income families.

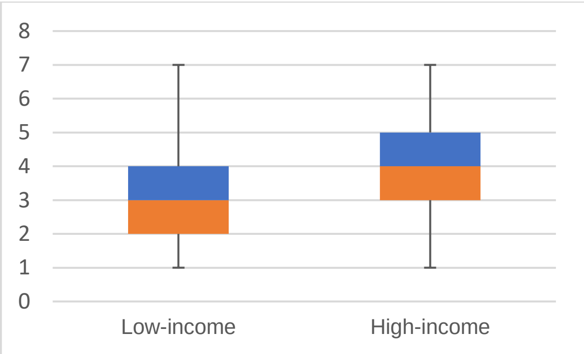

Fig. 3. Box plot for variable "confidence to assist with disaster management during an emergency"

10. Conclusion

Students are one of the most vulnerable and ignored groups of disaster-affected people. Hence, scholars and practitioners need to administer DRR education to help them gain the knowledge and preparation that are necessary to ensure their safety during a disaster. It is difficult to accomplish this task, as the current literature is barely sufficient to identify the impact of the students' demographic characteristics on their perception of disaster preparedness. This study addressed this issue by identifying the impacts of family income on students' perceptions of disaster preparedness and DRR education. A questionnaire was developed based on 22 variables, and 111 responses were collected. A statistical analysis revealed that family income has a significant impact on students' awareness of emergency procedures and communication systems offered by the university. It also impacts students' levels of confidence in assisting their university during a disaster. This study will help educational institutions and practitioners in developing DRR resources that are best suited for students with certain demographic characteristics.

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Impact of Natural Disasters on Construction Projects: Strategies to Prevent Cost and Schedule Overruns in Reconstruction Projects

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Abstract

The number of natural catastrophic events has increased remarkably in recent decades, and the resulting challenges of construction projects have increased even more. It is imperative to recognize these challenges and employ suitable strategies to mitigate them to avoid project failures, which is the basis of this study. To become more knowledgeable about this subject, more than 100 scholarly articles, including peer-reviewed papers and other types of publications, were reviewed and a list of eleven challenges was developed. The next step was to identify the management strategies that could be applied to overcome the challenges. The outcomes from this study concisely help decision-makers and project managers allocate their resources wisely after a disaster, implement construction activities more efficiently, and achieve higher rates of productivity while reducing the consequences of disruptive events.

Keywords: natural disasters, construction, strategy, overrun, cost and schedule

1. Introduction

The unexpected and destructive power of disasters diminish the social stratification and cause physical damage and psychological trauma to society and harm to the environment [1,2,3]. The number and severity of natural disasters has increased significantly in recent years [4]. There were only about 100 natural disasters reported annually worldwide during the 1980s, and that number has risen to over 300 since 2000 [5]. Disasters have impacted both developed and developing countries, and the United States is one of the top five countries most frequently impacted [5,6]. Both direct and indirect impacts of natural disasters are devastating to business activities and their community [7], as they affect many parties, such as company management, investors, suppliers, etc. [8]. The construction industry is in the maelstrom of the aftermath of the disasters, as they deal with damage to buildings and infrastructures that must be repaired immediately [9,10,11]. Disaster recovery made without knowledge of effective strategies results in an increase of losses [6,12,13,14,15], while studying natural catastrophes facilitates better decision-making regarding the timing and planning for reconstruction materials for future disasters [16, 17].

This study aims to investigate and analyze the impacts of natural disasters on construction projects and to develop a list of resultant challenges and management strategies to address them. These research results will help project managers identify, prevent, and manage the challenges caused by natural disasters in construction projects and help them allocate their resources effectively.

2. Methodology

This research methodology includes four main steps. A thorough literature search was conducted in the first step, and more than 100 scholarly articles were reviewed to meet the objectives of this study. In the next step, the existing database was scrutinized, and data was collected. In the third `

step, potential challenges were identified from the finalized database, and in the fourth step, the management strategies were identified from the literature. Finally, the conclusions were presented. Figure 1 shows the adopted methodology of this study.

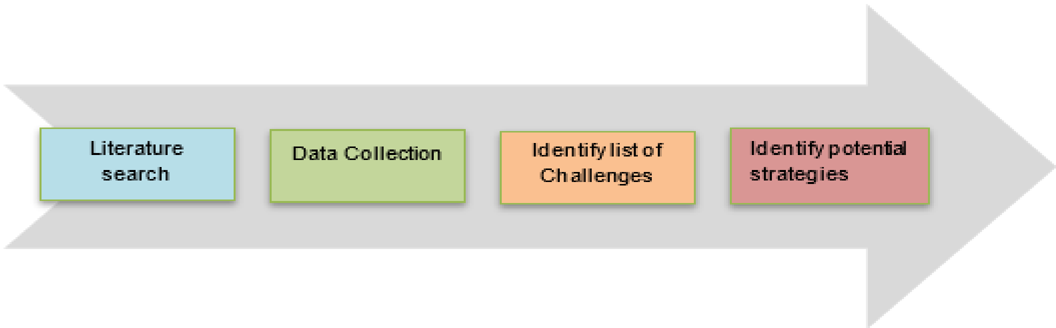

Figure 1. Research methodology

3. Data collection

As presented in Figure1, scholarly articles related to challenges in construction after a disaster were collected by entering various keywords in search engines like Scopus, Google scholar, Science Direct, etc. After reviewing the journal articles, essential information like the name and publication year of the articles were documented. Table 1 shows details of the reviewed journals and articles published in this area. It can be noted that the Natural Hazards journal ranked first with 9 papers, which accounted for 11% of all the papers.

Table 1. Frequency of studied journals

Journal Title	Frequency	Percentage
Natural Hazards review	9	11%
Journal of Computing in Civil Engineering	7	9%
Construction Research Congress	5	7%
International Journal of Disaster Risk Reduction	5	7%
Journal of Structural Engineering	4	5%
Journal of Construction Engineering and Management	3	4%
Social and Behavioral Sciences	3	4%
Sustainable Transportation Systems	3	4%
Nature	3	4%
Procedia Engineering	2	2%
Disaster Prevention and Management	2	2%
Applied Economics	2	2%
Building Research and Information	2	2%
Earthquake Engineering and Engineering Vibration	2	2%
Journal of Aerospace Engineering	2	2%
Others	27	33%
Total	81	100%

Although the effects of natural disasters have been experienced worldwide for many years, researchers have only recently begun to focus on the subject. The trends in the number of journal articles published over the years is depicted in the Figure 2.

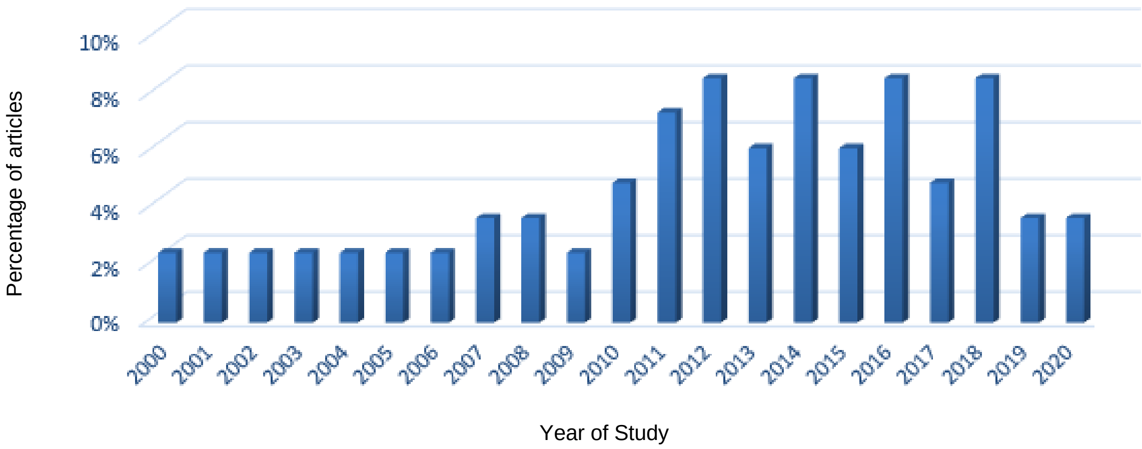

Figure 2. Distribution of articles based on year of publication

4. Identification of challenges for construction projects created by natural disasters

The 11 challenges observed through a thorough review of the literature are depicted in Table 2 and are discussed below.

Table 2. List of the identified challenges

#	Challenges	Source
C1	Increase in overhead cost and profit margins	[17]
C2	Disruption of transportation network (logistics)	[18]
C3	Psychological and environmental factors	[19]
C4	Damages to machinery	[20]
C5	Inflation of construction labor charges	[21]
C6	Increase in demand for labor and equipment	[21, 22, 23]
C7	Loss of lives and impact on neighboring communities	[24]
C8	Damages to materials in construction site	[25]
C9	Stability of structural components	[26]
C10	Project schedule	[27]
C11	Interdependent utilities	[28]

4.1. Increase in overhead costs and profit margins

Damage to the land and equipment, and loss of revenue were identified as sources of financial stress after a natural disaster. Damages to manufacturing equipment and machinery may be severe and disrupt production [20], and the loss of equipment and supplies can cause temporary cessation of construction projects, delaying the repair or restoration of structures [29]. In 2010, the aftershock of the Canterbury earthquake hit the South Island of New Zealand and impacted a large number of infrastructures, including natural heritage sites. This disaster resulted in damage to structures that led to reconstruction costs of approximately $5 billion [30]. The cost of labor tends to inflate in the construction industry after a disaster and is considered one of the factors for cost overruns in projects [31]. Large amounts of debris are accumulated at the site and must be hauled off and dumped, and the hazardous materials need to be discarded safely [32]. All the above mentioned tasks require additional labor and equipment that incur additional cost and time [22,33]. For instance, the material cost of strand board increased up to 30% and tarpaulin sheets increased up to 2000% after the Sydney hailstorm [17]. Contractors often increase the overhead and profit margins and may change the bidding values in the aftermath of disasters. They also tend to increase the cost of repairs, thereby increasing the overall project cost [17].

4.2. Logistics

Disruptions after disasters to public and utility services such as electricity, water supply and sewage, fuel, transportations, and telecommunications can be responsible for slowing down construction [18]. Lack of facilities and public infrastructures is also an expected effect that requires projects to look at an alternative for emergency logistic support [20]. Any failure in the civil engineering services results in a disruption in delivering emergency services such as rescue operations [34]; hence, it is vital that agencies related to emergency services stay aware of the vulnerability of critical infrastructure systems [35].

4.3. Labor

The demand for skilled labor and construction materials drastically increases after a natural disaster and usually results in massive price escalations [21]. Shortages of resources, together with the increase in the cost of materials, slow down the post-disaster construction process [36]. The increase in repair costs following large-scale natural disasters is measured as a percentage increase in construction costs and affects the supply of construction materials and labor [37]. Sudden and temporary escalation in the cost of construction materials, labor, and services due to the increased demand following natural disasters is called "demand surge" (Subcommittee on Ratemaking of the Casualty Committee 2000). Another impact of disasters on construction sites is the increased demand for skilled laborers [23]. In New Zealand, after the 2010 and 2011 Christchurch earthquakes, there was a high demand for skilled labor. The research reports that the complexity of structures increases as disaster resiliency must be increased, and the incorporation of revised building codes, the need for innovative construction, financial constraints etc., increase the requirements for skilled labor [23]. The demand for labor begins or escalates based on the impact of the disaster. The construction industry in general and the project managers specifically should take the workforce capacity into account in the planning phase by allocating a separate cost for it and considering the risks of labor shortages [23]. The questionnaire survey conducted by the research team at Christchurch revealed that 65 percent of the poaching of laborers from other construction companies began to increase after the Queensland earthquake. Experts believe that both time and money are wasted in the pursuit of skilled workers to deliver projects with the desired quality [23].

4.4. Psychological environmental factors

The frequency of disaster events across the globe has led to an increase in psychological environmental risks [2]. Psychological environmental factors refer to the culture, general practices, and climate of the workplace. Natural disasters create distress among construction firms' management teams and workers, which takes the form of job insecurity, uncertainty about work contracts, and discriminatory practices affecting salaries and career development. Natural disasters also influence organizational factors [19].

4.5. Loss of lives and impact on neighboring communities

Unsecured materials at construction sites are vulnerable to being converted into debris, thereby causing injuries to people at the site when it gets tossed about at a high velocity [38]. When the construction site is not secure, and if it is subjected to intense wind forces, the impacts resulting from it could create a series of further damages that disturb neighboring communities. Construction sites are exposed to different types of natural disasters, including fire. During the event of fire disasters, one of the factors to be considered on a construction site is the safety of the construction crew/employers at the site. This factor must be given higher consideration when it comes to high rise building projects, as the workers have to be evacuated from each floor, which consumes a lot of time [24].

4.6. Damages to materials and machinery at construction sites

Depending on the magnitude of the wind force, materials at construction sites, such as steel props, plywood, and other heavy objects, can be thrown about at a very high speed. Residential projects that employ light wooden frame construction are significantly impacted by disasters like hurricanes [25]. From several surveys conducted by the author to study the impacts of Hurricane Sandy, it became evident that the residential structures that were built using light wooden frames at Ortley Beach, located on the narrow peninsula between Barnegat Bay and the Atlantic Ocean, were hit the hardest by the storm surge. In coastal areas, frontal dunes act as shelter to other structures by absorbing the impact. The coastal dunes on Ortley Beach were damaged, and as a result the structures were exposed to higher loads from waves, which led to failure. In addition to damages resulting from storm surges, inadequately designed structures generate water-borne debris when they become fragments, resulting in increased havoc as it carries high impact from waves as well as the debris [25]. Huge amounts of raw materials are wasted at construction sites due to disasters. Generally, there is a high demand for procuring construction materials at a regional level following a serious disaster [32]. After the Wellington disaster in New Zealand, the demand for aggregates increased at the regional level, as the local markets were not able to produce adequate quantites because of the disaster's impact on the quarries [39]. Demands for cement also increased, and as the manufacturing unit was able to work only for a limited time and produce less, materials had to be imported from international markets which further increased costs [39].

4.7.Stability of structural components

Structures under construction do not have any fire protection systems or earthquake-resistant elements, which makes them highly prone to destruction during disastrous events [38]. Coastal structures and projects face inundation from storm surges, and the site can experience hydrostatic uplift as a result of the buoyant force that develops from air pockets and can turn into debris in the water or obstacles holding water. This results in weakening the structural components. Numerous structures and structures under construction were destroyed or weakened by storm surges during Hurricane Katrina [26]. The pavements had lower strength in the strength penetration tests conducted by the Louisiana Transportation Research Centre after the impact of the hurricane [40].

4.8. Project schedule overruns

One of the common issues that construction companies face following a disaster is schedule overruns [3, 27, 41]. In the Aegean Highway Project that involved three identical tunnels of 22 km length, one of the tunnels adjacent to an existing national road faced breakdown as huge rocks fell over the road, causing the death of the project manager on the site. The investigators were unable to determine whether the disaster occurred because of the natural phenomena or technical issues, but there was no emergency plan in place, which resulted in a delay in the completion of the project [16, 42]. Various unexpected situations can occur that impact the completion of construction and reconstruction projects and might increase the project costs [6, 43]. These unexpected situations can arise from factors such as a weakening of the economy; political wars; socioeconomic conditions; technical errors due to lack of skilled workers; improper site conditions; and natural disasters such as earthquakes, hurricanes, and floods [13,43].

4.9. Interdependent utilities

Huge catastrophic events like Hurricane Katrina affect construction sites by damaging equipment, disrupting utility lines such as those for electricity and water, and creating debris. In 2012, Hurricane Sandy resulted in $185 million damage to World Trade Centre construction site, and disrupted interdependent utilities. Underground infrastructures such as water distribution systems and waste-water collection networks are exposed to higher pressures and external loads during such events and require high levels of strength to withstand such intense pressures. Hurricane Rita that occurred in 2005 in Louisiana damaged the wastewater treatment plants to the extent that it took nearly two weeks to restore their function [28]. These types of underground structures and components will have a shorter life span than what was initially predicted for them because of corrosion caused by the accumulation of debris and water seepage during disastrous events like floods [44].

5. Identification of management strategies

Potential management strategies were collected from the literature to lessen the impact of challenges. Table 3 shows the list of identified strategies, some of which are discussed below.

Since disasters such as hurricanes and typhoons create serious damage to materials and machinery on construction sites, developments are emerging that will enhance the level of preparedness and reduce the amount of losses to the public [45, 46, 47, 48]. The literature highlights the importance of new imaging for simulation frameworks that aids in discovering the risks that are caused by wind-induced disasters [38]. The imaging depicts a clear picture of the extent to which the construction site will face damages by predicting the force at which the objects in the construction site could travel. This enables laborers to be proactive in preparing construction sites for possible disasters and at the same time reduce the number of laborers required to carry out the operations as a result, reducing the cost for inspecting the site [38]. Recently, the construction industry has begun to use radio frequency Identification technology (RFID), an automated tracking device that tracks materials at the site and has been shown to save 3.1% of the construction cost [49] in recovering construction operations.

Another recommended strategy is adopting the Geographical Information System, which helps in debris removal. The removal of debris following a disaster is a time-consuming, expensive, and intensive process that requires heavy equipment that sometime encounters spatial constraints [41]. The schedule and cost of a project overrun can be significantly reduced if proper preparedness tools are considered during the planning phase. A balanced scorecard method can be adopted [27], and plans can be put in place for procuring materials and modifying the construction in the event of disaster [39]. A recovery model was proposed for dealing effectively with unanticipated situations by using existing approaches and PMBOK's knowledge to recover construction projects after a disaster [42]. The model developed, by the author, focuses on identifying major hazards and planning effective methods to deal with such unanticipated situations in the pre-disaster phase, and planning activities that will help return the project back to its normal functioning state with as little damage as possible in the post-disaster phase.

Table 3. Strategies for the identified challenges

#	Challenges	Management Strategies
1	C3	Enhancing teamwork by team performance training
2	C9	Adopting AD-CIRC model to derive storm surge for identifying the damages caused to structural components
3	C6	Accessing Geographical Information System
4	C5	Using a simulation dynamics (SD) model to make decisions about the labor force
5	C1	Incorporating RFID to track materials in construction sites
6	C1	Using multi linear regression models for predicting an approximate increase in cost
7	C4, C8	Using imaging to simulate a framework to reduce the damage caused to materials, machinery
8	C7	Incorporating simulation software to create emergency plans for evacuation of workers
9	C2, C11	Employing the Bayesian network theory and system dynamics simulation to assess the criticality of the infrastructure
10	C10	Adopting the balance score method to reduce overruns

Although OSHA provides safety regulations for means of egress, the practical implementation can be attributed to the emergency plans adopted by the contractor. Emergency plans include real life drills that use fake alarm systems. These drills hinder the construction activity and schedule, causing minor delays in project activity and increasing the overhead cost. Irrespective of the number of practice drills, the behavior of the workers might vary during the actual evacuation environment. In order to overcome the above-mentioned challenges, the author in [24] proposes a simulation framework that assists contractors in assessing the evacuation of the crew throughout the project's duration.

Psychological and environmental factors affecting the working conditions of the crew can be improved by conducting team performance training and encouraging teamwork, thereby increasing the workers' behavioral attributes, collaboration within the construction crew, and production [50]. The author in [51] highlighted the importance of the AD-CIRC model, which helps predict storm surges and the damages that will be caused to structural components. This model provides an opportunity to design buildings that have the structural stability to withstand such heavy forces. In the aftermath of disasters, critical infrastructures must be identified, and their restoration must be given priority [17]. To assess the criticality of critical infrastructures, the author in [35] introduced a decision support system, using the Bayesian network theory and system dynamics simulation system. A multilinear regression model developed by the author in [52] can be used for predicting approximate increases in cost, which helps in allocating sufficient funds in the planning phase. The simulation dynamics (SD) developed by author in [53] helps managers maker sounder decisions pertaining to whether to hire more laborers or operate with the currently available workforce.

6. Conclusion

This study conducted a thorough literature review on the challenges and potential management strategies used in construction projects after a disaster and revealed 11 challenges that can significantly affect the progress of a project after a disaster. Increases in costs and overhead margins is one of the most important challenges noted in the literature; other important challenges are an increase in demand for labor and equipment and disruption of transportation networks. This review also identified 10 potential strategies that are effective in controlling the challenges. Among those strategies, accessing geographical Information systems, and using multilinear regression models and the Bayesian network theory were found to be the most important. It is expected that the outcomes of this study will help project managers and policymakers better understand the challenges following a natural disaster and will enable them to prioritize their resources in a productive manner.

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Is Virtual Reality Safety Training Making the Construction Industry Safer?

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Abstract

The construction industry by nature is an unsafe environment to work in. It's a large industry that employs a lot of people and unfortunately experiences a large number of accident's each year. Construction companies invest a lot of money in safety training trying to educate their work forces. The primary types of training are instructor led, through training manuals and hands on. 80% of accidents happen due to human error. This statistic shows the conventional ways of training need improvements. Virtual Reality's popularity has exploded over the last decade and its use in the construction industry has increased mainly due to the use of 3D modeling for construction designs. Construction companies have also started using it as a safety training tool. It provides the ability to put a worker in an unsafe situation virtually for them to think through the process and come up with a solution. This paper is intended to review the research that has already been conducted on the topic of virtual reality use in the construction safety training industry. It will also perform a survey of construction contractors to determine if they have used or are planning to us virtual reality safety training.

Keywords: Virtual Reality, VR, BIM, 3D modeling, construction safety, training

1. Introduction and background

In 2017 there were 4,674 worker fatalities within the private sector in the United States of America, the construction industry was responsible for 971 deaths, which is 20.7% ("Home | Occupational Safety and Health Administration," n.d.). The construction industry employees about 5% of workers (Writer, n.d.). Of the many reasons an accident can happen up to 80% are caused by human error (Garrett & Teizer, 2009). This is usually caused by lack of safety measures, training and lack of safety awareness (Li, Yi, Chi, Wang, & Chan, 2018). Safety training is one of the most effective ways to prevent accidents (Bin, Xi, Yi, & Ping, 2019). Anyone who has been through traditional safety training knows that it is viewed as more of a chore or inconvenience to the worker and its just a box that needs to be checked. This is due to the traditional training methods that cannot produce an immersive training environment (Bin et al., 2019).

Virtual Reality (VR) technologies and trainings have been developed to help provide a more immersive training, placing the user in a virtual environment that can mimic real situations. VR has been used to train pilots, put military members in combat situations, surgeons and test manufacturing methods (Bhoir & Esmaeili, 2015a). Recently companies have been developing construction safety specific training for subjects like trench safety, fall protection, working from heights, welding and lock out tag out operations (pixo2019, n.d.). VR training is designed to keep the participants interest through the entire training resulting in a higher retention of the safety material.

This paper is intended to review the research that has already been conducted on the topic of virtual reality use in the construction safety training industry. It will also perform a survey of construction contractors to determine if they have used or are planning to us virtual reality safety training. It will also survey roofing contractors to see if they have incorporated VR in their training regime.

1.1. History of Virtual Reality

Virtual Reality (VR) has been in development for over 100 years. The concept of virtual reality is "creating the illusion that we are present somewhere that we are not" ("History Of Virtual Reality," n.d.), then the beginning of the concept can be traced back early nineteenth century with panoramic paintings. Then throughout the late nineteenth and early twentieth century the stereoscopic viewer was created. This placed the same photo side by side in the viewer and the eyes would view the photos as a three-dimensional photo creating depth. Around this same time Edward Link created the first flight simulator called the Link trainer, which was patented in 1931. It was developed to safely train pilots and during World War II, 10,000 Link Trainers were used to train 500,000 pilots ("History Of Virtual Reality," n.d.). Also, in the 1930's a science fiction movie, named Pygmalion's Spectacles, about a pair of goggles that led the user to a fictitious world. Then in the 1950's Morton Heilig created Sensorama, which was a theater cabinet that provided stimulation to the eyes, ears, nose and touch through screens, speakers, smell generators and vibrators.

The first head mounted VR display was created in 1965, this allowed the user to view a video screen with each eye and incorporated a motion tracking system that was hooked up to a camera. Modern day virtual reality headsets were developed in 1987, by Jaron Lanier, called the EyePhone ("History Of Virtual Reality," n.d.). He also created the Dataglove to stimulate feel ("History Of Virtual Reality," n.d.). In the 1990's video games were created using virtual reality technology. At first the technology was expensive, so these games were only offered in video arcades. Sega created a prototype for what was thought to be the first mass produced VR headset and promoted it at the Consumer electronics show in 1993. This headset included speakers and LCD screens. Unfortunately, the headset was never finished. Nintendo also tried its hand created a household VR gaming system. Due to its lack of colors and difficulty of use it never took off and was discontinued after only one year ("History Of Virtual Reality," n.d.).

In 1999 the movie trilogy The Matrix was released. Although not the first film to depict a virtual reality world, it was the first that appealed to the mainstream public. In the twenty first century virtual reality development has soared especially with the fast advancement of computer and smart phone technologies. Also the video game industry is driving the technology, with systems like PlayStation and Xbox coming out with their own VR headsets and game controllers. Tech giants Facebook, Google and Samsung have either developed their own VR headsets or have bought virtual reality technology companies ("History Of Virtual Reality," n.d.).

1.2. Construction safety

The construction industry is a dangerous work environment with complex project sites and uneducated workers (Pedro, Le, & Park, 2016). Over the last two hundred years there has been major advancements in construction safety and workers' rights, but still the industry employs 5% of all workers and is responsible for 17% of workplace accidents (Writer, n.d.)

During the early 1800's safety in the construction industry was nonexistent. After the civil war workers began buying insurance incase of a job-related injury. Some employers began providing insurance and started paying higher wages, due to workers leaving high risk positions.

In the 1900s commissions began to form protecting construction workers, but unfortunately, they had little power and provided little benefit. New York was the first state to pass a worker's compensation law to dictate a fixed rate that employers would pay for injured workers. Then in 1913 the National Safety Council and the U.S. Department of labor was founded. These federal organizations promoted and focused on safe workplaces. In 1916 the Federal Compensation Act was established mandating benefits for workers who were injured or caught illnesses while working on the job. Within 5 years 44 states had adopted similar laws (Writer, n.d.).

Probably the most significant development in construction safety was the establishment of the Occupational and Health Act, which created the Occupational Safety and Health Administration (Writer, n.d.). OSHA's main goal is to oversee and enforce safe working conditions for workers by setting standards and providing training ("About OSHA | Occupational Safety and Health Administration," n.d.). They developed the 1926 construction safety manual that sets the minimum standards for construction job site safety. The Department of Defense developed the EM 385 which meets or exceeds OSHA's manual and is the manual in which safety regulations are enforced on government construction sites. With all this development in construction safety over the years, the industry lost 971 workers in 2017 ("Home | Occupational Safety and Health Administration," n.d.).

1.3. VR in construction

People learn in many different ways. Some people are auditory learners and prefer to listen to lectures than read note. Some are kinesthetic learners where they like to act out events to reinforce the information. Visual learners prefer seeing the information in diagrams, pictures or words. Lastly there are reading/writing learners who prefer their learning to be in the form of the written word. It is important to train workers in many ways to cater to every learning type (Bhoir & Esmaeili, 2015a). Virtual reality training has been introduced into the construction training sector for many reasons including its ability to recreate dangerous situations without being on a jobsite. It also allows students to train at their own pace, it is not weather dependent and can be conducted at any time (Bhoir & Esmaeili, 2015a). With this type of training workers assess dangerous situations, choose a course of action, and implement that action and see the results (Sacks, Perlman, & Barak, 2013). Virtual reality safety trainings have been developed for many different construction activities and benefits, see table 1(Bhoir & Esmaeili, 2015a).

Table 1. Summary of virtual reality applications in construction safety

	Purpose	Benefits/Contributions
Squelch (2001)	Developing a training simulator for identifying fall of ground hazards in mining industry.	Creating an effective medium for illiterate workers in the mining industry to identify hazards.
Hadikusumo and Rowlinson (2004)	Developing a design for safety (DFSP) tool.	Capturing the tacit safety knowledge from safety engineers about construction safety hazards and precautions.
Chantawit et al. (2005)	Developing a platform to integrate 3D models and safety concerns with a project schedule.	Enabling users to analyze construction sequence, measure spatial and temporal interactions, and monitor safety measures that are required to carry out specific works according to a project schedule.
Zhao et al. (2009)	Developing an electrical safety training program to enhance workers' awareness.	Developing several training modules allows sorting relevant hazards and scenarios to prevent overloading a user with information.
Dickinson et al. (2011)	Developing a serious game for trench safety education.	Engaging students and providing an innovative medium for hands-on activities.
Guo et al. (2012), Li et al. (2012)	Developing a multiuser virtual safety training system for construction plant operations.	Developing an easy multi-user virtual environment that allows trainees to collaborate with each other.
Park and Kim (2013)	Developing a framework to integrate Building Information Modeling (BIM) and location tracking, augmented realty, and game technologies.	Enhancing hazard identification and real-time communication between construction managers and workers.
Fang et al. (2014)	Developing a framework to integrate Building Information Modeling (BIM) and real-time location tracking technology in a virtual environment	Developing a close to real experience for training crane operators by simulating the as-built work scenarios.

2. Literature review

Virtual reality is a fairly new technology being utilized in the construction industry. It is mainly used in combination with 3D modeling to give stakeholders the ability to virtually walk through buildings to get a feel for the space and layout. Recently it has been used by the construction safety industry as a safety training tool. Since it is fairly new to the construction safety industry not a lot of research has been conducted on if it is making the construction industry safer. Most of the research done is the utilization and functionality of VR for construction safety. Figure-1 shows the number of paper s published per year from 2000-2017. With that said Sneda Bhoir and Behzad Esmaeili conducted research on the use of VR as a safety training tool. Their research, conducted in 2015, determined that it was being used by 0% of their survey responding contractors. They made the conclusion computer knowledge among construction workers is usually low. Contractors also did not have the specialized experience needed to change or modify virtual environments (Bhoir & Esmaeili, 2015a). Their research also revealed that only 7% of respondents indicated they may try VR technology within the next 2 years.

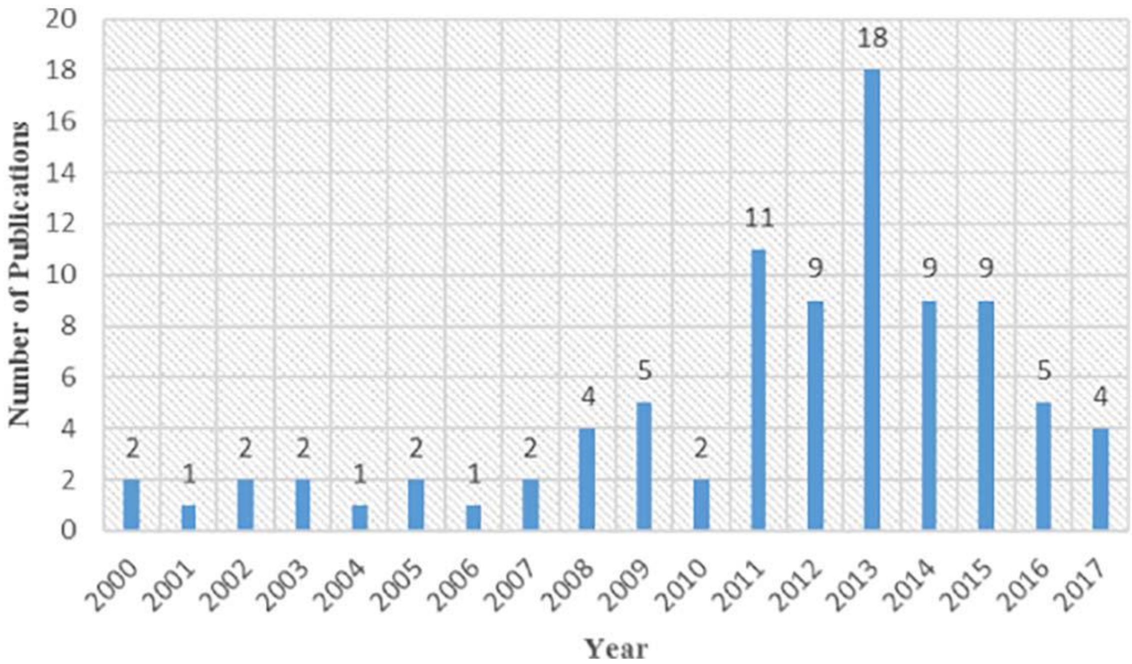

Fig. 1. Number of papers published per year on utilization and functionality of VR for construction safety (Li, Yi, Chi, Wang, & Chan, 2018)

3. Research methodology, results and analysis

3.1. Research Methodology

Research conducted for this paper was mostly reviewing prior studies and telephone surveys. As noted before Sneda Bhoir and Behzad Esmaeili, conducted research in 2015 which concluded, 0% of responding contractors were using VR as a training tool and only 7% plan on using it in the next few years. Those contractors were mostly using more conventional training tools like instructor led and hands on training. The breakdown of the training types from Bhoir and Esmaeili research are shown in table 2, below.

Table 2 Construction Safety Training Methods

#	Training methods	Percentage used	#	Training methods	Percentage used
1	Instructor led	100%	5	Computer based	50%
2	Training manuals	93%	6	Game based	29%
3	Audio/visual	86%	7	Workshops	21%
4	Hands on	79%	8	Virtual reality	0%

Telephone surveys were also conducted for this paper. The researcher first started to call general contractors from Engineering and Record (ENR) top 400 contractors list. He quickly realized the top companies are very large and finding the right person to speak with was very difficult. He then tried calling federal contractors that were working on Camp Lejeune and Fort Bragg, the two nearest military facilities. These construction companies are also large but connecting with the right safety person to survey was much easier. In total 12 construction companies were called 4 were actively using VR technology for construction safety training, 2 were not using safety training but did indicate that they had planned to in the next few years, and 6 responded that they did not plan on using this technology in the near future. Below are the survey questions used for this research.

1. Does your company currently use virtual reality as a safety training measure? If not why not?
2. If so what topics does the virtual reality training cover? (ie. fall protection, trenching, leading edge, welding)
3. Do you think that it helps keep the attention of your trainees better?
4. Do you think it helps with retention of the safety material?
5. Have you seen a difference in the amount of accidents your company has after including VR in your training?
6. What was your EMR before you starting using virtual reality? What is your current EMR?
7. What is the biggest advantage in using VR for construction safety training?
8. What needs to be improved to make VR a better training tool?
9. Are you planning to expand the use of VR in your training program? If so how?

If the company responded "no" to question 1, the follow-up questions are:

1. What training methods do you currently employ?
2. Do you plan to introduce VR into your training program?
3. Why has VR not been utilized up to his point?
4. Do you plan to introduce it within the next 2 years?

3.2. Survey results and analysis

3.2.1. Companies using VR technology

Of the companies surveyed 33% were currently using VR technology which is large increase from the response that Bhoir and Esmaeili received in 2015. Of the topics that they cover in their VR training all responded they use it for fall protection. One company used it for trench safety and two companies used VR for crane signaling, which was a use the researcher had not read about while conducting the literature research. All companies thought the VR training kept the attention of the trainees better and helped with the retention of the material. Most companies have teamed up with training developer to receive new and updated trainings on a regular basis. MindForge is a company that many of the contractors used that develops VR safety training scenarios.

One thing every contractor that uses the VR technology has in common is their dedication to safety. All these companies have very low EMR rates and have not seen a difference since starting to use VR technology because their rates have always been low. Therefore, they all answered that they have not seen a difference in their EMR rates. The advantages the contractors answered were being able to put personnel in dangerous scenario without being in a dangerous situation. They also answered that it engaged the trainees and made them process a situation, identify the problem and work through the solution. VR being a new technology has a lot of room for improvement. The improvements that contractors identified were the need for more content, VR becoming more portable and making the technology easier to set up on job sites. They all also plan on expanding their use of VR training with more content.

3.2.2. Companies that do not use VR

Eight of the twelve companies surveyed indicated that they did not currently use VR as a training tool. Two companies were using VR in conjunction with their 3D modeling for building walk throughs. Four companies did not know VR was being used for construction safety, which was surprising. The training methods used by these companies were OSHA 30 hour class, role playing, hands on and some used 3rd party training companies. Two companies indicated that they planned to try VR as a training tool in the next two years. Two companies stated they did not use VR because they did not think it was a better training tool then what they were doing now. They also said what they used was working so they had no reason to change their safety training strategy.

3.3. Survey conclusion

The survey results show that there is an increased use of VR technology for construction safety training. The companies using the training appear to be ones that safety is their number one priority and they are always looking for ways to expand on their safety culture and training. The companies that have begun using VR are all in and think the technology is very useful and plan to expand their use over the next few years.

Two companies indicated they plan to use VR technology over the next two years. They had not use it to this point because they had not heard or learned much about it. One company actually said the researcher had convinced them to try it. Both companies have a low EMR and are always willing to try new measures to train its employees. Both companies were using the VR technology already for 3D modeling walkthroughs of buildings, so the company in general incorporates and uses new and emerging technology.

Six companies do not plan to use the VR technology in the near future. This was due to being satisfied with their current training measures, that in their opinion worked, so not need to change it. They also indicated they can replicate the training scenarios onsite without the use of headsets. The companies that used third party training companies said VR was no something that was offered and if it was, they would be willing to try it, but had not heard that it would be offered in the future.

4. Conclusion and future research

Although the concept of virtual reality has been around for many years, its only recently that the technology has advanced enough for it to move from the video game world into business. The use of BIM and 3D modeling in construction introduced VR to the construction industry. Since then it has started to be used for construction safety training. Being a newer technology there has been limited research focused on its use in the construction safety industry. Most of the research to date appears to be focused on the technology itself and functionality of it. Bhoir and Esmaeili have conducted the only research found that focuses on it actual use by contractors. Their research was performed in 2015, since that time the virtual reality technology has advanced and so have construction companies use. Although not widely accepted as a standard training tool it is rowing in use and with that the available content is growing as well. Innovative and safety conscious companies seem to be the first that are trying out this technology. They have low EMR rates and are always looking for new training measures to keep their employees sharp. The research conducted in this paper shows that 33% of companies surveyed used VR and this is up form 0%, from Bhoir and Esmaeili's research. It is however inconclusive on if it's making the industry safer. The companies surveyed do not have data that would either support or not support if VR is making the industry safer.

The future seems bright for the virtual reality industry. The technology is advancing all the time, which is increasing its usage. The research in this paper shows a 33% increase in use from 2015's research. A similar research should be performed in 3-4 years to see if the usage is still increasing and at what rate. Also, research should be performed on what topics the companies are using VR training.

At the beginning of this research it was difficult to survey the large global contractors, due to not being connected with the right people. Some companies also refused to be a part of research of any kind. A good way to really survey construction contractors is to do it at a construction safety conference, where you have a large amount of safety professionals together. Also giving a demonstration of the VR technology and its use for construction safety then survey the conference about who plans to try and use it in the next two years.

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Noise Reduction and Ventilation System: A Design of a New Intelligent Window

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Abstract

In order to enable people to have a more comfortable living environment, a new type of intelligent window has been invented to solve the problem that traditional windows cannot meet the people's need for noise reduction and natural ventilation simultaneously. This intelligent window system uses light and environment-friendly materials, and equips with circuit system which can control the hardware to achieve the optimal opening size by scientific calculation method and monitoring real-time environmental parameters through multi-factor sensors, so that users can get the best acoustic environment experience and air-breathing quality. This system can also consider the residents' different living environment and surrounding sound field conditions, and make personalized adjustment according to the individual sensitive interval of different environmental parameters. The system is also installed a laboratory to test the ventilation and noise reduction performance. The experimental data showed the noise reduction and ventilation system performance was effective, and it could avoid the interference caused by noise and airflow disturbance to residents.

Keywords: natural ventilation, noise reduction, self-adjusting system, sick building syndrome

1. Introduction

Most people spend 80% of their time indoors. Due to the pollution of the indoor environment, the cases of physical and mental injuries of human beings gradually increase, which is also known as sick building syndrome. The objects that cause sick buildings are all kinds of pollution in the surrounding environment, including ventilation system pollution, lighting pollution, heat pollution and noise pollution. Therefore, in order to protect people's physical and mental health, we need to improve the indoor environment.

Up till now, more than 250 studies have shown negative effects of noise on humans, and studies with a median difference of 10-30 dB have suggested that combining acoustic interventions with other noise reduction strategies may yield positive results. A good sound environment should help people keep a good state.

There are successful cases and excellent technical schemes for the reconstruction of mechanical ventilation components, window groups and window ventilation and noise reduction functions in buildings. For example, an intelligent noise-reduction window invented by professor Kang Jian belongs to the technical fields of architecture, building technology, architectural physics, acoustics, noise control and ventilation, etc. It forms a ventilation passage through a digital interlaced glass and adds micro-perforated sound absorber into the glass to reduce noise.

Although these inventions can well solve the problem of noise reduction and ventilation, due to the complexity of forms and the way of up-down opening and closing is not in line with common habits, and the hardware cannot be flexibly adjusted to cope with the changes of various environmental parameters. Therefore, based on meeting the requirements of noise reduction and ventilation, we added sound level meter and air quality monitoring system, combined with the sensors to achieve automatic adjustment, which increased the flexibility of this intelligent system to cope with different scenarios and make the application prospect broader.

2. Related research

In 1983, the World Health Organization (WHO) defined a series of symptoms as sick building syndrome [1]. According to the preliminary statistics of the WHO, about 30 percent of the new and reconstructed buildings are considered to have sick building symptoms. Besides, there are some studies on sick building syndrome in residential buildings [2, 3]. The awareness of impacts that are posed by poor indoor environmental conditions has been studied across various research areas such as health and building sciences [4, 5, 6]. And Indoor Environment Quality (IEQ) refers to the acceptable levels of thermal, visual and acoustic comfort in addition to Indoor Air Quality (IAQ). Here are some aspects of solutions to improving IEQ:

2.1. Noise reduction in dwelling system

Building space design usually requires quiet rooms, through the design of key technical components such as partition wall and window, the purpose of noise reduction can be achieved [7]. Once Yang, Cho etc. suggested a new low-noise window under natural ventilation should be developed [8]. Also, some window systems have already been designed by Kang and Brocklesby [9] and Tang [10].

2.2. Ventilation in dwelling system

As we all know, for indoor space, ventilation is closely related to air quality and thermal comfort. In some circumstances, natural ventilation can provide a higher ventilation rate compared to mechanical ventilation, thus improving the air quality of indoor space, which can improve occupant health by reducing building-related health problems such as sick building syndrome. And a study in Singapore [11] also proved that ventilation problem led to higher CO2 concentration and lower relative humidity which was contributed to SBS. There was a study suggested that the vital predictor of sick building syndromes is ventilation within the indoor environment [12].

2.3. Automation in dwelling system

Building intelligence could have significant impacts on the energy saving of hybrid ventilation buildings. In a study, different building intelligence leads to typically 5%–15% difference in the average energy saving percentage in different climates [13]. And automation was shown to enable the practices from routines and can be regarded as an effective solution to influence resource use at home [14].

A key factor in achieving healthy environments in buildings is the provision of a high level of Indoor Environmental Quality (IEQ) [15]. The factors of thermal comfort, acoustic and IAQ define indoor environment quality [16, 17, 18]. And because of these factors, we could improve the sick building environment via these parts.

3. Window system design

3.1. Technical background

Designing green building envelopes is often associated with acoustic issues. For instance, double or multi-glazed windows are advantageous for both energy savings and noise reduction. On the other hand, encouraging natural ventilation is one of the important topics of green building, but opening windows often cause noise problems. Therefore, the development of a window system that ensures natural ventilation and efficient use of natural daylighting while reducing noise requirements can improve the overall sustainability of the building envelope. The main object of the invention is to develop a new type of window system through acoustic, daylighting and ventilation techniques.

3.2. Design content

The intelligent window is a new type of window system which is suitable for natural ventilation and can effectively reduce noise. The double-layer hollow glass structure of the digital staggered model is used to form a narrow and long ventilated space, and a micro-perforated sound absorption film is added to the inside of the glass to weaken the sound transmission, to achieve the effect of noise reduction. Motor sliding rails are installed on the top of two double-glazed Windows, which can adjust the opening and closing sizes of the Windows freely, so as to control the length of the noise reduction space, balance the ventilation and noise reduction functions, and adapt environmental parameters under special noise or climatic conditions. In this system, the glass and it is sound absorption film are almost completely transparent, which does not affect the daily exposure of natural light, and its size can be installed on the facade of existing buildings without affecting the appearance.

The window system is equipped with two sensors to meet the function of self-adaptation. The sound level meter is used to monitor indoor sound pressure level, and a digital anemometer is used to monitor wind speed in the ventilated space. This design can meet the needs of different people. For example, people's tolerance for sound is completely different during daytime activities and sleeping at night, and residents living close to the road area need to reduce the indoor sound pressure level, and residents living in quiet villa area need to increase the ventilation volume for better breathing experience. This system can adjust the proportion of its own parameters according to local conditions and personal preferences, which is the best distance for Windows to get the best living experience.

3.3. Conceptual drawing

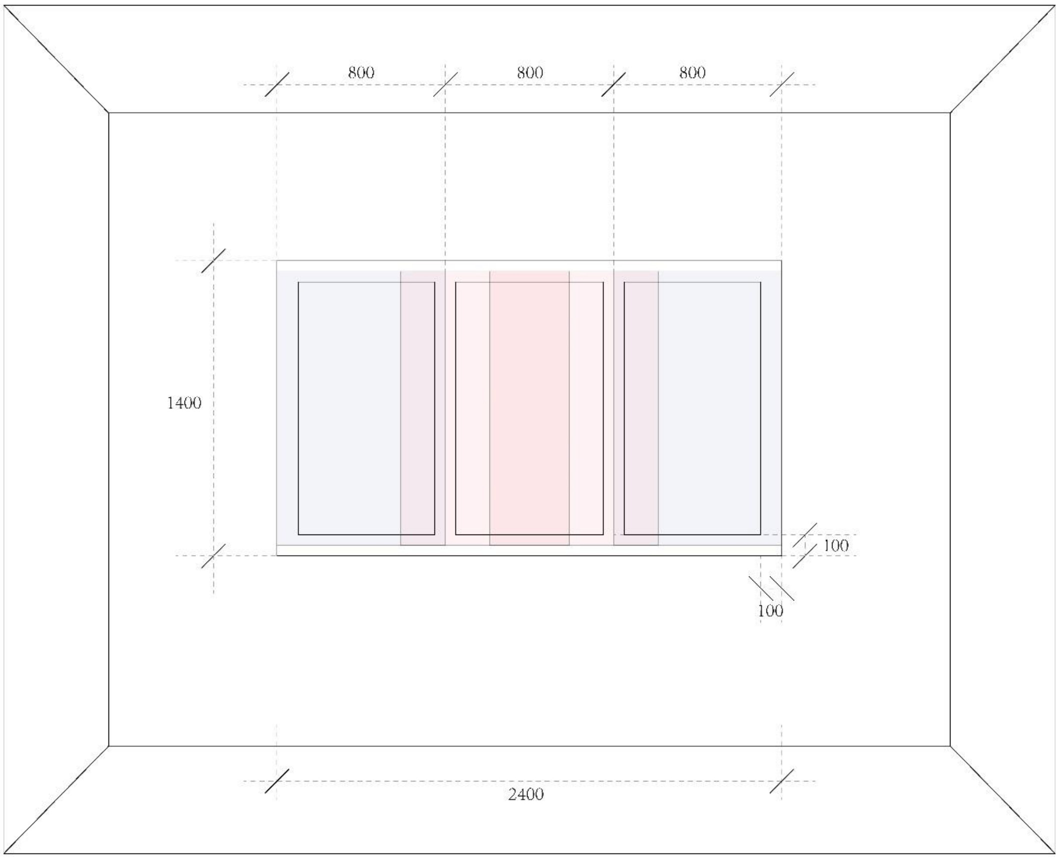

Fig. 1. Front view of the window system.

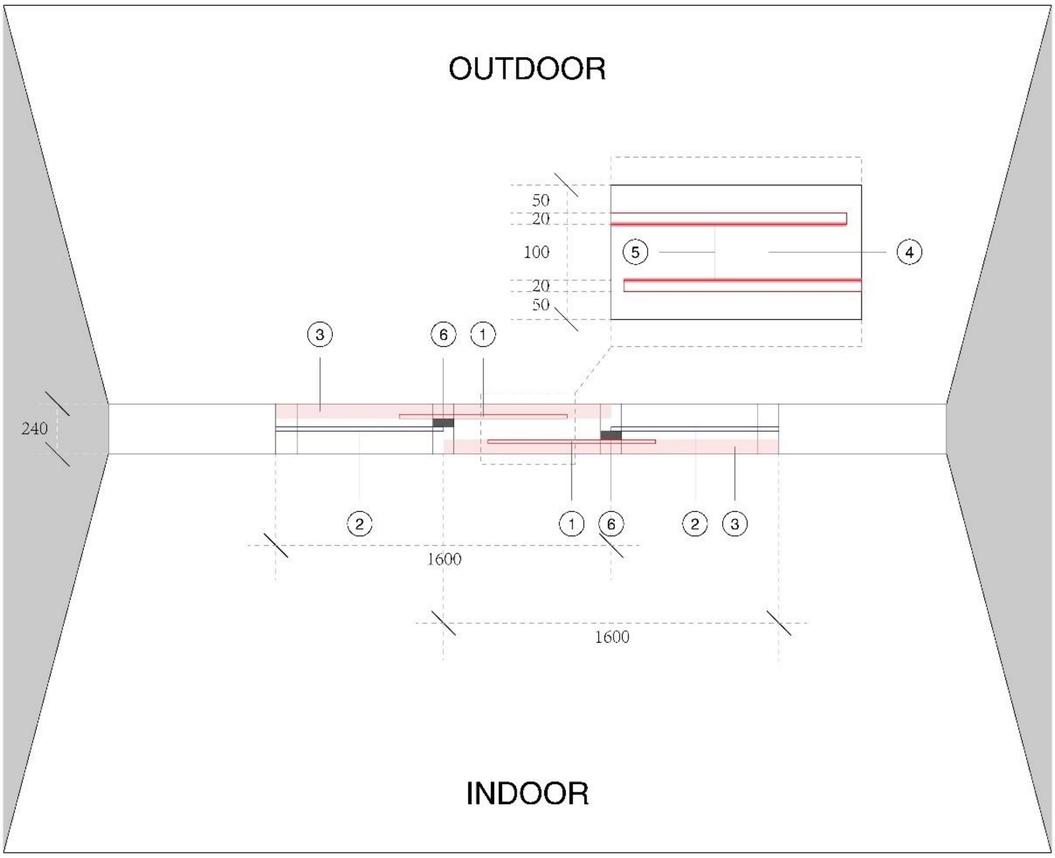

Fig. 2. Top view of the window system.

The main form is shown in the above (Fig.1). The entire outer frame is made of a lightweight aluminium alloy structure of 2400 mm wide multiply 1400 mm high. An equal width structure is set in each third of the middle for support. The metal frame structure of the main form is 100 mm thick. The entire window system uses four hollow double glazing (800 mm multiply 1400 mm), of which two blue ones are fixed position isolation glazing. The two red pieces are movable sliding glass.

The thickness of the entire window system is 240 mm from the top view (Fig.2). The upper part is outdoor space and the lower part is indoor space. Three layers of a track are nested in the aluminium frame. The upper and lower layers are red sliding glass tracks, and the middle layer is blue insulating glass track. The thickness of all double-layer insulating glass is 20mm. Two pieces of red sliding glass are separated by 100mm and can slide freely left and right in the marked red area, thus forming a ventilated space with a length range from 0 to 800mm. Because of the difference between indoor and outdoor temperature, this space can let the air form convection, to achieve the effect of natural ventilation. When the two pieces of red sliding glass interlaced, the narrow and long channel formed will weaken the transmission of sound. In addition, the glass inner wall is affixed with micro-perforated sound absorption film, which can better play the role of noise reduction.

The numbers in the figure are as follows:

1. Sliding glass.
2. Insulating glass.
3. Glass slip range.
4. Noise reduction space.
5. Micro-perforated sound absorption film.
6. Sound insulation pipe.

4. Laboratory test

4.1. Laboratory settings

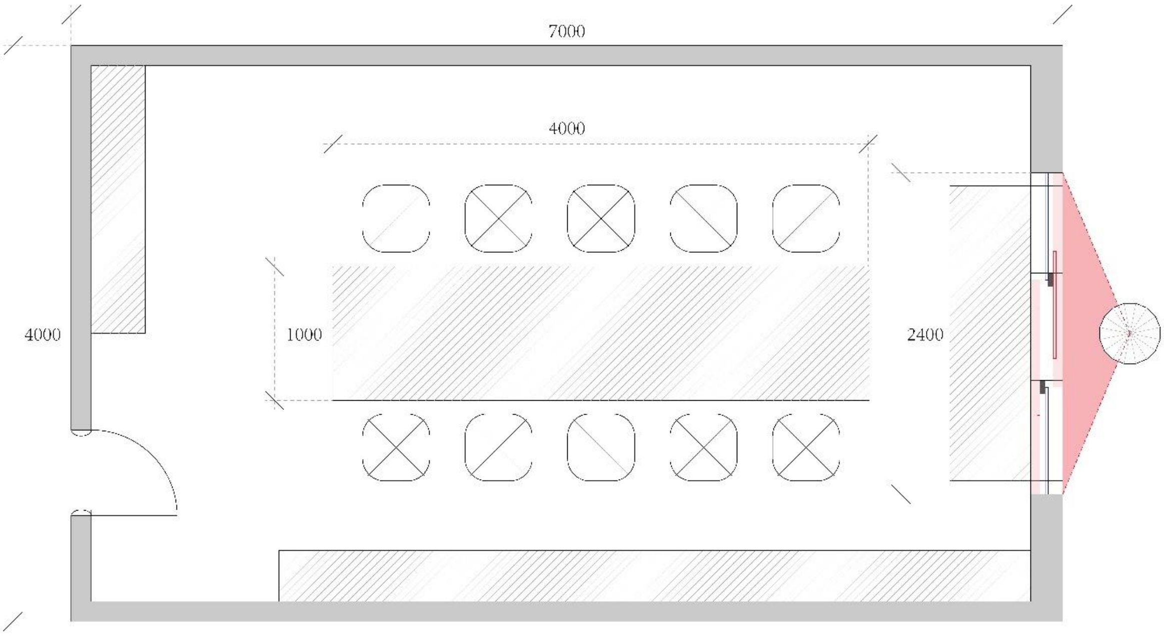

Fig. 3. Laboratory layout schematic.

The experiment was conducted in the audiometric laboratory of a university in Wuhan, China; the lab has a volume of 28 m2 and background noise of 25 dB(A). The figure above shows the layout schematic diagram of the laboratory (Fig. 3). The intelligent window is installed on the building exterior wall on the north side of the laboratory, and a dodecahedral sound source (MHY-14324) with independent power amplifier (HA12-AWA5870A) is installed on the outdoor platform opposite the intelligent window. A UNI-T digital anemometer (UT363) is used to test wind speed in the ventilated space, and a sound level meter (AWA5688) is used to test indoor acoustic data. The laboratory does not have additional noise sources and equipment to change the air quality, so the air quality and acoustic environment data obtained from the test are relatively closed and accurate.

4.2. Experimental method design

In this experiment, the noise reduction performance and ventilation effect of the Windows in five open and close states were tested. Five states correspond to the volume sizes of five noise reduction spaces respectively, with the maximum value of 0.112 m3 (Fig. 4A) and the minimum value of 0 m3 (Fig. 4E). Take the average values of upper and lower limits respectively to get 0.028 m3 (Fig. 4D), 0.056 m3 (Fig. 4C) and 0.084 m3 (Fig. 4B).

The power of 70dB is stably output by the non-directional sound source to ensure the even distribution of sound frequency. A sound level meter is set up in the room to measure the data for five minutes, which is used to measure the equivalent sound pressure level of each frequency under the weight of A meter, and draw the corresponding spectrum diagram.

The anemometer is placed in the noise reduction space to measure the wind speed to correspond to the ventilation volume, and the measured data is m/s.

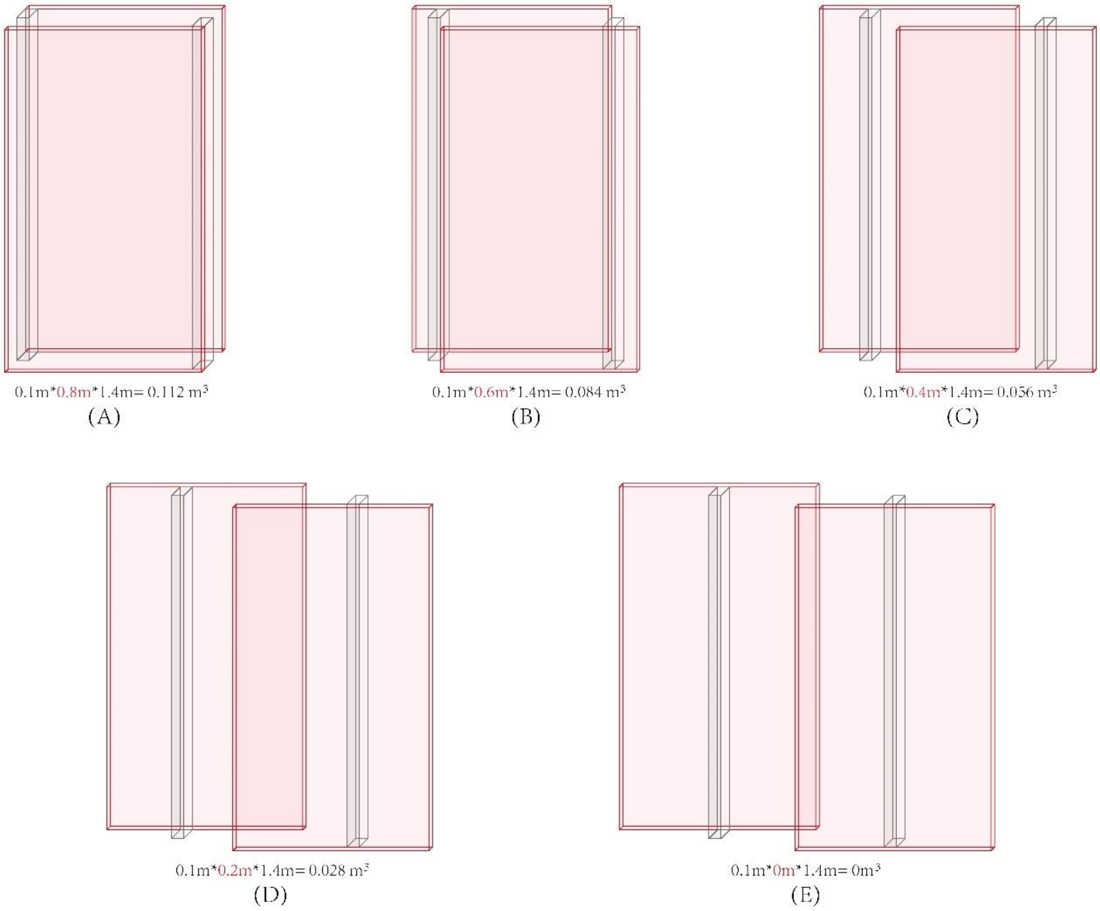

Fig. 4. Open and close gradient schematic.

4.3. Result

The spectrum diagram of corresponding states and the other sound data is shown below (Fig.5) (Table.1). Intelligent window can play a better role in noise reduction, and it can be found that the larger the noise reduction space is, the better the noise reduction performance is. As we can see the change of gradient is uniform.

Micro-perforated sound absorption film (MPA) has a good weakening effect on high frequency sound, but it is weaker than low frequency sound, The larger the volume of the ventilated space, the larger the difference in the attenuation effect of the high and low sound frequencies. With the Windows almost completely closed, sounds above 5000Hz almost faded away.

Table 1. Sound data.

State	Leq T (dB)	Lmax (dB)	Lmin (dB)	L90 (dB)	L50 (dB)	L10 (dB)
A	37.6	44.1	33.6	35.3	36.8	42.7
B	42.4	48.9	37.4	39.3	42.7	46.6
C	46.8	52.1	42.0	44.9	46.9	50.9
D	54.3	59.8	49.8	50.4	53.9	57.1
E	61.4	67.7	56.7	58.2	61.0	64.6

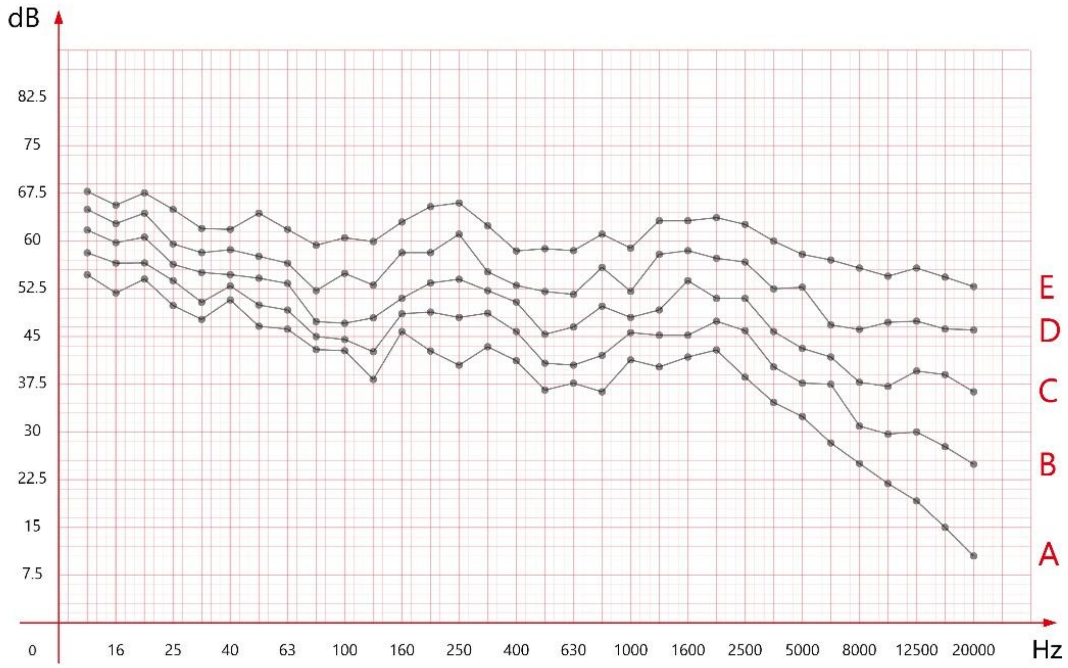

Fig. 5. Spectrum diagram of the test.

The ventilation data below (Table.2) shows that the ventilation volume increases with the reduction of noise reduction space, and the relationship is basically inversely proportional.

Table 2. Ventilation data.

State	A	B	C	D	E
Ventilation rate (m/s)	0.42	0.56	0.77	0.98	1.21

The ventilation data above (Table.2) shows that the ventilation volume increases with the reduction of noise reduction space, and the relationship is basically inversely proportional.

Therefore, the whole intelligent window system can be judged, and the effect of natural ventilation and noise reduction can be completed at the same time. With the movement of sliding glass, the noise reduction performance and ventilation effect can be deployed within a certain range, to easily cope with different environments and personal preferences.

5. Future directions and conclusion

The sound fields inside the intelligent window and their relationships with ventilation and noise reduction are examined in detail. Besides, attentions are paid on the feasibilities of using different materials of MPA. The results presented illustrate that it is effective to use this intelligent window system to reduce noise while still naturally ventilating at different opening sizes and show that reduction in noise is possible using MPA adhered to the air-tight double-glazing windows. The potential improvement of noise reduction could be made on dealing with lower frequencies of sound vibration when analysing the results which further suggest that this can be achieved using some adapted standard materials.

And that using natural ventilation during acoustic measurements suggest that, at normal air movement levels there is no negative effect on the noise reduction achieved using MPA, but a more quantitative and precise test is still required. We will use environment data sensors, such as small sound level meter, temperature and humidity sensor, rain sensor, to realize the automatic function of intelligent window for the future design. Users can set according to their own environmental comfort preferences.

The further studies about this intelligent window system need to be carried out to improve the effect of reducing lower frequencies, because the low-frequency sound has strong penetration and diffraction ability. In addition, studies for the development of low-energy and more intelligent window system and facilities will be needed through the development of modern and smart cities.

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Schedule Performance Analysis of Infrastructure Reconstruction Projects Due to Extreme Events

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Abstract

Timely post-disaster reconstruction of transportation infrastructures is vital, as it affects the pace of the overall physical and economic recovery of the disaster-ravaged area. To ensure the completion of the project within the optimum amount of time, it is important to know what factors affect the duration of the project, but it is difficult to find a comprehensive list of those factors in the current literature. This study aims to fill that knowledge gap by identifying the factors that affect the timely reconstruction of transportation infrastructures (PRTs) following a natural disaster. A survey was developed and distributed to collect data for this study, and the responses were analyzed statistically. It was found that the possibility of schedule overruns increases with the levels of complexity and damage. Hurricanes in particular cause sudden shortages of resources (experts, suppliers, laborers, materials, and equipment) that reduce the productivity and increase the duration of reconstruction projects. The results of this study will help practitioners and engineers take steps to complete reconstruction projects within the estimated schedule.

Keywords: identification of factors, post-disaster reconstruction, reconstruction time, transportation infrastructure

1. Introduction

Transportation systems are key to public mobility, access, economy, safety, and the environment [1, 2] therefore, it is essential that they be returned to a safe and operational state within the shortest possible time and within a reasonable budget after a natural disaster [3, 4]. For instance, critical highways were disrupted at four locations in the northwestern Los Angeles metropolitan area by the 1991 Northridge disaster [5], leading to substantial disruptions in the movement of people, and the closure of parts of Interstate 10 (Santa Monica Freeway) led to economic losses that were estimated at $1 million per day [6]. After the disaster in Aceh and Nias [7], the damages to the transportation systems were responsible for 19.7% of the total estimated damages caused by the disaster. Similarly, in 2004, in Sri Lanka, losses and damages to roads and other parts of the transportation sector accounted for 22% of the total damages. These are only a few examples of the socioeconomic disruptions that communities experience until the transportation systems are restored to their pre-event condition.

Natural disasters, especially hurricanes, create shortages of resources such as laborers, equipment, and materials that make it difficult for reconstruction to be completed within the estimated time [8, 9, 10, 11] and the public reacts by exerting additional pressure on the local governments when the contractors are not able to deliver their services on time [12, 13, 14]. In addition, the complicated, hectic, and dynamic nature of transportation reconstruction exacerbates other problems and increases the likelihood of schedule overruns and reworks [15, 16]. The dearth of research that addresses the issue of schedule overruns makes it difficult for practitioners to complete their projects on time [17].

Therefore, this study aims to identify the factors that affect post-disaster reconstruction time of transportation infrastructures (PRTs) to fill the abovementioned gap of knowledge in the literature. Several objectives were formulated to fulfill the goals of this study: i) identify the potential critical PRTs that affect the post-disaster reconstruction duration of transportation infrastructures, ii) categorize the identified PRTs, and iii) identify the most significant PRTs. The result of this study will help practitioners and engineers take the proper steps to complete their reconstruction projects within the initially estimated schedule.

2. Literature review

Hurricanes cause serious losses and damages that result in serious disruptions in the U.S. [18, 19]. Hurricane Katrina and Hurricane Rita led to tremendous socioeconomic damages. The accumulated direct and indirect economic losses and damages after Hurricane Katrina amounted to roughly $1845 billion, while the primary estimation was $160 billion [20]. The destruction caused physical and psychological distress to the victims, adversely impacted the environment, and rendered many of the critical infrastructures inoperable. Transportation systems are one of the infrastructures most severely affected by disasters [21, 22, 23]. The storm surges that accompany a hurricane affect the coastal areas, damaging many of the roads and depositing large amounts of debris, which can increase the cost and delay recovery activities for a prolonged period [24]. Following Hurricane Katrina, for example, economic loss for debris removal was approximately $200 million [25]. Damaged transportation systems cause disruptions in traffic flows and slow the pace of overall recovery, resulting in more indirect than direct losses [26]. Thus, the reconstruction of transportation infrastructures is critical to the recovery of affected areas after any disaster [27].

In 1987 [28], Pinto and Slevin espoused that a project can be considered successful if it is completed on time, on budget, meets all its objectives, and satisfies the client. Various studies have been conducted on successful construction projects, using their definition [29, 30, 31, 32, 33, 34, 35]. Almost all researchers believe that staying within the budget, adhering to the schedule, and achieving a quality project performance, referred to as "the iron triangle" by Atkinson [36] is necessary for the success of a construction project [37, 38, 39, 40]. Transportation agencies are experiencing unprecedented pressure to deliver projects on time and on budget, with an adequate level of quality [41, 42, 43], and an obvious response to this pressure is to improve the project delivery process by adopting effective project management strategies [44, 45, 46, 47].

Every reconstruction project is unique in nature; hence it is difficult to determine the factors that will determine the success or failure of a project [48]. Similarly, it is difficult to determine the exact causes of schedule overruns in post-disaster reconstruction projects. Table 1 depicts the a few of the challenges that researchers have determined affect the success of post-disaster reconstruction projects by causing schedule overruns.

As shown in the table, Ika et al. [49] believed that ineffective designs are one of the main reasons for failing to complete a project within the estimated schedule. Delays in decision making during different stages of projects have also been attributed to delays that ultimately affect their success. The pace of recovery and the return of society to its norm is highly determined by the fastest possible recovery of the transportation infrastructures [50]. Hence, it is imperative that the reconstruction is completed with least possible schedule overruns [51]. Understanding and identifying the factors that will eliminate schedule overruns is absolutely necessary for this purpose [52], and this study aims to identify such factors.

Table 1. Challenges affecting success and schedule of post-disaster reconstruction projects

Challenge	Previous Study
Delays in delivering resources	[53, 54]
Inappropriate assessment	[55]
Ineffective design	[49]
Temporary paths	[56]
Difficulties in damage evaluation	[57]
Low pace of decision-making	[58]
Number and quality of inspections	[59]
Inability to relocate functions	[60]
Permitting and consenting	[61]

3. Research methodology

3.1. Framework

The four-step methodology shown in Figure 1 was followed in this study. In the first step, a comprehensive literature review was performed. After rigorously screening the articles, 89 were shortlisted for thorough study, and a list of potential PRTs was developed. In the second step, a survey was developed, pilot tested, and distributed. In the following step, the survey responses were statistically tested to identify the significant PRTs, and the results were interpreted, employing the expertise of the authors.

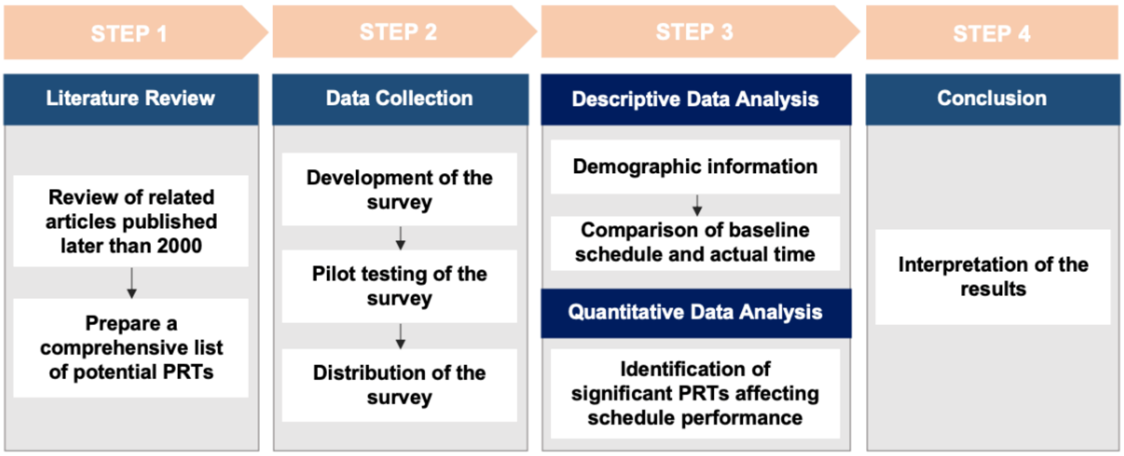

Fig. 1. Research methodology

3.2. Statistical tests

Three of the most popular and effective types of statistical tests were used for this study. The two-sample t-test was used for the continuous data that follows normal distribution, the Kruskal-Wallis was used for the seven-point Likert scale data that does not necessarily follow a normal distribution, and the Chi-squared test was used for the binary data of the survey questions that were answered by “yes” or “no.”

4. Data collection

4.1. List of potential PRTs

More than 200 relevant peer-reviewed journal articles, conference papers, dissertations, and research reports published on post-disaster reconstruction of transportation systems were collected for this study. Of those, over three-quarters of the articles were from journals because of the rigorousness of their review process. The research team established the following criteria for the articles that would be used: they must have been published in English after year 2000, they must be relevant to the post-disaster reconstruction of transportation systems, and they must be associated with engineering areas. After screening the articles, 89 of them were short-listed for thorough study. Short-listed articles were reviewed in depth to investigate the PRTs that significantly affect the cost and schedule performances, as well as the cost of reworks of post-hurricane reconstruction of transportation infrastructures.

Two main steps were taken to identify the potentially significant PRTs: i) identify the potential PRTs that affect the schedule performance post-hurricane reconstruction of transportation infrastructures; and ii) determine which of the potential PRTs were cited the most often, retain them, and exclude the rest.

A list of 30 PRTs was developed of substantial factors for successful post-disaster reconstruction. They were classified into eight categories: general information, physical characteristics of the project, damage level, resources, environment and safety, project management, local, and legal.

Table 2. List of potential PRTs

Category	List of PRTs	Category	List of PRTs
Physical Characteristics	1. Number of main/truck lines	Quality	16. Quality issues of materials
	2. Total length		17. Quality issues of equipment
	3. Level of complexity	Project Management	18. Frequency level of logistics/management issues
	4. Distance from highly populated area		19. Quality of on-site inspections
Damaging Level	5. Level of damage		20. Frequency of on-site inspections
	6. Level of traffic disturbance		21. Information management
Resource	7. Shortage of experts		22. Pace of decision-making process
	8. Shortage of field laborers		23. Implementation level of risk management
	9. Productivity level of contractors		24. Coordination
	10. Shortage of materials		25. Pace of workers' mobilization
	11. Shortage of equipment	Environment & Safety	26. Volume of debris
	12. Inflation of labor wages		27. Environmental/safety issues prior to execution of the project
	13. Availability level of on-site infrastructure		28. Work suspension through execution of the project
	14. On-site accommodation level for staff	Legal	29. Regulatory requirement
	15. Shortage of suppliers	Local	30. Availability of required temporary pathways

4.2. Survey development and pilot testing

A 46-question survey was developed, based on the potential list of PRTs (Table 2). It consisted of three types of questions, namely continuous, seven-point Likert scale, and binary. Questions regarding the respondents' demographic information were also included. Several of the questions from the survey are shown in Figure 2.

I. How many numbers of main/trunk lines did the selected reconstruction project consist of? (Main/trunk line refers to the primary linkage serving main arteries of interaction and commerce in transportation networks.)

Number: ________________

II. What was the total lengths of the selected reconstruction project?

Number: ________________

Fig. 2. Two sample questions of the survey

The survey was pilot tested and modified based on the responses.

4.3. Survey distribution

Specific criteria were established for those who would be invited to participate in the survey. One of them was that they must have experience in working on and/or monitoring the reconstruction of a transportation project. A list of potential participants was prepared and included program managers, directors, project managers, and engineers from different governmental and private agencies, state transportation agencies, and departments of transportation etc. They were contacted through email, and the surveys were distributed to them via electronic media after receiving a positive response. After multiple follow-up emails, 30 completed responses were collected.

5. Descriptive analysis

5.1. Demographic information

The demographic information of the survey respondents is presented in Table 3, which shows that about 70% of the respondents had more than 20 years of work experience, approximately 25% of them were program managers or directors, and the rest were project managers or engineers. All of the respondents were involved with the owner stakeholders.

Table 3. Demographic information of respondents

Years of Experience	Percentage (%)	Current Role in the Company	Percentage (%)
Less than 10 years	12.5%	Program Manager	8%
Between 10 and 20 years	21%	Director	17%
Between 21 and 30 years	37.5%	Project Manager	30%
More than 30 years	29%	Engineer	45%

5.2. Comparison of projects' baseline schedules and actual time

Box plots were used to demonstrate the baseline schedule and actual time of the selected reconstruction projects for which the respondents provided information, and the results are presented in Figure 3. It was observed that the maximum values of the projects' actual time and baseline schedules were about 90 months and 60 months, respectively. The medians of actual time and baseline schedules were roughly 12 months and 20 months, respectively. Both of the results demonstrated the marked differences in the baseline schedules and the actual time of the selected reconstruction projects.

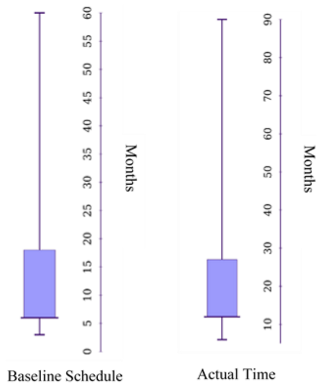

Fig. 3. Comparison of projects' baseline schedules and actual time

6. Quantitative analysis

6.1. Identifying significant PRTs affecting projects' schedule performance

The survey was constructed using three types of data: 1) continuous, 2) seven-point Likert scale, and 3) binary. Three types of statistical tests, the two-sample t-test, 2) Kruskal-Wallis test, and 3) Chi-squared test were used for the types of data, respectively. The P-values that identified the PRTs that most significantly affect the schedule performance of post-hurricane reconstruction of transportation infrastructures are presented in Table 4 and show that 20 out of 30 identified PRTs were statistically significant.

Table 4. Results of significant PRTs affecting reconstruction schedule

Category	List of PRTs	*P*-Value
Physical Characteristics	PRT1. Number of main/truck lines	0.022**
	PRT2. Total length	0.850
	PRT3. Level of complexity	0.042**
	PRT4. Distance from highly populated area	0.078*
Damaging Level	PRT5. Level of damage	0.011**
	PRT6. Level of traffic disturbance	0.061*
Resource	PRT7. Shortage of experts	0.011**
	PRT8. Shortage of field laborers	0.012**
	PRT9. Productivity level of contractors	0.025**
	PRT10. Shortage of materials	0.037**
	PRT11. Shortage of equipment	0.017**
	PRT12. Inflation of labor wages	0.290
	PRT13. Availability level of on-site infrastructure	0.750
	PRT14. On-site accommodation level for staff	0.410

	PRT15. Shortage of suppliers	0.020**
Quality	PRT16. Quality issues of materials	0.081*
	PRT17. Quality issues of equipment	0.021**
Project Management	PRT18. Frequency level of logistics/management issues	0.013**
	PRT19. Quality of on-site inspections	0.032**
	PRT20. Frequency of on-site inspections	0.422
	PRT21. Information management	0.068*
	PRT22. Pace of decision-making process	0.041**
	PRT23. Implementation level of risk management	0.082*
	PRT24. Coordination	0.046**
	PRT25. Pace of workers' mobilization	0.258
Environment & Safety	PRT26. Volume of debris	0.124
	PRT27. Environmental/safety issues prior to execution of the project	0.274
	PRT28. Work suspension through execution of the project	0.001**
Legal	PRT29. Regulatory requirement	0.205
Local	PRT30. Availability of required temporary pathways	0.163

**denotes significant differences with 95% confidence
* denotes significant differences with 90% confidence

6.2. Interpretation of the results

The physical characteristics of a project have a significant impact on the project schedule. Table 4 shows that three PRTs, namely PRT-1 (high number of main lines), PRT-3 (level of complexity), and PRT-4 (distance from highly populated area) have significant p-values because they often result in complex plans and schedules. In addition, their presence might increase the number of discussions between the stakeholders and cause delays.

The level of damage also affects the reconstruction project schedule appreciably. For instance, a highway or bridge with a high level of damage creates a major traffic disturbance, and the delays that are inherent in providing a temporary route for the disrupted traffic frequently cause delays that translate into schedule overruns for the project.

A lack of resources is one of the major causes of the failure of transportation reconstruction projects. Table 4 illustrates that shortages of experts, laborers, materials, equipment, and suppliers affect the reconstruction schedule. The contractors' level of productivity is also a major factor in whether a project will be completed on time, as all reconstruction projects after natural disasters are complicated, unexpected, and need a quick turnaround.

Quality is another important category in controlling the schedule of reconstruction projects, and unexpected issues with the quality of materials (PRT16) and/or equipment (PRT17) can cause delays.

The time and budget constraints of reconstruction projects require that they be efficiently managed. Ineffective coordination (PRT-24) means lack of alignment among project organizations and/or team members. The process of communication can be time-consuming and affect the schedule performance.

The environment and safety, legal, and local categories have less impact on the duration of reconstruction projects of transportation infrastructures, but if the work has to be suspended because of issues related to any of these categories, it negatively impacts the schedule of the project.

7. Conclusion

Transportation infrastructures are highly affected by natural disasters, especially by hurricanes, and the recovery pace of the affected community depends largely on their reconstruction. For this reason, it is necessary to ensure the completion of the reconstruction of transportation infrastructures after a disaster within the estimated time and budget. Unfortunately, it is not rare for such projects to be prolonged for various reasons, which adversely affects the overall recovery of the community. The existing literature lacks lists of significant factors that affect the reconstruction schedule of transportation infrastructures after natural disasters; therefore, the aim of this study was to identify those critical factors To this end, a survey was developed and distributed to a select group of experts, and after the 30 responses were collected and statistically analysed, it was found that the possibility of schedule overruns increases with an increase in the complexity and damage levels of the projects. The shortages of resources (experts, suppliers, laborers, materials, and equipment) that accompany a hurricane reduce productivity and increase the estimated time of completion. The result of this study will help practitioners and engineers take the steps that are necessary to complete reconstruction projects within the estimated schedule.

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Sleep Duration and Results of the Psychomotor Vigilance Test in Construction Workers: A Preliminary Study

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Abstract

The construction industry is known by its high rate of accidents. Among the different possible causes of this situation we could find lack of sleep and fatigue. Chronic sleep deprivation is a determining factor in the deterioration of vigilance and alert, and consequently a risk factor for occupational accidents. Fatigue is the answer of our organism to sustained physical and mental effort. Construction workers are prone to fatigue, since their work is characterized by heavy lifting and awkward work postures, so it is relevant to study it more thoroughly, especially regarding its association with sleep efficiency and quality. Regretfully, those topics have been very poorly studied in the construction industry. To understand better these phenomena and to propose strategies to mitigate it and contribute to the reduction of accidents in construction projects, the objective of this study was to understand if there is a relation among sleep duration and fatigue. We worked with 154 male construction workers from one Chilean construction company. To asses sleep quality we used the Pittsburgh Sleep Quality Index. One of their questions asked for average sleep hours in the last 4 weeks. To evaluate fatigue, we used a personal computer version of the Psychomotor Vigilance Test (PC-PVT) that measure alertness and vigilance. This 5-minute test was performed by construction workers on site in the morning. People was classified into groups according to self-reported sleep hours, namely: 7-9 hours (26%), 5-7 hours (61.7%) and <5 hours (12.3%). These results were compared for 3 variables (Mean Reaction Time, 10% faster and 10% slower) using an ANOVA test. Differences were found for Mean RT and Slowest10%, the difference being greater in the group that reported sleeping <5 hours, but without statistical significance. Studies with a greater number of subjects and measurements are required throughout the working day.

Keywords: construction workers, fatigue, sleep duration, vigilance

1. Introduction

The construction industry has one of the greatest accident rates worldwide [1], and an elevated probability of injuries and occupational illnesses [2]. In Chile, the construction industry has an accident rate of 3.9%, much higher than the national average of 3.1%, considering 38 casualties due to work related accidents in 2018 [3]. Fatigue is recognized as an accident causation, being a trigger to human error [4]. In the construction industry the impact of fatigue is likely to be more serious, as the construction environment is dynamic and risky [5]. In fact, risks on construction sites may be heightened due to inclement weather and mobile equipment, as well as changing and demanding schedules requiring additional work hours [6]. According to Techera et al. [7] the most relevant drivers of fatigue are sleep deprivation and work environment factors such as noise, vibration, and temperature. Sleep deprivation contributes to fatigue, affecting an individual's wellbeing, work performance, and safety [6]. Construction workers are prone to fatigue, since their work is characterized by heavy lifting and awkward work postures, so it is relevant to study it more thoroughly, especially regarding its association with sleep efficiency and quality. Regretfully, those topics have been very poorly studied in the construction industry. To understand better these phenomena and to propose strategies to mitigate it and contribute to the reduction of accidents in construction projects, the objective of this study was to understand if there is a relation among sleep duration and fatigue. The following section of the article will introduce the work methodology carried out in this project, as well as the theoretical framework supporting the main topics studied. Later, the main results of this study, as well as a discussion and conclusion section, will be presented.

2. Fatigue and Psychomotor Vigilance Test (PVT)

Fatigue can be described as a reduced ability to perform activities at the desired level due to lassitude or exhaustion of mental and/or physical strength [4]. Fatigue can have different causes such as sleeping a short number of hours and poor sleep quality, and consequences such difficulties concentrating or thinking clearly, and risking falling asleep easily, jeopardizing personal safety or that of others [8]. In fact, because of physiological degradation, the ability of an individual to work safely and efficiently can be severely compromised by fatigue [4]. Related with fatigue are two key physiological factors, loss of sleep and disruption of the circadian cycle. In both cases adequate sleep is the only naturally occurring cure [6]. Then, people who suffer from fatigue acquire a sleep deficit that is probably not noticeable in the early stages, attributing this condition to other variables [8]. Fatigue can be evaluated using the Psychomotor Vigilance Test (PVT) that measure alertness and vigilance. The reaction time (RT) is measure as an indirect assessment of fatigue [9]. PVT is considered the only technology with strong evidence of validation by independent researchers, laboratory studies, and field studies, being considered by most researchers as the eminent method to objectively measure fatigue [9].

3. Sleep quality

Currently, the role of sleep has been relegated and the time spent sleeping has been decreasing over the years, as for many the sleep period is seen as a waste of time, even though we know that the consequences of poor sleep quality go beyond simple discomfort, affecting health conditions and life quality [10]. Sleep disturbances are also associated with increased risks of workplace accidents and car accidents due to daytime sleepiness as a result of bad night's sleep [11]. Sleep quality refers not only to the fact of sleeping well at night, but to have an adequate performance the following day. This is important as a determining factor in health and is also a precursor to a good quality of life [12]. To maintain performance and healthy neurobehavioral functioning, the average adult needs at least 7 hours of sleep per night, as recommended by different sleep organizations, but many people do not sleep so many hours, transforming chronic sleep loss in a significant public health issue [13]. Sleep deprivation can result from factors such as lifestyle, stress, poor sleep habits, and sleep disorders such as sleep apnea and restless legs' syndrome, putting people at higher risk of accidents [6]. To understand better the situation of people regarding sleep quality we can applied different psychometric instruments, such as the Pittsburgh Sleep Quality Index (PSQI). The PSQI is an instrument that measures the quality of sleep and its alterations based on references from the last 30 days. It is a standardized instrument used in the detection and evaluation of sleep problems developed by Buysse, Reynolds, Monk, Berman and Kupfer in 1989 in the United States, with the objective of evaluating the quality of sleep and its clinical alterations. It has questions that are organized into 7 aspects such as subjective sleep quality, latency, duration, efficiency, sleep disturbances, use of sleep medication, daytime dysfunction [14].

4. Research methodology

An observational, cross-sectional relational study was carried out in May 2019 whose population corresponded to workers in five construction projects in Santiago, Chile (N = 1,700). A random sampling was performed, reaching a sample size of 154 subjects. To be included in the study the workers must have been in the company for more than 1 month and have at least 1 year of work experience in the field. The exclusion criteria include the following: a) have had a surgical intervention that required general anesthesia in the last three months b) have a life expectancy of less than three months, c) have addiction to illegal drugs and/or alcohol; d) people who work shift systems (since it alters wakeful sleep cycles), e) people with living conditions that prevent them from sleeping through the night (for example, having dependent people in their care) and f) people with psychiatric disorders (except depression). The research team visited each one of the construction projects to interview the workers. In each visit the following information was gather a) Sociodemographic information such as sex, occupation, schooling, and marital status, that were asked through a questionnaire designed for the study; b) Quality and quantity of sleep. This was evaluated through the application of the Pittsburgh Sleep Quality Index (PSQI) through an interview. Here, the score ranges from 0 to 21. A score greater than 5 is rated as a poor sleeper; and c) Fatigue level. To measure this variable, we used a personal computer version of the Psychomotor Vigilance Test (PC-PVT) that indicates the reaction levels that are homologated to the fatigue level.

5. Results

The sample included 154 male construction workers. The age of the participants fluctuated between 20 and 72 years with an average of 44.17 years. Regarding the years of study, the average number of years was 10.47. Concerning nationality, 82.5% declare themselves Chilean, followed by 8.4% of Peruvian workers, 3.9% of Haitians and 3.2% of Colombians. The rest is divided between Argentines, Ecuadorians, and Venezuelans. Most construction workers declare that their perception of health is good (51.9%), 22.7% say they have very good or excellent health, while 25.4% consider that their health is fair or poor. 50.6% do little or no physical activity, while only 18.2% do not declare themselves sedentary (Table 1). In relation to comorbidity, the declared condition more prevalent in the sample is hypertension (13.0%) followed by diabetes (5.8%) and diseases of the musculoskeletal system (3.2%). There were no cases of stroke, arrhythmia, or heart failure. It is highlighted that 60.2% of the sample is overweight or obese and 36.4% have a high cardiovascular risk (CVR) (Table 1). Regarding sleep-related events, 24.7% of the interviewed construction workers sleep the average hours, that is, between 7 and 8 hours, while 74% sleep less than 7 hours. The most prevalent condition is the presence of snoring (56.5%), followed by fatigue (44.8%) and drowning (40.3%), as shown in Table 2.

Regarding 44.8% of the workers who declared fatigue, there is no evidence of a relationship between hours of sleep with fatigue ($t = 1.618$; $p = 0.108$), this means that the presence of fatigue is distributed equally among those people who sleep less than 7 hours, between 7 and 8 hours and more than 8 hours, that is, the hours asleep versus the presence or not of fatigue are independent (Table 3). When analysing the quality of sleep according to Pittsburgh, only 23.4% of the sample presented a good sleep (<5 Pittsburgh) (Table 4). 76.6% report some degree of difficulty sleeping. Of these, 37.7% (5-7 Pittsburgh) could present more than some unsuitable condition for quality sleep, that is, snoring or nightmares, among other conditions that occur less than once a week for the last month. Similarly, another 37.7% could present these conditions one or more times a week. When analysing the performance parameters in the psychomotor surveillance test (PC-PVT), a significant association between the age group of 20-29 years was observed with a better performance in the PC-PVT in all the compared parameters (Mean RT, Fastest10% and Slowest10%) (see Table 5). Likewise, it is observed that workers with higher educational level have better performance of the PC-PVT in all the parameters, as shown in Table 6. Regarding the number of hours of sleep, a better performance in the test was observed in the group that reported sleeping between 5-7 hours per day on average, although it reached statistical significance only in the Fastest10% (results of the 90th fastest percentile) (see Table 7).

Table 1. Sociodemographic and health characteristics of the sample.

Age (average)		44.17 (SD: 12.72)
Schooling (average years)		10.47 (SD: 3.31)
Perception of Health	Excellent- Very Good	22.7%
	Good	51.9%
	Regular- Bad	25.4%
Exercise	Not done	50.6%
	> 3 times a week	18.2%
Comorbidity	Arterial hypertension	13.0%
	Diabetes	5.8%
	Acute myocardial infarction	1.3%
	Locomotor system	3.2%
	Respiratory	0.6%
	Neurological	0.6%
	Mental health	0.6%
	Obesity (BMI> 30)	32.7% (range 30.05-40.82)
	Overweight (BMI 25-29.9)	27.5% (range 25.12-29.83)
	Moderate CVR (Waist circumference> 94)	28.6% (range 95-101.5)
	High CVR (Waist circumference> 102)	36.4% (range 102-126)

Table 2. Features related to sleep events.

Sleep hours	< 7 hours	74.0%
	7- 8 hours	24.7%
	> 8 hours	1.3%
Events during sleep	Snore	56.5%
	Drown	40.3%
Daytime conditions	Fatigue	44.8%

Table 3: Relationship between hours of sleep and declared fatigue.

	Fatigue	N	Mean	SD	
Hours of sleep	Yes	69	5.72	1.24	t = 1.618
	No	85	6.04	1.19	P = 0.108

Table 4. Sleep quality according to Pittsburgh.

Pittsburgh		Frequency	Percentage	Valid percentage	Accumulated percentage
Valid	< 5	36	23.4	23.4	23.4
	5 - 7	58	37.7	37.7	61.0
	8 - 14	58	37.7	37.7	98.7
	>15	2	1.3	1.3	100.0
	Total	154	100.0	100.0	

Table 5. Comparative results of performance parameters in PC-PVT according to Age Group (ANOVA).

Parameters	20 - 29 years n=29	30 - 39 years n=24	40 - 49 years n=41	50 - 59 years n=40	60 - 75 years n=18	p-Value
	Average (±SD)	Average (±SD)	Average (±SD)	Average (±SD)	Average (±SD)	
Mean RT	274.54 (26.21)	290.32 (35.32)	320,.72 (119.01)	305,41 (37.76)	341.88 (63.24)	0.01
Fastest10%	208.86 (16.73)	212.27 (17.09)	226.93 (38.56)	223,04 (22.60)	241.94 (27.03)	0.00
Slowest10%	402.70 (52.26)	488.44 (171.65)	554.51 (328.58)	529,89 (178.05)	669.57 (290.51)	0.00

Table 6. Performance results in the parameters of the PC-PVT according to Educational Level.

Parameters	Low (<8 years) n=44	Medium (8-12 years) n=85	High (>12 years) n=25	p-Value
	Average (±SD)	Average (±SD)	Average (±SD)	
Mean RT	327.99 (74.67)	301.14 (77.92)	277.50 (26.01)	0.02
Fastest10%	236.44 (37.73)	217.98 (21.24)	208.93 (18.67)	0.00
Slowest10%	599.10 (284.63)	505.42 (229.81)	431.83 (104.96)	0.01

Table 7. PC-PVT performance results according to self-reported sleep hours.

Parameters	<5 hours n=52	5 - 7 hours n=84	7 - 9 hours n=18	p-Value
	Average (±SD)	Average (±SD)	Average (±SD)	
Mean RT	314.63 (103.57)	294.23 (35.42)	327.19 (89.03)	0.11
Fastest10%	222.32 (29.31)	217.44 (19.71)	240.56 (47.43)	0.01
Slowest10%	544.40 (305.96)	499.33 (164.38)	548.02 (304.27)	0.49

6. Discussion

Regarding clinical parameters, the average body mass index (BMI) is similar, and the waist circumference is lower than the study of Chilean workers [15]. Compared to the general Chilean population, the proportion of overweight workers is lower and the proportion of obese is similar. Regarding the suspicion of hypertension, risk of diabetes, and risk of myocardial infarction, the prevalence of workers are lower than the figures found in the Chilean population in the National Health Survey of 2017 [16]. Probably these better figures are explained because the sample is made up of people who are working in a job and therefore in health conditions that allow them to do it. Regarding sleep hours, 74% of workers sleep less than 7 hours. The situation of Chilean workers is worrying since Powell and Copping [6] shows that those who sleep less than 8 hours have an 8.9% increased risk of accidents. Also, they shows daytime fatigue, psychomotor impairment, deterioration of physical and psychological health and poor academic or work performance [17]. Regarding the quality of sleep evaluated by Pittsburgh, the study by Baron [18] reports that 61% of workers in manufacturing companies present sleep problems with a score greater than 5, a figure lower than the findings of this study where a 76.6% report some degree of sleep problems. Workers with Pittsburgh greater than 5 have a 1.78 times more risk of occupational injuries compared to those with a rank less than 5 [19]. In the present study, 44.8% of the workers felt fatigued when carrying out their daily activities. These results are superior to that of Uehli et al. [20] where only 22% report high levels of fatigue. Observing the results obtained in the psychomotor surveillance test (PC-PVT), it is observed that the higher the educational level, the better performance is achieved in all the parameters, which coincides with that indicated by Wendt et al.[11]. Although it seems that there is a relationship between sleep duration and fatigue, this study is not conclusive to report this relationship, given that 44.8% of workers who declared fatigue did not have significant differences regarding the number of hours asleep when compared between groups sleeping less than 7 hours, between 7 and 8 hours or more than 8 hours. To conclude if there is a relationship, more studies are required to delve into fatigue, its forms of measurement and the differentiation that must exist between the concepts of fatigue and drowsiness.

7. Conclusion

This study sought to describe sleep quality in construction workers, finding that less than a quarter of the sample (23.4%) presented good sleep quality (Pittsburgh <5) and two thirds sleep less than 7 hours. People between 20 and 29 years of age, with a higher educational level and who slept between 5 and 7 hours, presented the best performance in psychomotor surveillance evaluated by the PC-PVT test, which is the objective means of evaluating fatigue. Even though most of the workers had a positive perception of their health, they presented different chronic health problems that affect their life quality and their performance at work, especially in relation to overweight, obesity and cardiovascular risk. Although this is representative of what is happening in the country, given the great physical effort that working in construction means, it is important that these conditions are faced in a structured way, ideally from the construction company itself, as a benefit for its workers. To better understand the situation experienced in construction projects, more in-depth studies are required to better assess the health status of workers. It is important that construction companies are aware of the importance that sleep quality has in their workers, both personally and at work. In the latter case, the impact on safety and the accident rate has been widely demonstrated, making it relevant to carry out programs that educate workers on these issues to change their behaviour. Given the above, in the next stages of this research, interventions will be carried out with workers to provide them with tools to improve their sleep quality, and then evaluate their impact on their fatigue levels. In this study, fatigue was measured in the morning, which could have influenced performance. In order to have a better understanding of the phenomenon and have more information to compare the perception of fatigue and daytime sleepiness of workers, it is necessary to make more measurements with the PC-PVT at different times during the workday.

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The Contribution of BMS Application Towards the Sustainability and Life Cycle Costs Optimization of Buildings: A Case of Public Utility Facilities in Poland

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Abstract

BMS (Building Management System), i.e. the central building control, assumes integrated control of all building functions - from air conditioning and heating to lighting, access control and security issues. Properly designed BMS solutions improve the operation of the building service, allow for a quick reaction in case of emergency situations and significantly facilitate maintenance activities. Building automation systems also allow for data collection and analysis, which can be used among other things, to optimise energy and water consumption in buildings.

The aim of the paper is to provide and to discuss findings of the analysis of the impact of the BMS application in the city stadium design, which is an example of a public facility, on the possibility of controlling the life cycle costs of the facility under examination.

In the first step, on the basis of the design documentation and the stadium operation schedule prepared by the authors, the life cycle costs of the analysed facility were calculated in accordance with the methodology recommended by the Polish public procurement law with use of the SMART SPP calculation tool. The functional assumptions of the BMS designed for the stadium were taken into account. Then a change was introduced to the analysis at the input consisting in the simulation of BMS removal from the facility and then the introduction of the risk factor of human error on the part of the staff during the annual operation of the stadium in relation to the operation of the lighting system of the facility. The analysis is summarised by comparing the calculation results for both scenarios. The findings indicate the benefits of using BMS in facility management.

Keywords: BMS (building management system), life cycle costs analysis, sustainability, SDG, energy consumption, smart buildings

1. Introduction

The construction sector has got a significant unused energy saving potential. According to the Roadmap of Actions planned at the level of the European Union to implement the rules of the low-emission economy in 2050, it is estimated that emissions from built-up areas could be reduced by about 90% by 2050 by introducing passive technologies in new buildings, modernisation of old buildings to improve their energy efficiency and replacing fossil fuels with electricity as well as RES in heating and cooling systems [1]. At the beginning of June 2018, the Directive 2018/844 of the European Parliament and of the Council (EU) of 30 May 2018 amending the Directive 2010/31/EU on the energy performance of buildings and the Directive

2012/27/EU on energy efficiency was published. The new legislation entered into force on 9 July 2018 and the EU Member States had 20 months from the date of entry into force to transpose the Directive into their legal systems. The deadline was on 10 March 2020. In accordance with the Directive 2018/844, the Member States were obliged to establish a long-term strategy to support the renovation of the existing resources of residential and non-residential buildings, including both public and private, in order to achieve high energy efficiency equivalent to nearly zero energy consumption buildings by 2050. New buildings must meet two conditions at the same time: firstly, it is a condition of adequate insulation of the building external partitions and secondly, a condition of annual primary non-renewable energy demand below values specified by the Directive.

The energy efficiency of a building is determined primarily by three elements - well insulated external partitions and joinery with appropriate parameters, a source of heat and cold and the possibility of optimising energy flows in the building's technical systems [2]. Ensuring optimal operating parameters of individual systems is the main function of automatic control and regulation systems, i.e. automation as well as control and measurement equipment. Modern buildings contain many technical systems, and this requires integration and coordination of their operation. This task is to be met by BMS systems (Building Management Systems) [3,4,5].

An analytical tool integrating the issues of environmental efficiency, including energy and economic issues is the Life Cycle Cost Analysis (LCCA). The concept of a building's life cycle is comprehensively defined in the ISO 15686-5:2017 standard. The aim of the standard is to disseminate the practical use of the LCCA in the construction industry to support effective planning and control of the costs associated with the operation of different types of buildings, and to support the development of the market practice in the application of the criterion of the cost of the life cycle of buildings in the public procurement.

2. Method

The aim of the paper is to provide and to discuss findings of the analysis of the impact of using BMS in the design of a city stadium, which is an example of a public facility, on the possibilities of cost control and energy efficiency during the life cycle of the examined facility.

First of all, on the basis of the design documentation and the schedule of the stadium's operation over 25 years, the costs of the life cycle of the analysed facility were calculated in accordance with the methodology recommended by ISO 15686-5:2017 and the Polish public procurement law. The first year of construction of the facility was assumed to be the base year, i.e. the moment when the life cycle accounting period begins.

The SMART SPP calculation tool was used. The functional assumptions of the BMS, designed for the stadium in question were taken into account. Then a change was introduced to the input assumptions of the analysis consisting in a simulated removal of the BMS from the facility and introduction of a risk factor for human error on the part of manual operation, during the annual operation of the stadium in relation to the operation of the facility lighting system. The analysis is summarised by comparing the results of the calculation for four variant scenarios.

The product life cycle analysis assumes examining potential environmental impacts, from the excavation and transport of raw materials, through the processes of product manufacturing, distribution, operation, reuse of recovered materials, to the management and final disposal of waste. Consequently, the LCCA examines the above mentioned stages of the product life cycle in a modelled approach. Due to the focus of the analysis on the impact of the BMS system on the results of the energy consumption by the examined object's lighting system, a significant limitation has been adopted for the analysis, consisting in the fact that the limits of the product system were determined starting from the purchase of ready-made equipment forming the lighting system. The processes of raw material acquisition and production of these devices are not included here. The analysis is limited to the stage of construction and then use and demolition of the object. This is a significant simplification, but it was introduced due to the purpose of the study. The authors of the ISO 15686-5:2017 standard emphasise that the calculation of life cycle costs of a building facility may be of significance at each of its stages, therefore the assumptions made for the study concerned are consistent with the general guidelines of the cited standard.

The presentation of the results of calculations and comparative analysis was preceded by discussing the literature review. It was carried out with the use of Scopus, Web of Sciences and Google Scholar scientific publication databases. In order to obtain relevant articles relating to the problem undertaken in the study, common keywords were adopted including such phrases as "Life Cycle Cost Analysis", "Construction sector", "Building Management Systems". The search was limited to articles published in the last decade, i.e. from 2010 to 2019 inclusive. The total of 30 articles was finally selected to be valid for further analysis.

3. Results of the literature review

In modern buildings, in addition to the regulation elements and control of individual technical systems such as heating, air conditioning, lighting, etc. the possibility of controlling the cooperation between the systems is assumed. The integration of control and regulation systems in a building is a basic feature of the BMS [6,7]. The aim of using integrated systems is to reduce building operating costs while maintaining proper parameters of the internal environment. Additionally, attention is paid to increased technical safety of the integrated systems, optimal operating parameters of individual systems and easier detection of faults and failures [8,9].

One of the basic functions of automation, which allows to achieve the greatest savings during the operation of the building, is the appropriate control of light and the thermal environment of rooms, while maintaining the requirements in the existing standards and regulations [10]. The basic functionality related to the lighting system is the automatic switch-on/switch-off combined with the lighting intensity control and the so-called light scenes [11]. The lighting control function is often integrated with presence sensors and threshold light intensity sensors. This allows the lighting to be automatically switched on when motion is detected if the natural light is too low and switched off when the room is not used for a longer time. In the BMS lighting systems, a comprehensive solution is most often used, including the possibility of their zoning within the building or rooms [12]. More advanced systems use additional lighting intensity control systems depending on the daylight intensity or operational schedule. An additional function of the system is to monitor the condition of lighting. [13,14,15,16]

In the buildings with nearly zero energy consumption, sustainable and equipped with smart technologies, control systems above the standard are often used. These include adaptive regulation that uses information collection and algorithm synthesis based on the current behaviour of a particular system, and fuzzy regulation based on the transformation of information using fuzzy logic [17,18,19]. Control algorithms more and more often include modules using neural networks or genetic algorithms, which increase the efficiency of collecting and managing information about the behaviour of the building, system and users. Among the most advanced control systems, which are in the implementation research phase, there is a combined system using both historical data and prediction methods. For controlling in this system, models of building functioning are used, verified on the basis of data from the past, as well as predicted values coming from e.g. weather forecast and forecast of the building use by users [20,21].

The way the BMS is used to optimise the performance of individual technical systems, including lighting, affects cost-effectiveness, as shown, for example, by the research carried out on the basis of a case study of the first zero-energy building in the Southeast Asia, using passive and active BMS strategies [22].

The analyses discussed in the publication [xx] show, inter alia, that energy cost is a weighting of 48% of a building's total life cycle budget, with this ratio increasing above 60% when it is only weighted against the building's operating costs [23].

Current BMSs use two-dimensional vector graphics to help facility managers manage their buildings. However, the system is not fully interactive and can only be operated by a trained operator. One of the methods to improve the functioning of the BMS could be to introduce an information-rich BIM model that provides real-time information through the BMS [24,25,26,27].

The information on the life cycle of a building must be developed and maintained from the preliminary design to the operation stage. Well defined and available BIM information allows for life cycle analysis at every stage of the project. However, an economic analysis alone is not sufficient, and it is recommended to consider the relationship with the environmental impact [28].

The life-cycle cost assessment (LCCA) of sustainable building designs has been developed for more than a decade and studies show that the use of this analytical technique brings benefits in the decision making process as it can be used to review and assess the concept of sustainable development measures throughout the whole life cycle of a building, including the determination of the carbon footprint, the simultaneous analysis of energy consumption in assessing the environmental performance of buildings and the analysis of the economic efficiency [29,30].

The latest technical standards concerning the LCC issues include the ISO 15686-5:2017 standard, published in July 2017. The LCC according to the standard means "the cost of an asset or a part of it over its entire life cycle while meeting performance requirements: it applies to the UK construction industry and to key stages of the procurement process".

4. LCCA calculation results

4.1. Description of the investment under analysis

The subject of the analysis is the construction of the Children and Youth Training Centre together with the reconstruction and extension of the football stadium, football pitches and accompanying infrastructure. The capacity of the facility will be about 20 500 seats. Four football pitches will be built, including three full-size and one with an artificial surface reduced by about 10% in relation to the size of the grass pitch dimensions. In order to achieve optimised control of the technical functions of the building, a building automation and safety system (BMS/SMS) was designed. It was assumed that the designed BMS/SMS would provide a coherent interface for all systems –building automation, fire protection, security systems, including access control, intrusion and robbery alarm system, CCTV. The basic functions of the designed BMS/SMS system included:

- monitoring the operation of selected equipment in the building
- archiving and viewing data
- supporting the facility maintenance services in emergency situations
- controlling the devices in an automatic way.

4.2. Results of calculations

The data needed for the LCCA were obtained from the Investor's documentation and from the lighting manufacturer. The annual operation schedule of the stadium was adopted for the analysis in relation to the programme assumptions of the facility with regards to the planned football matches (tab.1).

Table 1. Schedule of the annual operation of the stadium.

Football matches	Level of lighting of the pitch [%]	Level of lighting of the pitch [LUX]	Match duration [h]	Number of matches per year
Club international matches	100%	2000	7	3
National premier league and league matches	100%	2000	6	20
National matches of 3rd and 4th leagues	50%	1000	3	15
Children and youth club and training matches	20%	500	2	300

The lighting of the pitch according to the construction design consists of 196 lamps suspended from the roof structure of the stadium.

Four optional scenarios were adopted for the analysis (tab.2):

S.1 The lighting of the pitch is controlled automatically by the BMS system,

S.2 The lighting of the pitch is controlled manually. This variant takes into account the human error of mistakenly failing to switch off the lighting at a certain time - as a consequence, the lighting time is extended by 1 h in case of each planned match (taking into account the time needed to get to the control point),

S.3 The lighting of the pitch is controlled manually. This variant takes into account the human error of setting the level of lighting higher than assumed and than necessary in the national matches of 3rd and 4th leagues, children and youth club and training matches,

S.4 The lighting of the pitch is controlled manually. This variant takes into account the human error of leaving the lighting on at night in 1/3 of the number of all matches - as a consequence, the lighting operation time is extended by an additional 12 hours.

Table 2.

The lighting of the pitch - scenario	Total time in [h]	Quantity of kWh/h 1 lamp	Total quantity of kWh
Scenario 1 (S.1)	786	0.57	87 867.78
Scenario 2 (S.2)	1124	0.53	117 437.32
Scenario 3 (S.3)	786	1.43	220 300.08
Scenario 4 (S.4)	2130	0.49	203 903.70

The analysis was carried out for the period of 25 years, and a discount rate of 3% was assumed. The results presenting the life cycle costs were obtained in the annual and summary approach for the lighting system with the assumption of four variants of controlling of the system (tab.3). The share of particular costs in the LCC for the examined variants was also calculated (fig.1).

Table 3. LCCA for the scenarios S.1 – S.4.

	S.1		S.2		S.3		S.4	
	EUR	%	EUR	%	EUR	%	EUR	%
Acquisition costs [EUR]	530786,52	78	530786,52	75	530786,52	67	530786,52	68
Operational costs [EUR]	77862,91	11	103532,20	15	195340,29	25	181388,16	23
Maintenance costs [EUR]	7899,70	1	7899,70	1	7899,70	1	7899,70	1
Other costs e.g. taxes [EUR]	63197,60	9	63197,60	9	63197,60	8	63197,60	8
LCCA TOTAL [EUR]	**679746,73**		**705416,01**		**797224,10**		**783271,97**	

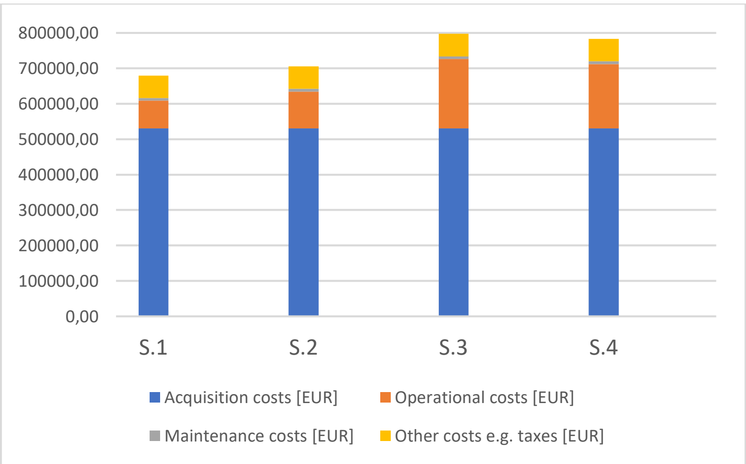

Fig.1. Total costs by categories

5. Discussion and conclusion

The results of the calculations for the four variants confirmed that the use of BMS has got a positive impact on the reduction of life cycle costs. The analysed variants focused only on the costs of electricity consumption used for the pitch lighting, due to the fact that the analysis was carried out as a preliminary one, with the assumption of continuation of the deepening the LCCA issue and supporting the digital technologies in the control of the costs of construction facilities.

Based on the case of the analysed variants, the possibility to assess the impact of the BMS on life cycle costs using the LCCA calculations is presented. The analysis showed that the highest financial losses occured in variants 3 and 4, which is a consequence of the impact of the operation phase on the sum of all life cycle costs of a facility.

The percentage increase in the life cycle costs of variants 3 and 4 compared to base variant 1, which uses the BMS to control the pitch lighting, is 15% at the interval of 5 years. This is a significant monetary loss, especially in the context of simplification of the analysis, resulting from including only the lighting system in the calculation.

The paper presents the results of the LCCA calculations confirming the beneficial impact of using BMS in public facilities on the possibilities of the life cycle cost control of building facilities.

The method of analysis used refers to the assumptions of the ISO 15686-5:2017 standard, which provides instruments to analyse designs or existing buildings in a wide range. The standard includes both the building life cycle cost calculation methodology (LCCA) and the Whole Life Costing methodology, which allows to extend the calculation with the costs of environmental externalities and social costs. The continuation of the research described in the paper will be the analytical works extending the scope of the analysis to include further technical systems, which are part of the integrated set of systems serving the technical functions of the building with the use of the BMS and calculations covering the gradually extended range of the boundaries of the system of products (devices and systems) forming the examined technical systems.

6. Limitations of the study

The study, the findings of which are discussed in the article had some limitations which could affect the final results. The study, the results of which are discussed in the article had some limitations which could affect the final results.In order to obtain more ubiquitous results, similar calculations should be made for at least several similar investments. However, this would require access to design documentation for other investments, which was not possible at the stage of this study. The second major constraint is that the analysis is limited to the lighting system, and to gain a fuller understanding of the importance of BMS in controlling life cycle costs, the scope of the analysis should be extended to other systems. The limitations indicated above are related to the preliminary nature of the study carried out, which will be continued in a wider range.

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Towards Sustainability of Real Estate Development: An Integrative Review of Smart City Planning Considerations

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Abstract

With the ever-increasing urban sprawl in African cities, more attention should be paid to the provision of real estate infrastructure to cater for the population. Ways to harness Africa's possibilities and leverage the opportunities available in the fourth industrial revolution, to diminish housing infrastructure backlogs, warrant consideration. The current study therefore aims to identify the factors that influence the sustainability of real estate developments in recent times, with attention to the planning considerations. An integrative review was conducted with literature from databases including Scopus, Google, Google Scholar, Publish or Perish, Academic Search Complete and Emerald. Synthesis was undertaken using thematic content analysis to identify themes on the factors influencing real estate developments and its sustainability. The distillation of literature revealed that institutional and economic factors were considered the most important factors, while developer's attitude and socio-cultural factors were the least occurring among the sampled literature. By establishing these factors, the current study provides important information for housing and construction stakeholders to be informed and guided in the planning and implementation of real estate development policies in order to provide for and sustain the needs of the current population and future generations given the need for smart cities.

Keywords: development, real estate, smart city, sustainability, urban housing

Introduction

The construction sector and the property market (the real economy part) are important for meeting mass housing demand and thus are pillars of the country's economic growth [1, 2]. The real estate industry generally supports the core business of organisations and the services sector in particular, to provide for the citizenry and contribute significantly to national growth [1]. The performance of real estate developments has primarily been assessed based on periodical returns or appreciation, which are calculated based on the difference of log-prices in time, or fluctuations in transaction prices in liquid markets as used in investment markets [3, 4]. Indices from transaction-based and valuation-based approaches, which are sometimes difficult to predict or estimate, subject to bias (with the use of historical comparable), and extremely scarce from infrequently-trades assets such as real estate, have been used for modelling and market studies over long terms. However, real estate is no longer just about the cyclical undulation of returns. The impact of demographic, social and technological trends on the built environment is coming to the fore of real estate investment decisions and development patterns [5]. To enable the real estate sector to develop in a healthy and sustainable manner, strategies geared toward the future sustainability of such projects need to be developed, especially at the time of planning for such developments, in order to create smart cities.

Smart cities host investments in infrastructure, which drive sustainable socio-economic development and improved quality of life for citizens [6]. Therefore, constructing smart cities could have evolutionary consequences for the real estate business since it can add value to properties, as well as boost consumer trust, profit yields and market competition [6]. Hence, the process of real estate development should be guided by participatory and engagement approaches holistically involving consideration of factors that will affect its sustainability. This is especially important given that real estate demand is moving more quickly in recent times than at any other point [5]. According to new data from the U.S. Housing and Urban Development and Commerce Department, total new construction increased 3.8 percent in October 2019 to a seasonally adjusted annual rate of 1.31 million units, 8.5% higher than in 2018 [7]. This was partly due to numerous factors, which affect the supply and demand, and in turn the prices of homes. Concerns abound among real estate investors, around economic uncertainty and at the same time, they are forced to overhaul traditional business and valuation models in response to rapidly-changing consumer demands [5]. Nevertheless, top cities for real estate investment in 2019 were in Canada, Europe, Asia Pacific and United States [5]. This suggests that Africa is being left behind despite the increasing urban sprawl in most cities. With the rapid growth of African cities, it is estimated that 1.2 billion people, or 60 of Africans, will live in urban areas by 2050. Although, urbanisation is a positive force underpinning grave social, political and economic transformation, the challenge is to help Africa to better harness the productive potential of their cities and to cope with the increased demands for decent housing and municipal services [8, 9]. The rapid and projected urbanisation poses substantial and exceptional challenges with regard to sustainability [10]. Therefore, the question that arises is "what factors influence real estate investments in Africa and should be considered in the planning of such developments, in order to find ways to mitigate their impact in the long run?

Previous studies have focused on locational factors for real estate developments [11]; returns on investment [4] and real estate investment decision factors in Malaysia [12]. Other studies dwelt on liquidity of real estate assets and the role of real estate investment trusts (REITs) as a partial hedge against flight-to-safety with regard to risky assets [13]; as well as legislation around REITs [14]. Likewise, different kinds of risk that should be assessed in commercial real estate developments including land cost (usability, restrictions, local authorities, etc.), financial risk (interest rates, delays, etc.), construction (late changes, big financial risk, exposure, etc.), delays, and sale/rents (faulty assumptions) were identified [15]. However, these studies were singularly focused on factors affecting either a decision to purchase or a particular type of property. Further, [1] and [14] focused on entity's performance, which may be limited in scope on what is desirable in smart city real estate development. The current study broadly identifies factors that affect real estate investments and therefore development patterns, and which should be considered at the planning stage in order to achieve sustainable smart cities. Projects have a greater chance to succeed if appropriate and adequate time and effort are committed to the planning stage to understand challenges/risks and opportunities that might be present throughout the project [16]. The current study reviews extant evidence to identify contemporary ways of helping Africa to deal with its housing infrastructure backlog and sustain real estate investments. The results from this integrative review could contribute to the development of planning and implementation strategies for the sustainability of the real estate sector.

2. Review of literature

2.1. Sustainability of real estate developments

Real estate developments, globally, attract huge financial investment in recent years [17]. The real estate investment space comprises direct (residential, retail, commercial and industrial), indirect (REITS, mortgage-backed securities, property company securities, etc.) and synthetic (such as index notes, return swaps and forwards) properties [18]. Direct real estate investment, which is the focus in the current study, is a multidimensional process with activities ranging from the restoration of brownfield sites to the purchase of raw land to the renovation of existing buildings and to the sale of serviced sites [16].

In practice, the real estate asset market generally involves a relatively favourable risk or reward profile, with relatively low liquidity (ease of entry and exit) [19]. It is also inefficient and hard to price or predict accurately [18]. However, the sustainability of real estate has to do with more than price; it encompasses reliability, technology, effectiveness, environmental effects, as well as governance and policy issues, optimal management, finance issues, adaptation and redevelopment [17]. These are aligned with the triple-bottom line, encompassing environmental, social and financial aspects for sustainability in cities [17]. Consequently, appropriate planning should be undertaken, especially at the ideation or conception stage of such projects, where opportunities are identified, designed and planned for [16]. Beyond that, to design, construction, hand-over and letting or occupying the building, risk is a common feature [15].

Value creation in developing real estate assets derives from providing usable space over time with associated services [20]. However, value is mostly created at the ideation stage more than at any other phase in the real estate development process (Figure 1) [16]. This suggests that unpacking the conceptualisation activity, which permits the identification of sub-issues or tasks, with the perception or recognition that opportunities and/or risks exist, is paramount to the success and sustainability of real estate developments. Projects have a greater chance to succeed if appropriate and adequate time and effort are committed to the planning stage to understand challenges/risks and opportunities that might be present throughout the project [16]. Therefore, plans to support environmental sustainability, increase the value of assets, and improve the wellbeing and productivity of users, all at limited costs, should be made at the planning stage in order to ensure achievement of desired outcomes from real estate investments [1]. All potential risks to the project, which may be systematic or uncontrollable (for example, market risk, interest risk) and/or unsystematic should be identified [15]. These may include operational, business, transactional, reputational and developmental risks to the project. However, ultimately, the price that a property commands should reflect the benefits, which justify that the project is worthwhile [20].

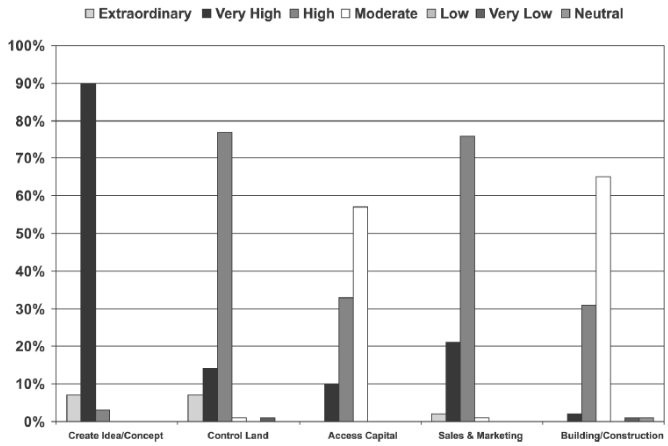

Fig. 1. Value creation at different stages of real estate development [16]

2.2. Smart city and real estate sustainability

Smart cities are sometimes deliberated to be about new technologies and opportunities/solutions, which they bring. However, smart cities are much more than technology and are related to sustainability [17], [21]. The smart city is an iteration of a highly modern impetus to imagine and shape the future of the city and of urban society [21]. A city is considered smart if it has one or several initiatives to develop an economy, governance, mobility and/or sustainable housing, among other factors [22]. This is especially the case with real estate investment where value is determined (created or destroyed) by a myriad of factors including globalisation and exposure to emerging economies, sustainability (energy-efficient and water-saving strategies), and innovation (advancement in new technologies and information sharing, availing real-time data) [18]. Further, the anticipated growth of cities creates unprecedented sustainability challenges, increasing demands for basic services (energy, water, sanitation, education, healthcare, housing, transport and public service) and testing the limits of city infrastructures. In 2015, 828 million people lived in temporary housing that lack basic services like sanitation and access to drinking water [23]. In addition, other externalities such as government policies and stakeholders, and availability of financial incentives and recourse influence real estate development [16]. Therefore, smart city should also involve a continuous transformative process, based on stakeholder engagement and collaboration, and building different types of human, institutional and technical capacities, driven by public value in all economic, environmental, social, ecological, and political dimensions [23].

The construction of smart cities therefore has possibly evolutionary consequences for the real estate industry sustainability, as this can boost the real estate market, add value to properties, and thus exponentially increase profit yields, consumer trust, and fierce market competition [6]. Advances in information technology provide the necessary tools to complement global real estate developments and smart city orientations [18]. However, the vision of smart city should not focus merely on technological development, but also highlight improvements in the economic, social, cultural, ecological, and governance dimensions, given the high market instability and unreliable nature of real estate developments [6], [23].

Although traditional approaches to risk assessments have been used (such as risk matrix ioMosaic, Bayesian belief network, Monte Carlo simulation and multi-criteria decision analysis), they mostly depend on results derived from either panel discussions or the ranking method, which are not always convincing enough due to the lack of quantitative measurements and strong theoretical bases [15]. In addition, the DCF/NPV techniques do not highlight the added value from managerial factors and flexibility [20]. Consequently, the factors that could potentially affect the sustainability of real estate projects should be identified in order to adequately plan and make reliable decisions as well as develop strategies to mitigate their impact. These findings are presented in a subsequent section, following a discourse on the data collection and analytical techniques employed to achieve the objective of the study.

3. Materials and methods

To achieve the objective of the current study, an integrative literature review was undertaken. A literature review was contemplated to assess and synthesize collective evidence from various articles from different sources on factors affecting real estate investments [24]. Since the review aimed to evaluate current knowledge on a particular topic, identify, analyse and synthesize important aspects of real estate investments from independent studies and reveal what questions can be addressed from identifying these factors, an integrative approach was deemed suitable [10], [25], [26].

The review followed a phased approach as outlined by [25]. First, relevant keywords including real estate, investment, housing and development, were used based on the guiding research question and thus results of interest. The keywords were used in conjunction with demand, supply, and pricing, in various permutations. Databases including Scopus, Google, Google Scholar, Publish or Perish, Academic Search Complete and Emerald, were subsequently used to identify relevant articles. These databases were available to the researchers from the university’s repository. Articles, including journals, conference proceedings, and online articles, were sought according to their currency (mostly articles spanning over a 10-year publication period) and possession of the relevant keywords. The identified articles were thereafter synthesized using thematic content analysis, to extract factors affecting real estate investment and development and explicate their import in a subsequent discourse. The frequency of occurrence of the factors among the sampled literature was also noted, where a higher frequency was deemed the most important among the sampled literature.

4. Factors affecting real estate development and investment

Real estate development and investment decisions are influenced by location, demographic factors (location and neighbourhood characteristics, income level, household size and structure, satisfaction, affordability (home prices and living costs), value of property, home ownership rules [19], [27], [28]. However, these factors mainly influence the decision to purchase or invest in new property in a particular location, or alternative investments (indirect and synthetic property). Other studies identified environmental, social, economic, technological, and political risks as broad factors, which pose risks to commercial real estate developments [5], [15]. The factors identified in this section are focused on direct real estate investments and factors that influence their development patterns. These factors are summarised in table 1. From the table, it can be seen that institutional factors occurred the most among the sampled literature, followed by economic factors. The least occurring factors were developer's attitude and socio-cultural factors. These findings are further discussed.

Table 1. Findings on factors affecting real estate development and investment.

		FACTORS						
LITERATURE SOURCES		Economic policies (monetary policies interest rates)	Environmental and physical factors (conservation, location and neighbourhood attributes)	Institutional factors (legal system and governance / political support, transparency)	Socio-cultural dynamics and demographic trends	Technology and innovation	Developers' attitude (Rigidity to adopt new ways; and competition among developers)	Finance and related costs (building materials land acquisition, transaction and construction costs)
Adegoke	2014	X	X	X	X			
Bah et al.	2018	X						
Baldi	2013			X		X		X
Boudry et al.	2018							X
Boudry et al.	2019	X						
Caprotti	2019			X		X		
Carstens and Wesson	2019	X						
Carnoske et al.	2010			X		X	X	
Delmendo	2019	X		X				X
Edelstein et al.	2011			X				
Eproperty News	2018			X				
Fereidouni & Masron	2013	X		X				X
Gavu & Owusu-Ansah	2018			X				
Liedtke	2018					X		
Mariadas et al.	2016		X					X
Odunsi	2015	X						
Oloke et al.	2013		X					
Owusu-Ansah	2014	X		X				X
Owusu-Ansah et al.	2018	X						X
PWC	2019	X	X	X	X	X		X
Ramabodu et al.	2007	x	x	x	x			
Roulac et al.	2006	X		X				X
Seth	2017		X					
Thilini & Wickramaarachchi	2019	X	X	X	X	X		X
Tiwari & White	2014		X			X		
Turner	2017						X	
Ullah et al.	2018					X	X	
WEF	2016			X		X		
Williams	2006				x			
Frequency of occurrence		13	8	15	5	9	3	10

4.1. Institutional factors

Institutional factors including the legal system, transparency, governance and political support influence the extent of real estate investment and development [20], [29]. The high attention given to the collective "institutional factor" may be due to its many facets and associated grave impacts which a proposed or existing real estate project could face if favourable conditions do not exist in a country, as discussed below.

4.1.1. Legal system

A country's legal system can generate the necessary protection for investors, or conversely, impose restrictions on the behavior of investors and developers through laws, liability standards and enforcement procedures [29]. For the real estate sector, a well-functioning legal system provides socially beneficial risk reduction in the capital market as well as in the operations of real estate companies, where asset acquisitions and dispositions require consistent legal and regulatory frameworks that insure property rights [29].

4.1.2. Transparency

Transparency encourages investment. Governance mechanisms can also ensure that shareholders receive transparent, appropriate information about returns on their investments [29]. Governments are increasingly recognising how a transparent real estate market can boost foreign direct investment, increase business efficiencies, enhance living standards as well as support and maintain a safe environment [30]. It is imperative for long-term planning, economic growth and investment in high-quality urban infrastructure and housing. Operational “transparency” can also benefit investors by improving their understanding of real estate company performance. In theory, a country with a superior legal system would lower the risk premiums required by real estate investors [29]. Transparency in real estate increases accountability and quality of governance, and improving transparency plays a central role in providing healthy, productive and competitive environments for communities and businesses to thrive [31]. Further, in an effort to promote transparency, government initiatives can motivate towards more data digitization an openness with information [30], [32]. This suggests that technological advancements in the recent day can influence real estate development.

4.1.3. Governance

Governance, which supports participation of the private sector and local community in decision-making influence real estate development and sustainability [33]. Government can create an “enabling environment” for private sector investment and accelerate real estate development [34]. In addition, in some places, local governments have encouraged certain developments through changes in their land development code or through incentives for developers, who may or may not choose to respond [35]. Land use decisions are sometimes made by local governments, which have influential impacts on activity-friendly community environments. Further, government support that enforces constitutionally-driven community participatory model of development planning at the grassroots level is important [36], [37].

4.2. Economic factors

Economic factors were also considered important among the sampled studies. Economic uncertainty affects interest rates and monetary policy (lower-for longer) benefits real estate over other asset classes [5]. Economic conditions such as recession, unemployment rates and gross domestic product rates, as well as fiscal policies and regulations including interest rates and mortgage/lending environment, influence the rate at which investors and developers want to enter the real estate market [37], [38].

In addition, when planning regulations are tight, less housing construction will be initiated, because less land will be made available to investors [39]. Tighter regulations and restrictions on land use or density of development may affect investors’ interest and the timing of proposed land development in the presence of uncertainty [20]. These forces may also produce a clustering and localized pattern of urbanization, where new development has tended to infill around existing development, as well as a dispersed trend [11]. Additionally, inadequate land policies and poor consultative processes result in inefficiencies in the process of making land available for housing development [40]. The difficulty in accessing development funds, underdeveloped mortgage market and high interest rates, land tenure arrangements, lengthy building permit/warrant approval and land acquisition and registration processes discourage real estate investments in Ghana [33]. Similarly, sound financial and economic structure, stability of the economy, restrictions and regulations on investors and legal regulation are the most important issues affecting the market attractiveness in Southeast Asian cities [41].

4.3. Finance and related costs

The most significant risk and uncertainty toward investment return is the income stream, in terms of the possible events that affect the income stream and uncertainties of the probability of the outcomes of these events. Access to capital and subsequent funding has an impact on the sustainability of real estate [16]. This is related to risk absorption and the availability of recourse to financial incentives to address the externalities. Planning considerations should therefore include tenant risk, demand and supply for the particular type of property being proposed, and in the particular location, the liquidity potential of the property, associated costs and expected benefits, delay premiums, and other assumptions that may lead to lower income than expected [15].

Further, as a result of housing supply constraints, high prices are a reflection of rising construction costs seen in more expensive materials like Canadian lumber or Chinese steel and a shortage-driven increase in labour costs [42]. The underlying cost of labor, land and materials in delivering the housing to the market is a concern. Lower financing costs and higher levels of transparency in real estate market attract greater amounts of real estate investment [41]. In addition, transaction and building material costs influence development in real estate [15], [20], [28].

A study by [39] revealed that the cost of construction variable has mostly been found to be insignificant in Ghana, partly because construction costs (as house prices) are influenced by housing supply levels and would generally decrease if the supply increases and demand remains the same. Conversely, in a recent study by the Price Water House Coopers [5], construction and land costs ranked the highest in importance among real estate development issues in the US real estate sector. Nevertheless, more reliance on local building materials and labour, which are more affordable could support and sustain the real estate sector in the provision of housing, as viewed [33], [36].

4.4. Technology and innovation

Technology and innovation were considered important in some of the literature examined. The few mentions could probably be due to the fact that advocating for the adoption of new technologies and disruptive innovation has only increased in recent times, with efforts geared towards the creation of smart cities. Innovation has made information available in real-time, changing the way real estate business is conducted [18]. While disruptive technologies are revolutionising the modern world, they present a challenge for traditional industries such as construction and real estate [17]. However, technological innovation and adoption of new digital technologies such as blockchain for land registries or 'smart' buildings, together with the digitisation of existing processes, offer opportunities to leapfrog the traditional routes to transparency and improve methods of collecting market data as well as transacting [30]. Digital reforms around land records and management can lead to greater access to land, reduced speculation, increased tenure security and, hence, more affordable housing also increases real estate development rates [35].

4.5. Environmental factors

Environmental sustainability is a concern in real estate development. Developers and investors are realizing that investing in available energy and water-saving technologies can produce low-risk returns creating more valuable and marketable real estate assets [18]. In relation to this, physical environment factors such as location and neighbourhood influence the market value of a specific investment [27]. Neighbourhood factors that may affect decision to invest and development patterns are safety, proximity to workplaces, travel time, sense of community, as well as affordability/value of properties in the area [35]. This suggests that the decision on location mainly depends on other factors such as accessibility to buyers' opportunities to support their needs (eg., places of education, worship, and shopping). For buyers who purchase for personal investment, locations that have the higher rental value will affect the investment or buying decision [43].

4.6. Socio-cultural factors

Social risks in commercial real estate development are mostly described in subjective forms. However. real estate development involves social-related risks and should be considered during the planning of such projects [15]. Furthermore, since smart city focuses on a continuous transformative process, based on stakeholder engagement and collaboration, and building different types of human, institutional and technical capacities, it is important to consider the local community and the potential impact of the development on their quality of life, capabilities and general wellbeing [23]. In addition, the participation of the community in the delivery of real estate projects would ensure acceptability of the projects [36]. Acceptability and cultural compatibility of proposed projects could be measured using degree of benefits, and public hygiene, using the degree of impacts on local public health and safety because of the development of specific projects [15].

4.7. Rigid development patterns by private sector partners

Although this factor occurred the least among the sampled literature, the role of developers as private sector to understand the persistence of conventional sprawl development and adopt sustainable alternatives to penetrate conventional markets has been emphasised. Developers have large control over the form and function of urban landscapes directly through construction activities that determine landscape configuration [44]. In some instances, the participation of the private developer is critical to making decisions about the desired function of a proposed development, as well as in the eventual success of real estate projects by the marketing strategies they use [35]. Desired functions on urban resilience within cities are closely related to land planning and development decisions that determine the composition and configuration of urban lands and the ecosystem services urban systems can provide [44]. Therefore, failure or unwillingness of developers to adopt new innovative alternatives to develop real estate is a concern. Further to this, competition may also have a significant effect on real estate development, especially commercial property, interacting with volatility so as to lower the value of the developer's option to defer its investment [20]

In summary, smart city development is complex. However, smart sustainable cities should include open government initiatives and environment to ensure access to data, stakeholder participation, leverage innovation, employ collaborative approaches and consider the impact of real estate developments on the populace who make use of the infrastructure. Further, in order to deliver real estate projects at reduced and affordable costs, while at the same time, ensuring that the objective of the developments are achieved and sustained in the long-run, the factors identified should be considered at the planning stage, which presents an opportunity to identify potential risks and alleviation strategies in the short and long-term.

5. Summary and conclusion

The current study set out to identify factors that could potentially affect the sustainability of real estate developments and thus should be considered at the planning stage of such projects. The findings were that institutional and economic factors were considered the most important, while developer's attitude and socio-cultural factors were the least occurring among the sampled literature. Since housing is a vital component of any economy, efforts should be made to identify risks, which may potentially hamper the success and sustainability of real estate development and the sector as a whole. The present study argued that identification of these factors at the ideation and planning stage of real estate developments would ensure that strategies are put in place to eliminate the occurrence of such risk or mitigate their impact on the success of projects.

The major limitation of the current study lies in the fact that it is a literature review and may not really reflect what the evidence in reality. Nonetheless, the use of relevant secondary data to distill information from primary research conducted on the subject, provides reliable evidence. The findings of the study are envisaged to be beneficial to real estate sector in developing strategies to manage the risks and implement policy.

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A BIM-Based Conceptual Model to Manage Knowledge in Construction Design

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Abstract

Managing knowledge had always captured the attention of researchers, since Plato's epistemology till now, where it is seen today as the most valuable asset of any organisation, and in a rapidly growing world as ours, the key to success is not perceived anymore as money, but mainly as knowledge. Construction is not different, where knowledge plays a vital role in its projects success, construction design phase in particular is one of the highest activities in terms of knowledge generation, however, designers still have got no clear process to manage knowledge efficiently. On the other hand, BIM or Building Information Modeling; a revolutionary framework that invaded construction market through the last decade, has a fundamental effect over the whole industry and over the way of how things are done, therefore, among the hundreds of applications and benefits of BIM, knowledge management could be one of them. This Paper attempts to fill that gap, by suggesting the use of BIM as a powerful tool to manage knowledge efficiently within the construction design activities to help in finally overcoming all limitations of the previous traditional knowledge management models, this is done through proposing a conceptual model that adds knowledge as an extra dimension to BIM, and which can capture knowledge generated during projects, assign it to the corresponding model building components, using the BIM parametric option, where it can be shared and easily recovered later when needed. New definitions are introduced through this paper and an illustrative hypothetical case study is conducted by the end of the study, to validate the proposed framework and demonstrate its effectiveness, benefits and expected limitations.

Keywords: BIM; knowledge management; construction design

1. Introduction

Knowledge has been always perceived in the past and the present as one of the most important resources of any organisation, twenty years ago, Stewart and Ruckdeschel (1998) stated that "Knowledge has become the most important asset of companies", while after the world economic crisis in 2008 and then the Oil prices drop in the Middle East in 2015, the importance of knowledge grew more significantly and became obviously the key to organisational excellence. Literature has always been highlighting the importance of knowledge, where many researchers and authors have concluded a direct relation between knowledge and attaining competitiveness, survival and success (Deshpande et al., 2014, Egbu, 2004 and Quintas, P. 2005). Knowledge basically refers to the awareness, understanding and experience gained and accumulated by time, it involves best practices, lessons learned and gained skills. A decision made based on effective knowledge can save a lot of time and money, and that what urged different organisations to start investing in knowledge management. On the other hand, Knowledge management refers to any process that aims to save knowledge from being lost, the Online Business Dictionary defined knowledge management as "the strategies and processes designed to identify, capture, structure, value, leverage and share organisational intellectual assets to enhance it's performance and competitiveness", similar meanings and definitions for knowledge management were discussed by studies in the past (Lin, Y.,2005, Davenport and Prusak, 2000, Tan, H., 2010, Bhatt, G., 2001) most of them have agreed that knowledge management is all about a group of processes that aims to manage and make the best use out of gained knowledge, common processes include: knowledge capture, knowledge sharing, knowledge maintenance and knowledge reuse.

Moving to Construction industry, where no project looks like the other and only few or negligible similarities exist, as each project has got its unique needs, challenges and circumstances (Boyd, 2013), each construction project generate its own knowledge and lessons learned. Moreover, construction is widely known for its fragmented and diverse nature, due to the participation of various stakeholders from different backgrounds, also Olawale, Y. and Sun, M. (2015) added that construction activities are characterised by its high creativity and dynamism. All of these facts make construction one of the most knowledge-intensive industries in the world market, and gives the area of knowledge management a vital importance. However, Knowledge management is still suffering within the construction fields, and is not being adequately addressed by researchers or considered by industry members, this led to a negative impact over the efficiency of the construction output, where the industry became famous for being an environment of repeated mistakes, wasted time, over-budget and never-achieved quality.

When splitting the construction project life cycle into two main phases; site and off-site, clearly, most of the research effort was focused on the 'site' project activities when examining knowledge management, while keeping the 'off-site' phase which mainly refers to the design stage, lacking the sufficient research and study needed to come out with innovative and efficient knowledge management solutions. Design stage is sometimes seen as the most essential part of any project due to the fact that critical decisions that can have a whole life impact over the project are being taken during this stage, and although the design has the lowest proportion of the project time and budget, but programme extensions and budget variations that take place during design may lead to a significant change in the whole project. Eastman, C. et al. (2011) have discussed how a lot of time and money are being wasted during construction design stages while preparing project documents as drawings, cost estimates and quantity schedules, where most of the wasted time and money could have been saved if lessons learned in the past were managed effectively.

On the other hand, over the recent years, Information technology or IT had broken into many industries leaving a huge impact over the profitability and success of organisations, Construction was not different, where IT had also emerged across it clearly, and on the top of its applications was Building Information Modeling or BIM, a totally new framework that is supposed to be integrated in the whole life cycle of construction projects, starting from design phase till the facility operation, aiming to attain a higher level of coordination and integration. Although BIM is still developing, but there are already enough BIM completed projects in the recent years worldwide that can enable us to determine how much BIM can improve the construction industry and the design activities in particular. BIM could clearly accelerate the completion of projects, lead to reduction in total costs, improve labor productivity and enhance the value and quality of design output.

Moreover, the rapid growth of BIM over the globe and its mandatory implementation in some countries motivates involving and utilising it in improving the construction off-site knowledge management. However, the process of integrating knowledge management and BIM during design is still far from being well explored compared to other benefits of BIM, and compared to other phases of construction. Some researchers have already attempted to approach this area, but most of them failed to offer an applicable model that could be developed and incorporated into the design phase daily activities to enhance the knowledge management environment significantly (Meadati et al., 2010, Wu, 2013, Deshpande et al., 2014, Amireddy, 2014, Fruchter et al., 2009)

This study is aiming to fill that gap, add to the previous research and contribute to solve the problem of inefficient knowledge management environment that construction design is suffering from, this will be done through proposing a model that integrates Knowledge management traditional principles with the growing contemporary BIM tools, and has the capability of capturing knowledge generated during projects design phases, categorise it, store it and make it recoverable for the future projects, in the fastest and most efficient possible route, making advantage of the already growing technologies of BIM worldwide.

2. Methodology

In order to achieve the research aim, which is formulating a conceptual model that can enhance the knowledge management environment within the construction design phase through using BIM tools, the paper adopted a road map that consists of four steps; First, introduction to the new concept of a Building Knowledge Modeling (BKM) which is developed out from the Building Information Modeling (BIM), Second; Categorisation of design knowledge into specific number of categories so they can be easily managed within the model, Third, introduction to the three pillars of the proposed model, which are BKM Parameters, BKM Library and BKM clash detection system, Finally; the paper presents a hypothetical case simple project to validate the proposed framework and gives a better understanding to the reader.

3. Building Knowledge Modeling

Building Information Modeling is known for its capability to include an unlimited number of dimensions, where the 3D model for instance can be developed to a 4D model by adding time dimension, or to a 5D model by adding cost dimension, and recently, researches have discussed new dimensions as the 6D for sustainability, 7D for facility management, and more dimensions are still on their way. The Concept of Building Knowledge Modeling (BKM) can simply refer to adding Knowledge as a new dimension to BIM Models, where knowledge management principles are integrated with BIM tools to formulate a model that can help in managing knowledge in the design fields.

Although the BKM Concept is still a newly introduced topic, but it has been slightly approached by few studies over the last couple of years. Almost ten years ago, authors started to suggest the integration between Knowledge and BIM (Fruchter et al., 2009, Meadati et al., 2010). Five years later, Wu (2013) introduced the first conceptual applicable BKM model through proposing an HTTP development that is able to send lessons learned from BIM users to a knowledge repository, the paper was a positive contribution and a step further to the development of BKM, however it was still seen as a raw approach that lacked technical details or practical validation. One year later, three more major studies in the field were introduced (Deshpande et al., 2014, Amireddy, 2014, Lin, 2014) where the authors started to put the BKM concept into the real life context and design applicable conceptions.

Any Building component inside a BIM model should have non-graphical information attached to its 3D geometry, while in the proposed BKM model, the component should have one more attachment, which is knowledge. Table (1) is an attempt to illustrate the differences between various building components in the ordinary CAD (Computer Aided Design), current BIM (Building Information Model) and the proposed BKM (Building Knowledge Model), in terms of the data that can be extracted from the model in each case.

Table 1. Comparison between CAD, BIM and BKM in terms of attached data

Building Component	CAD	BIM	BKM
Definition	2D + 3D	2D + 3D + Information	2D + 3D + Information + Knowledge
A Door	Geometrical Dimensions	Information; *Manufacturer*	Knowledge; *End User feedback*
A Column	Geometrical Dimensions	Information; *Load*	Knowledge; *Structural Standards*
An Air Conditioning Unit	Geometrical Dimensions	Information; *Power*	Knowledge; *Installation User Manual*
A Lighting Unit	Geometrical Dimensions	Information; *Wattage*	Knowledge; *Supplier Guidelines*

An Architectural building component as a simple door, was viewed only as a geometrical component within the basic CAD environment, where data as the door width and door height were the only kind of information that could be extracted, after the emersion of BIM, other types of information could be extracted, as the manufacturer details, fire rating, finish material, colour, cost and hundreds of other related data, while if the proposed BKM concept is implemented, it means that knowledge will be also available and attached to each building component (*eg. a door*), the "end user feedback" or how the users have reported and evaluated the door after usage, is a clear example for the type of knowledge that can be available, but then, this leaves us in front of a vital and important question, what are the categories to be considered as knowledge in the construction design environment?

3.1 Design knowledge categories

In order to formulate a BKM conceptual model that can manage design knowledge, there was a strong need to categorise knowledge within the design field. There had been always attempts to categorise and classify knowledge through previous literature, some authors divided knowledge into explicit and tacit (X. Zhang et al., 2009) where explicit refers to the part of knowledge that can be easily written and recorded in documents, while the tacit is the knowledge gained through experience and may not be recorded in documents. Others classified knowledge into Passive and Active (Boyd, 2013) where the passive knowledge is the part related to the way of thinking, while the active is related to the way of doing tasks, similarly Tan H. et al. (2007) divided knowledge into General, specific and process. However, there was almost a negligible effort made to categorise design knowledge.

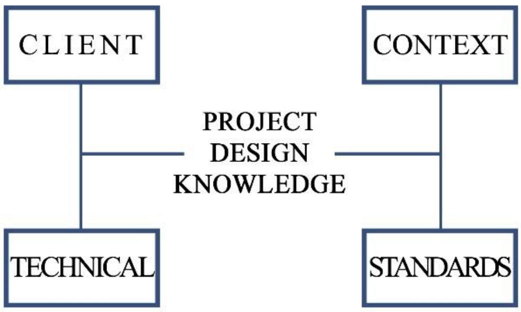
Interviewing was found to be an effective method to explore the different types of knowledge within design organisations, due to the deep and detail access to human experience and impression that it can allow during the interviewing, moreover, interviews allows the discussion to be directed in a way that serves the aim of the research. The Interview design was based on its purpose, first the interviewee receives an introduction to knowledge and its importance in the field of construction design, then, he or she is requested to list few examples of knowledge from his or her experience in the field. Five interviewees were selected, based on the accessibility, willingness to help, and mainly the extent of how much he or she are involved in the design process and have an interest to improve it.

Interviewee #1 was a 43 years old consultancy general director, when asked about types of knowledge within the design field, he stated that '*Data about the different clients in the market is considered to be a very essential and valuable part of knowledge, each major client in the market has got their own values, priorities, criteria and requirements, such type of knowledge can only be gained through lots of effort and over many years, and most probably it gets lost*" Interviewee #2, a project design manager, narrated an incident that took place during one of his projects, and which highlights one of the most important type of knowledge in the design work, '*after we have fully completed the design of a warehouse facility project whose main function was to store sensitive documents, and while we were finalising the design documents, we have discovered that we missed an important stamp for such types of projects, the National Archive Authority Approval for the design, a public authority that should have been get involved in the early stages of design, but we missed it, I personally had never heard about it at that time, if we knew about it, we would have saved a lot of wasted time, money and effort". Therefore,* local permits, design review reports and authorities' approvals can all be considered as an important part of design knowledge that only comes with experience. Interviewee #3 believed that all the problems solved, lessons learned and best practices found during design activities, technical processes and business meetings, in addition to the feedback of the end users of the designed facilities, all represents the real core of design knowledge. While Interviewee #4 argued that '*International design standards*' type of knowledge, are seen to be the most part of design activities consuming time and effort and which needs to be stored efficiently somewhere. Finally, the last interviewee, being an architect, claimed that design contextual knowledge, is a very essential subject, where designers spend a lot of time in researching, surveying and studying in order to have access to such knowledge. Table (2) shows a summary of the Interviewees details and their corresponding answers:

Table 2. Interviewees details and answers

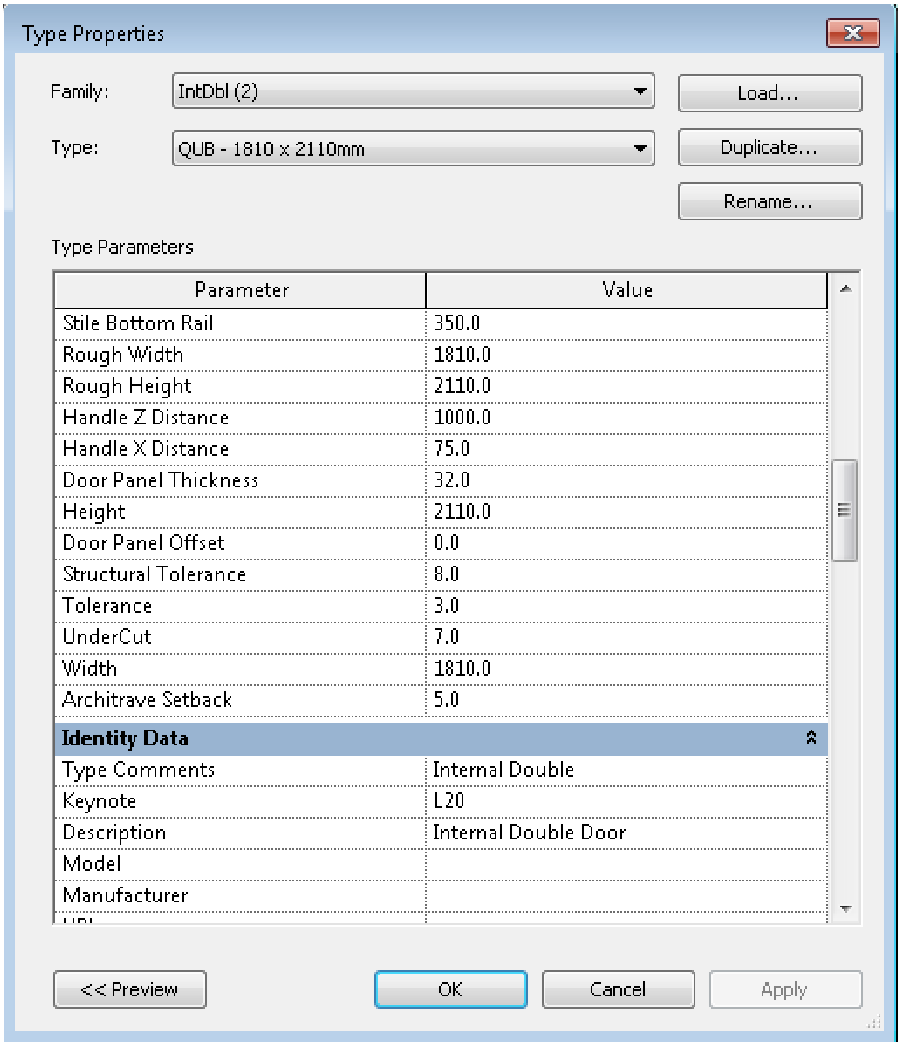
#	Professional Title	Experience	Knowledge Examples provided
1	Consultancy Director	43 years	Client Knowledge
2	Project Manager	24 years	Permits and Approvals
3	Design Lead	7 years	Problems solved and Lessons Learned
4	Architect	8 years	Standards
5	Architect	27 years	Contextual Knowledge

As shown in Figure (1) and based on the interviews responses, the design knowledge could be classified into four major categories, that all relates directly to the design project.



First, the **Client Knowledge**, where there could be a database of different market clients and organisations, showing their priorities, evaluation criteria, values, needs and policies of each client, in addition to the details of the key personnels of each organisation, such type of knowledge could save a lot of time wasted by designers in knowing more about their clients, whereas this time could have been utilised in satisfying the client needs and design requirements. Second, the **Context Knowledge**, and this is the part of knowledge that is related to the place where the project takes place, as the project location is directly impacting its design, a database that consists of architectural styles, urban patterns, infrastructure networks, governmental legislations, municipal regulations and many other aspects, could be formulated, and knowledge would be classified according to different cities and regions of the world, to provide designers with the needed contextual information based on the location of their project. Third, **Technical Knowledge**, which refers to all the technical aspects of the design teams, and represented by a knowledge library that include solutions to problems that have been solved before, best practices that had been proven to be efficient in the past, lessons learned and also all the feedback of all the design process members, as architects, designers, managers and even end users. Finally, the Fourth category of design knowledge is the **Standards Knowledge** and this refers to all types if design standards, which represent a major controller of the design process, this may include architectural standards, structural standards, health and safety standards, local or international.

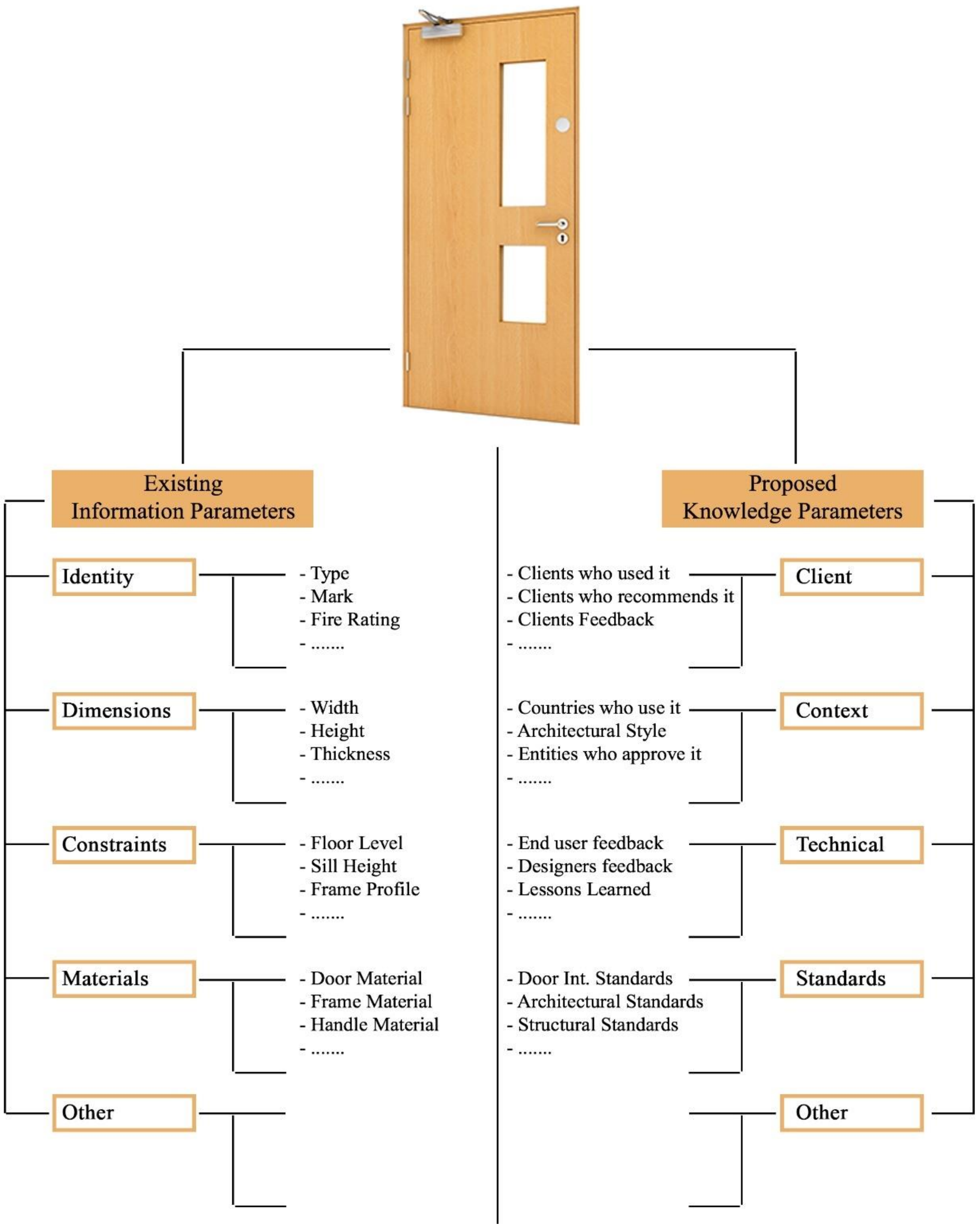
3.2 BIM knowledge parameters



Knowledge categorisation made through the previous section makes it easier now to move to next step and integrate knowledge in a BIM model, but to do so, '*Parametric option*' of BIM should be introduced first.

Parametric option is a unique characteristic of BIM models and which makes it different from normal CAD drawings, where CAD building components are only geometry, while the BIM building components have got parameters attached to the geometry, BIM parameters are placeholders for information, and each parameter should be defined by descriptive titles. Figure (2) shows the information Parameters of a Door type, in 'Autodesk Revit', a widely used BIM authoring software, as clearly shown, each parameter has got a descriptive title (eg. Width, Height, Tolerance, Keynote, etc..) and each parameter title has got a corresponding value. Moreover, it can be noticed that the parameters are categorised, where each group of similar parameters are placed together under one head title, (eg. Dimensions, Materials, Identity, Other, etc...)

Based on Knowledge categories proposed in this study and using the parametric categorisation set in 'Autodesk Revit', knowledge can then become attached easily to different building components inside a BIM model, and this can be achieved by setting up five categories of Knowledge parameters (Client, Context, Technical, Standards and Other), where each category comprises set of different parameters, ready to store knowledge and share it with designers who use the same building component. Figure (3) shows the two types of BIM parameters, the existing information parameters, and the proposed knowledge parameters, with few examples for each parameter category for a better understanding.

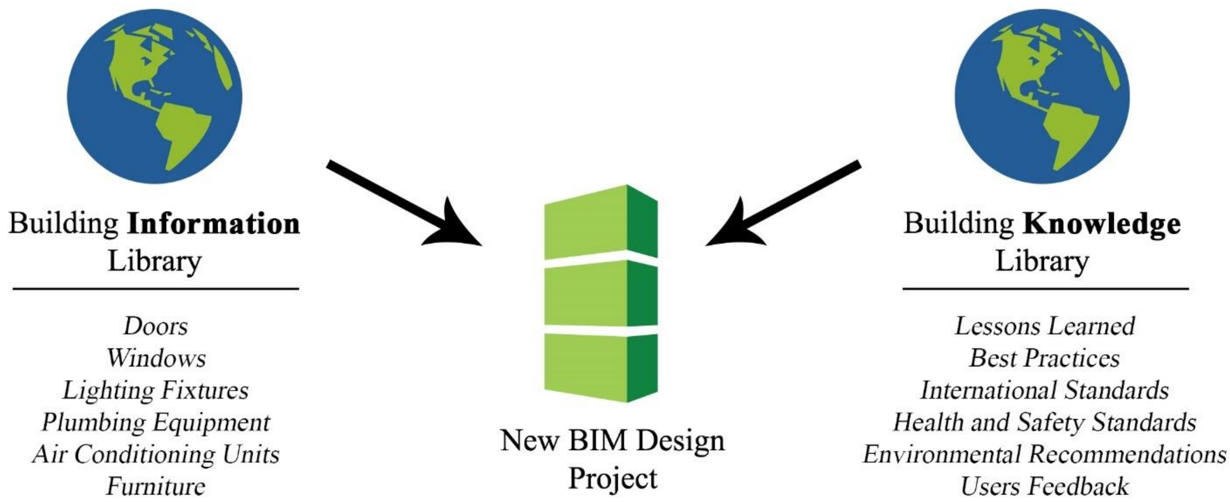

Existing Information Parameters
Identity
- Type
- Mark
- Fire Rating
- ....
Dimensions
- Width
- Height
- Thickness
- ....
Constraints
- Floor Level
- Sill Height
- Frame Profile
- ....
Materials
- Door Material
- Frame Material
- Handle Material
- ....
Other
Proposed Knowledge Parameters
Client
- Clients who used it
- Clients who recommends it
- Clients Feedback
- ....
Context
- Countries who use it
- Architectural Style
- Entities who approve it
- ....
Technical
- End user feedback
- Designers feedback
- Lessons Learned
- ....
Standards
- Door Int. Standards
- Architectural Standards
- Structural Standards
- ....
Other

3.3 Building Knowledge Modeling (BKM) Library

One of the key features of BIM is the online library, where different members of the industry (eg. designers, suppliers, manufacturers) anywhere could create a unique building component and share it with the rest of the world, for example, Philips Lighting International, the Dutch technology company, created all of its products in the form of BIM digital components in Autodesk Revit file format, and share it via its online website, these components contain all the necessary information parameters and properties as per Philips product standards (eg. dimensions, light colour, light intensity, model name, etc..), so designers could make use of them.

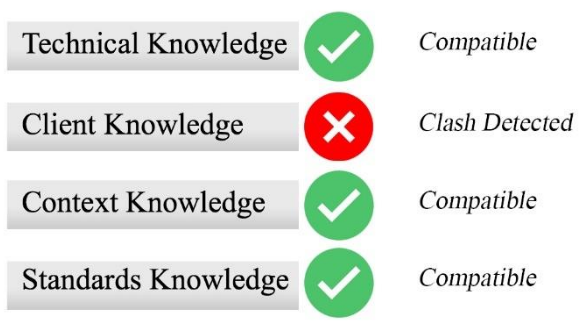
This takes us to the concept of developing a Building knowledge modeling (BKM) library, a library that has a similar approach to the existing BIM online library, but with knowledge stored instead of information, an online global repository that is able to receive knowledge from all members of the industry (eg. designers, clients, suppliers, contractors, etc..), maintain and categorise it based on the knowledge categorisation technique, share it with the world, and keep it available for the future reuse of designers through their BIM models.

As the case of the BIM library, a BKM Library develops itself by time, where the more input it gets in from different industry members, the more useful it becomes to designers, Figure (4) shows the two types of BIM libraries to be available for the designers.



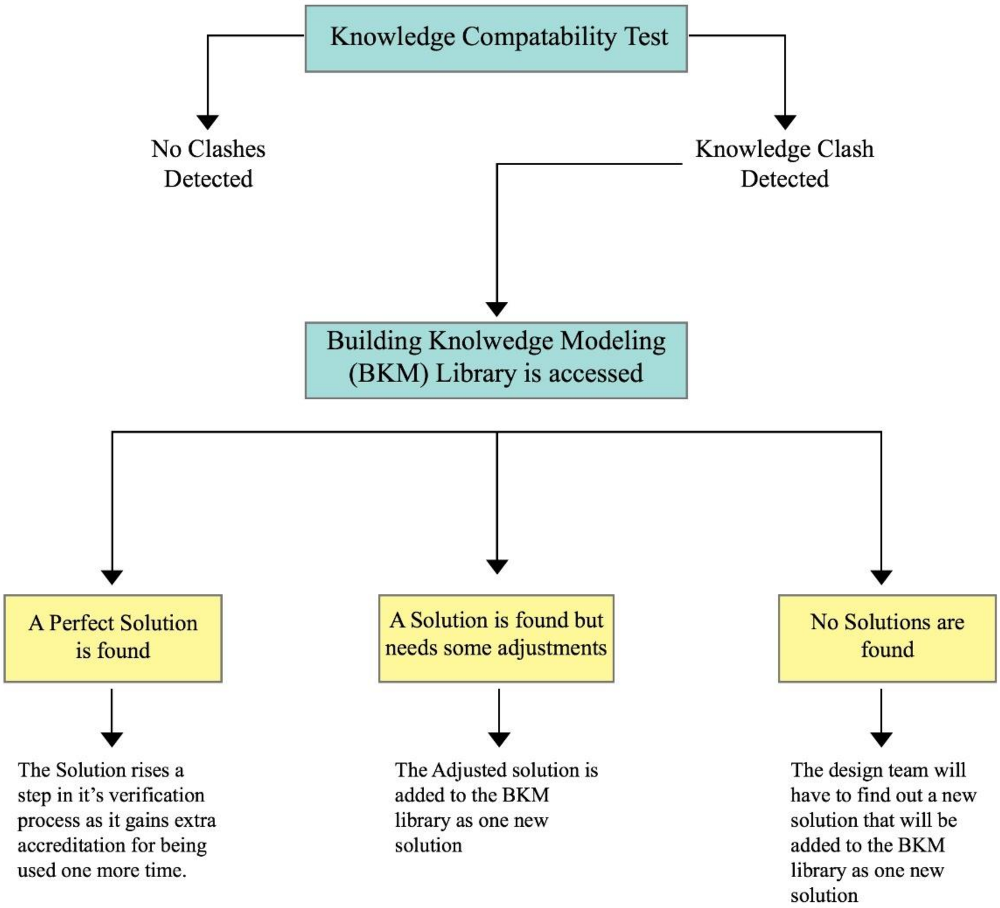
3.4. Knowledge clash detection

One more major benefit of BIM is clash detection, clash within design refers to the case when project components are not spatially coordinated, whether two or more components are occupying the same space, or even a component is not given the spatial tolerance it requires to be installed or maintained. BIM provide designers with the ability to spot clashes at an early stage, where they should be much easier, cheaper and time saving to rectify at that stage than in site.



Using the previous findings and proposals discussed in this study, BIM could also be utilised to find out knowledge clashes, where developed tools and software can have the potential to carry out a compatibility test, where it compares the design with the verified and trusted knowledge stored within the BKM library, and automatically detect clashes between the design parameters and knowledge if found, as when in Figure

(5), and it instantly inform the design team with the clashes, and could also contribute to resolving them by suggesting solutions based on the database of similar problems solved in the past and was stored to the BKM library, the design team will then face three different options, first, to find the perfect solution for resolving the clash, second, find a solution that needs some more work to make it fit, or finally to find no solutions where they will have to propose their own, the reaction of the design team to each of the three options ensure a continuous development and validation to the global BKM library, the reactions are shown in Figure (6).



4. Case study application

In order to give a better understanding for the proposed conceptual model, a hypothetical design project is given in the following part of the study, to show clearly how such a model could be applied. The Project details are as follows:

Location: *London, UK*

Client: Bank of England

Project: Design of a 20 storeys Administrative building

Building Component to be examined: *Building Main Entrance Door*

It is the responsibility of the design team to fill the Building Information Model for the project with the details parameters mentioned above since day one, once the project details are entered, the model should be able to search into specific areas of the BKM library. For instance, regarding to Context knowledge, the model should refer only to all projects completed in London, make sure the selected door is available in UK, could be supplied, manufactured or even imported, it also could confirm if it has been used in UK before, or if it has been approved by a British entity.

Moving to the Client knowledge, the model will look for all projects owned by the Bank of England, and check weather that type of doors had been used before or not within their projects, and if yes, what was their feedback.

On the other hand, in the Standards knowledge area, the model should refer to British, European as well as the International standards of doors design, and make sure that the design parameters made by the design team is compatible with all the standards, (eg. dimensions, material, use, etc...)

Finally, Technical knowledge, where the model will look in every piece of knowledge related to Doors, including lessons learned from those who used that type of doors in the past, weather designers, suppliers or even end-users, in addition to best practices, installation guidelines, design recommendations and many other knowledge parameters, that should grow and develop by time.

After the design is completed, a Compatibility test similar to what is shown in Figure (5) is made, where clashes will be spotted, and a group of solutions to resolve those clashes will be offered based on the Knowledge extracted from the BKM library, for the design team further action.

5. Conclusion

Despite the rapid growth and development of the Construction industry all over the world, this paper highlighted a gap found in the design phase of construction, the lack of an efficient knowledge management framework to manage the lots of knowledge lost during design activities and projects. The study proposed utilising and exploiting BIM as an existing growing technology in filling that gap, through adding one more dimension to the Building information models, which is Knowledge, thus open the doors for a new generation of BIM uses and definitions. Adopting the concept of BKM the paper has introduced a group of new definitions which act as the main aspects of the proposed model (eg. BKM Parameters, BKM Library and BKM Clash detection system).

The Proposed model shows a promising ability to aid in improving the knowledge management environment within the construction design phase, knowledge will be stored and maintained, it will also be available for reuse in future design projects, the model has also got the ability to develop and update itself continuously through time.

Future Research may consider developing a sophisticated software tool or a plugin that can transform this proposed conceptual model into a real application that can be incorporated into a BIM common platform, also future studies may include adding more categories of design knowledge beside the four categories proposed in this paper, or classifying those four titles into detailed subtitles, this would enrich the model and enhance the general process of knowledge management.

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A Comprehensive Map for Integrating Augmented Reality During the Construction Phase

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Abstract

The construction industry has undergone a significant and radical transformation in its design and documentation process as it evolved from the days of the drafting board to today's Building Information Modeling (BIM) process. At each stop along that journey, gains were made in information density and exchange. However, for all the progress made thus far, the paradox of designing the 3D in 2D space remains. This paradox indicates that new visualization technologies are needed to leverage the use of information in construction. Augmented Reality (AR), a pillar of the fourth industrial revolution, is an emerging technology that has great potential to transform the construction industry. AR can be described as an information aggregator that allows the user to passively view displayed information, actively engage and interact with published content, and collaborate with others in real-time from remote locations. While AR holds the key to advance the construction industry, no research project has yet comprehensively investigated the holistic integration of AR in construction. The contribution of this paper to the body of knowledge is a comprehensive map that establishes a sound framework for specifying the appropriate integration of AR into the construction phase. The comprehensive map is based on the Task-Technology Fit theory, where 23 use-cases of AR in the construction phase are identified and outlined as a function of nine AR capabilities and 14 AR potential benefits. The AR use-cases, capabilities and potential benefits are first discussed in the paper. Then, two AR applications are explored where the underlying use-cases are discussed and mapped as a function of their corresponding AR capabilities and potential Benefits. These AR applications provide an example illustrating the concept behind the comprehensive map. Finally, the comprehensive map is developed to provide a holistic framework to understand the integration of AR into the construction phase.

Keywords: augmented reality, framework, taxonomy, task-technology fit, visualization

1. Introduction and background

Construction plays an important role in the prosperity of nations and is expected to grow to a global expenditure of $15.5 trillion in 2030 [1]. This significant expansion along with the increased complexity and sophistication of construction projects and rapid advances in emerging technologies has fuelled companies' interest in innovation as a source of competitive advantage. Researchers argue that technology-enabled innovations can provide companies significant opportunities to maintain their vitality and competitive edge. One technology that has gained great interest in recent years is Augmented Reality (AR), one of the nine pillars of Industry 4.0. AR can be described both as an information aggregator and a data publishing platform that allows the user to (1) passively view displayed information, (2) actively engage and interact with published content, and (3) collaborate with others in real time from remote locations [2]. As industrial interest in AR has increased in the past decade (in sectors such as gaming, automotive, aerospace, military, and marketing), the construction industry has begun to follow suit in this area. AR is said to transform the construction industry and provide companies with a new frontier for gaining competitive advantage.

While previous research studies have investigated opportunities to integrated AR into the construction phase of a construction project, no research project has yet comprehensively assessed the relationship between the technology itself, the use-cases to be implemented, and the anticipated benefits. This study contributes to the body of knowledge by linking the AR capabilities to construction use-cases and connecting each use-case to the perceived benefits of integrating AR. Inspired from the Task-technology Fit model introduced by [3] which aims to assess the match between the task and technology characteristics, this research proposes a comprehensive map that outlines the relationships between the capabilities of AR, the identified AR use-cases, and the potential perceived benefits associated with AR. While users can experience AR through Head-Mounted Displays (HMD) or Hand-Held Displays such as mobiles and tablets, HMD provides the user with more flexibility as they enable hand-free operations [4]. Additionally, a study conducted by [5] surveyed 128 construction professionals and showed that HMD are becoming more commonly used in the construction industry. Thus, the comprehensive map presented in this paper is developed with HMD in mind.

2. Components of the comprehensive map

The comprehensive map has three main components: AR Use-Cases, AR capabilities and AR Potential Benefits. The following sections will identify and explain each of these three components.

2.1. Augmented reality use-cases in the construction phases

In recognition of the potential of AR in construction, researchers have conducted several reviews of AR-related efforts in the industry. Numerous efforts have been undertaken to explore AR use-cases and investigate ways to integrate the technology into construction. Some studies have focused on a certain phase of the construction lifecycle such as design, pre-construction, construction, and operation and maintenance [6–9]. Other research endeavours have conducted a comprehensive assessment of AR use-cases throughout the project life-cycle – from conceptual planning to decommissioning. This paper builds on the work of [5,10,11] and presents 23 AR-use cases for the construction phase of a project. The 23 AR use-cases are outlined alphabetically in the middle column of Fig. 5.

2.2. Augmented reality capabilities

Prior to integrating AR into a use-case (i.e. task), it is important to analyze the extent to which AR can support this use-case. Davenport (1993) explained that opportunities for supporting a process with Information technology (IT) fall into nine categories. The opportunities to integrate AR – an emerging and promising technology in the realm of IT – into a use-case can be also lumped into those nine categories, defining the capabilities of AR, as explained (in an alphabetical order) below:

C1 **Analytical**: The analytical capability is related to decision making enhancement and improving information analysis. In addition to providing real time in-situ information to visualize data [13] AR provides a platform to visualize and interact with data leading to better user cognition and environment perceptive[14].

C2 **Automation:** The automation capability is described as reducing human labour through automating different tasks. AR systems have the ability to automate processes by generating information automatically in real-time and visualizing it in a real construction working environment [15].

C3 **Disintermediating:** The disintermediating capability is best described as removing intermediaries from activities. AR is one of the digital era technologies with an ability to add or remove intermediator processes [16]. For example, using AR can substitute the processes of manually capturing, storing and analyzing data.

C4 **Geographical:** The geographical capability is related to coordinating activities and taking decisions across distances, irrespective of the location of decision makers. AR promotes new types of collaborative interfaces to enhance face-to-face and remote collaboration [17].

C5 Informational: The informational capability assists in understanding a process. AR offers opportunities to display, capture and store information for later analysis [18].

C6 Integrative: The integrative capability is the coordination between tasks and processes. AR can capture and generate context-rich data that facilitated the coordination between cross-functional teams [19].

C7 Intellectual: The intellectual capability is the capturing and distribution of intellectual assets. AR supports tacit knowledge exchange, allowing remote expert, for example, to transfer their knowledge through the AR medium using demonstrations such as graphics, audios, and videos [20].

C8 Sequential: The sequential capability is related to changing the sequence of processes and/or enabling parallelization. AR systems, enabled with remote collaboration, allow different activities/tasks to be performed in parallel [15].

C9 Tracking: The tracking capability is related to the close monitoring of process status and objects. AR superimposes digital models onto the real world, allowing users to track progress [21].

2.3. Augmented Reality Potential Benefits

The wide range of AR use-cases and the evolution of the capabilities of the technology highlight a new era for the construction industry [9]. The suitability of a technology and the success of its integration are manifested by its benefits. This study adopted the benefits identified in [5] but excluded two of them: “Improving the corporate image” and “Improving growth and success by creating new business models”. The rational for removing these two benefits stems from the fact that this paper focuses on the construction phase and these two benefits are long-term benefits that impact the organization rather than the construction site. The 14 AR potential benefits are outlined in the rightmost column of Fig. 5.

3. Examples illustrating the concept of comprehensive map

This section includes some applications of AR on construction sites to illustrate the concept of the comprehensive map. After an explanation of the applications, the connected capabilities and benefits are explained.

3.1. AR Application 1: Remote Expert System (RES)

A remote expert system (RES) connects a technician on the construction site with one or more remote experts sitting in their offices. In a simple version, the person on the construction site has glasses with a small screen and a small video camera – like Doka’s remote instructor [22]. The remote expert has access to a live-video stream from the construction site and can give written or voice advices that are transferred onto the small screen. Two of the authors have previously worked on a more advanced RES that equips the technician with AR glasses or a tablet and the remove expert with a computer program. Fig. 1 shows this remote expert system in the left picture. The remote expert program is displayed on the monitor and is featured with a live-video stream and the option to create markings. The upper left corner reflects the view of the HMD device of the technician. The application of RES is extended with the use of a camera to the generation of a 3D environment model (see Fig. 1, right image). The remote expert can switch from the live view to a 3rd person view, in which the 3D environmental model is shown

Multiple AR use-cases are supported through this AR application, particularly, UC14 (real-time support of field personnel) and UC16 (remote site inspection). Fig. 2 shows the corresponding AR capabilities and potential benefits for AR use-case UC14.

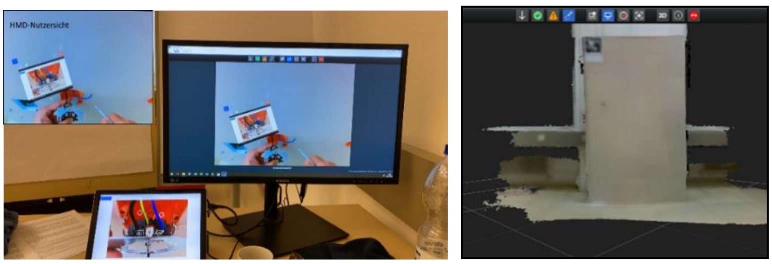

Fig. 1. Remote site inspection with Remote Expert System

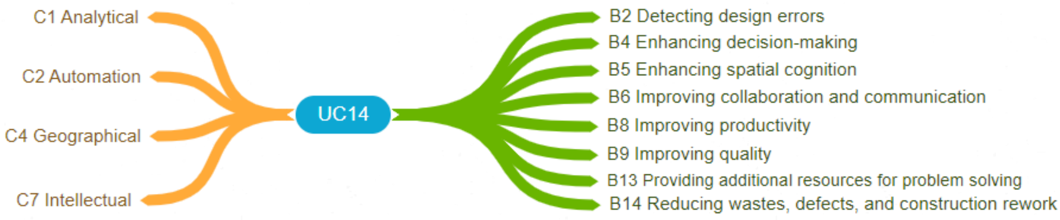

Fig. 2. AR capabilities and benefits connected with UC14 (generated using Coggle.it)

3.2. AR Application 2: Doka Verification Buddy with Augmented Reality and Artificial Intelligence

The formwork company Doka is developing a formwork verification buddy for its system formwork Frami Xlife [22]. This AR system shows the right locations of the clamps, the fixing bolts and the corner connectors for the formwork (Fig. 3). Additionally, an Artificial Intelligent system checks if any of these connection parts are missing – a challenging task given that the parts have the same colour as the frame of the formwork. The system marks the correctly placed parts in green and the missing parts in red, supporting unexperienced workers when erecting the formwork. The Doka Verification Buddy can, therefore, be used for detecting errors as well as for training purposes. The system is still in its development stage and is expected to be developed for HMD.

The Doka verification buddy supports UC8 (on-site inspection). The corresponding capabilities and benefits for this use case are shown in Fig. 4. It should be noted that while benefits B6 and B10 apply to UC8, they do not apply to the current version of the Doka verification buddy.

Fig. 3. Doka Verification Buddy: Visualization of augmented work instructions in the field in combination with AI

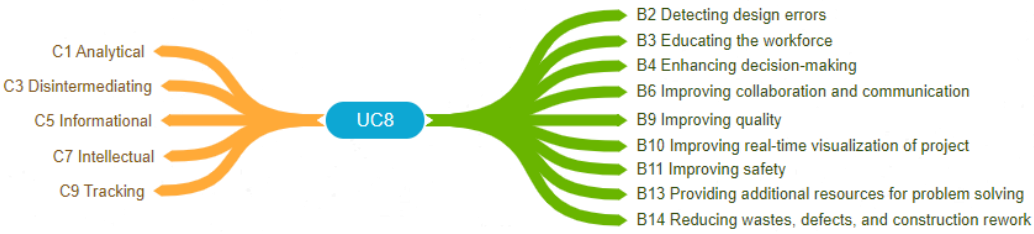

Fig. 4. AR capabilities and benefits connected with UC8 (generated using Coggle.it)

4. Comprehensive map

The culminating effort of this paper is a comprehensive map (Fig. 5) that outlines the relationships between 23 AR use-cases in the construction phase, the nine different capabilities of AR, and the 14 AR potential benefits. Fig. 5 shows that while the nine AR capabilities are essential to the integration of the technology into construction use-cases, *Automation* (C2), *Geographical* (C4), and *Information* (C5) are three capabilities that are applicable to most of the 23 AR use-cases. Additionally, *Enhancing decision-making* (B4), *Improving Collaboration and Communication* (B6), *Improving Productivity* (B8), *Providing additional resources for problem solving* (B13), and *Reducing wastes, defects, and construction rework* (B14) are found to be the most frequently expected benefits.

C1 Analytical	C2 Automation	C3 Disintermediating	C4 Geographical	C5 Informational	C6 Integrative	C7 Intellectual	C8 Sequential	C9 Tracking			B1 Allowing real-time data collection	B2 Detecting design errors	B3 Educating the workforce	B4 Enhancing decision-making	B5 Enhancing spatial cognition	B6 Improving collaboration and communication	B7 Improving owner's engagement	B8 Improving productivity	B9 Improving quality	B10 Improving real-time visualization of project	B11 Improving safety	B12 Improving the quality of planning and scheduling	B13 Providing additional resources for problem solving	B14 Reducing wastes, defects, and construction rework
✓	✓		✓	✓		✓			UC1	3D scans included in AR	✓	✓		✓	✓	✓		✓	✓	✓				
✓	✓		✓	✓	✓		✓		UC2	4D Simulations on site (augmented simulated construction operations)		✓	✓	✓		✓		✓	✓		✓		✓	✓
✓	✓		✓	✓	✓	✓	✓	✓	UC3	Augmented Mock-ups	✓	✓	✓	✓	✓	✓	✓		✓			✓	✓	✓
✓	✓	✓	✓	✓			✓	✓	UC4	Detection of changes between former state and current state	✓	✓		✓	✓	✓		✓		✓			✓	
✓	✓		✓	✓				✓	UC5	Construction progress visualization and monitoring				✓		✓				✓		✓		✓
✓	✓	✓	✓	✓	✓	✓	✓	✓	UC6	Create design alternatives on-site	✓	✓		✓	✓	✓		✓	✓			✓	✓	✓
✓	✓	✓	✓	✓	✓			✓	UC7	Monitoring progression of workflow and sequence	✓			✓	✓	✓			✓	✓			✓	
✓		✓		✓		✓		✓	UC8	On-site inspection		✓	✓	✓	✓	✓			✓	✓	✓		✓	
	✓	✓	✓	✓				✓	UC9	On-site material tracking	✓					✓		✓			✓			✓
	✓		✓	✓			✓		UC10	On-site navigation				✓	✓			✓	✓		✓			
	✓	✓	✓	✓		✓	✓		UC11	On-site instructions			✓	✓		✓		✓	✓		✓		✓	✓
✓		✓	✓	✓	✓			✓	UC12	On-site safety precautions			✓	✓				✓			✓			✓
✓	✓		✓	✓				✓	UC13	Planning the positioning and movement of heavy/irregular objects/equipment			✓	✓	✓	✓		✓			✓	✓	✓	✓
✓	✓		✓			✓			UC14	Real-time support of field personnel		✓		✓	✓	✓		✓	✓				✓	✓
✓	✓	✓	✓	✓		✓		✓	UC15	Real-time visualization/review/analysis of data (worker, equipment, etc.)	✓			✓		✓		✓	✓	✓	✓	✓	✓	✓
✓	✓		✓	✓	✓	✓	✓		UC16	Remote site inspection				✓	✓	✓	✓			✓	✓			✓
	✓	✓	✓	✓					UC17	Site layout without physical drawings		✓	✓	✓	✓			✓						✓
				✓		✓			UC18	Visualization of augmented drawings in the field		✓	✓	✓	✓	✓	✓	✓		✓				✓
✓	✓	✓	✓	✓				✓	UC19	Visualization of augmented work instructions/procedures in the field			✓	✓		✓		✓	✓		✓		✓	✓
	✓		✓	✓	✓		✓		UC20	Visualization of the construction systems/work		✓	✓	✓	✓	✓		✓	✓	✓			✓	✓
	✓	✓	✓	✓			✓		UC21	Visualization of the proposed excavation area			✓			✓		✓				✓	✓	✓
	✓	✓	✓			✓			UC22	Visualization of underground utilities			✓			✓					✓		✓	✓
	✓		✓	✓	✓	✓	✓		UC23	Visualizing layout and integration of prefab components in the shop		✓			✓	✓		✓				✓		✓

Fig. 5: Comprehensive Map

5. Conclusions and further studies

As interest in AR continues to grow in the construction industry, it is important to explore the suitability of the technology. This study focuses on the opportunities and benefits of integrating AR into the construction phase of a project. Twenty-three AR use-cases were extracted from the literature, nine AR capabilities were discussed, and 14 AR potential benefits were identified. Based on the Task-Technology Fit theory, this study developed a comprehensive map that outlines the relationships between each of the 23 AR use-cases and their corresponding AR capabilities and perceived benefits. The map revealed that Automation, Geographical, and Information are the most commonly used AR capabilities during the construction phase. The results also showed that Enhancing decision-making, Improving Collaboration and Communication, Improving Productivity, Providing additional resources for problem solving, and Reducing wastes, defects, and construction rework are the five AR benefits that are frequently perceived to result from the integration of AR into the construction use-cases. This paper contributes to the AR implementation roadmap by providing industry practitioners an understanding of the capabilities and benefits for integrating AR into construction tasks. Further research could expand the scope of work and examine AR use-cases throughout the lifecycle of a project and their relationships to the AR capabilities and AR potential benefits. Researchers could also build on the comprehensive map presented in this study and develop prototypes to validate the outlined relationships.

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A Computer Vision-Based Approach to Classifying and Storing Image Data for Construction Safety Management

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Abstract

The safety issues on construction site have been a critical problem and has received increased attention. The safety management approaches based on computer vision provides more chances to rapidly identify the unsafe hazards and instantly alert. However, related research mainly focused on specific scenarios or tasks and therefore lack of holistic and systematic discussions. On the other hand, the storage and processing mechanism of the collected image data is not timely and efficient enough, so it's impossible for managers to quickly extract the required information. In order to better apply computer vision into practice, a classification and storage approach for site images based on computer vision is proposed. Firstly, this paper provides well-organized descriptions and classifications of the site hazards based on the survey results. Secondly, according to the literature review, sort out the current applications of the computer vision technology in construction safety management, and analyze the various types of site information it requires. Finally, the safety management requirements and on-site technical information are comprehensively processed to establish a framework to classify and store the site image. Then, we assessed the actual effects with this framework in conjunction with a case study. The results imply that the approach proposed promotes the application of computer vision from a holistic view and improves the efficiency in safety management.

Keywords: construction safety management, image data, computer vision, classification, storage

1. Introductoion

In the past 10 years, the total output value of the domestic construction industry has continued to increase, bringing important contributions to the national economic development. However, due to the complex and changeable construction environment, safety accidents have occurred frequently, and the accident rate remains high. According to a report released by the International Labor Organization in 2013, the fatalities of workers in the construction industry are 2 to 3 times higher than in other industries. Therefore, it is necessary to strengthen the safety control measures of construction site to reduce accidents.

In recent years, the rapid development of computer vision technology has made automatic identification of construction hazards possible. This approach mainly collects on-site images, extracts key elements from them, and conducts analysis and training to obtain safety-related information. Compared to traditional safety control measures, computer vision technology is more timely and effective and will not interfere with the working process. Additionally, the surveillance camera is widely used in the construction site and easy to obtain.

However, there are still some difficulties in applying computer vision technology to the practice. The current research results are more focused on specific scenarios, types of work, or operating behaviors, and not general enough. At the same time, due to the large storage capacity of image data, it has an impact on the efficiency of data analysis. Aiming at the data classification and storage problems in construction site image detection, this paper combines the requirements of safety management with the characteristics of computer vision technology to construct a data storage structure suitable for general site management, thereby supporting timely and effective data analysis.

2. Related work

According to different recognition targets, the application of computer vision technology on the construction site can be divided into action recognition, object detection, and interaction detection.

2.1. Action recognition

Action recognition based on computer technology, mainly through two-dimensional color images of workers [1] or depth images [2,3]. Combined with training or non-training methods to achieve action classification and recognition. Ding et al. [4] used deep learning methods, convolutional neural networks and Long Short-Term Memory (LSTM) to distinguish related actions on the herringbone ladder from two-dimensional images. Han and Lee [5,6] extracted the three-dimensional skeleton of the human body after obtaining the depth image from an infrared camera. Furthermore, they [7] used the stereo camera to simultaneously capture two ordinary images with different angles of view to obtain depth information and achieved the three-dimensional reconstruction of the human skeleton, and finally, classified ladder-related unsafe behavior.

2.2. Object detection

The scope of object detection in this study includes worker wearable entities such as PPE (personal protective equipment) and non-wearable entities such as on-site materials. As the fundamental of image recognition, a number of models have been developed. Much of the literature on PPE concerns safety helmets and safety belts. Wu et al. [8] uses advanced imaging algorithms and a three-dimensional computer aided design perspective view to identify concrete columns from the construction site image. Zhu and Brilakis. [9] utilized shape, color and material information to identify concrete from the image column. Golparvar-Fard M et al. [10,11] proposed a method for classification and recognition based on image excavator behavior with higher fineness.

2.3. Interaction detection

Based on worker action recognition and object detection, we can obtain the interaction information after supplementing the spatial or logical relationship. Fang et al. [12] uses deep learning methods to detect the PPE usage of workers who go to the outer wall through windows to work at height. Chen et al. [13] revealed that the appearance of a person or an objec instance contains informative cues is useful for facilitating interaction prediction. Georgia et al. [14] carried out a model that can predict an action-specific density over target object locations.

Taken together, these studies clearly indicate the importance and feasibility of applying computer vision in the construction site. And object detection has a more mature approach compared with the others, which can play a significant role in this study.

3. Methodology

In order to solve the problems mentioned above, this study proposes a holistic classification and lightweight storage of images approach to support further data analysis and safety management. First, based on the related rules published by Oregon OSHA, we established the classification framework. Second, combined with the image recognition technique, we sort out the elements from image to store. In section 4, a case study was used to show how to conduct this approach.

3.1. Classification of image data on construction site

The Oregon OSHA’s safety and health rules for the construction industry has 24 subdivisions. We sort out 14 types of hazards related to workers, three of which are health-related hazards that cannot be captured by the image, which are ①toxic and hazardous substances (e.g. air contaminants), ② noise, and ③X-ray and other radiation. For the remaining 11 hazards (A-K in Fig.1), they are classified into unsafe conditions and unsafe practices according to the relationship with workers. In addition, we added the unsafe practices (L in Fig.1) such as using mobile phones and smoking, considering that there are some unsafe situations without interactions between workers and hazards.

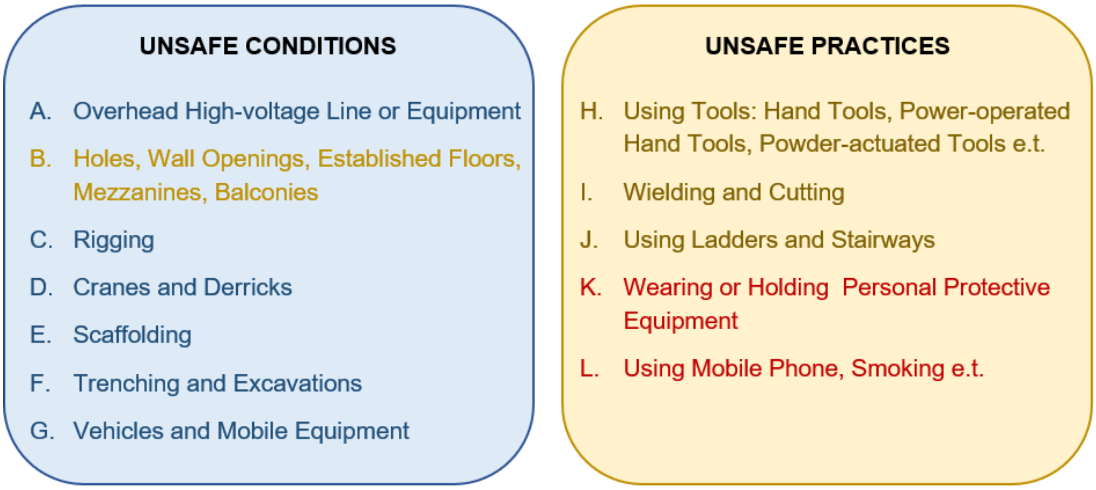

Fig. 1. unsafe conditions and practices in construction site

According to the characteristics of the above hazards and computer vision technique, we classify the images into macro-image and micro-image. Macro-images with longer distance between the camera's location and the object or workers identified, can attain the classification but is difficult to gain the operation information exactly. Such images mainly include outdoor images with wide coverage on the construction site. Micro-images, with shorter distance, can achieve the accuracy of identifying the specific operation and mostly be obtained by the indoor camera.

Overall, the main monitoring target of macro-images is unsafe conditions, and micro-images is mainly for unsafe practices. However, there are two special situations. ① The type B mainly exists in the indoor environment which is supported by micro-images. ② The detection of type K and L are equally important in both images. Therefore, according to the safety management requirements, as shown in Fig.1, the blue font is the main detection target of macro-images, the yellow font is for micro-images, and the red font should be included in both.

3.2. Storage of image data on construction site

Using computer vision to obtain the required safety information is generally divided into two steps. The first is to obtain the detection result from the image, which means identifying the existence of the objects or workers. Then, to further estimate whether the worker is in an unsafe condition or performs an unsafe practice, the logical or spatial relationship from the detection result should be supplied. In this study, by storing the results after detection, the image data is lightened.

Combined with the classification of image data in section 3.1, the storage structure of the data is divided into four situations, as shown in Fig.2.

Unsafe conditions in macro-image
(A, C, D, E, F, G)

Unsafe practices in micro-image
(H, I, J)

Unsafe conditions in micro-image
(B)

Unsafe practices in macro-image and micro-image
(K, L)

Fig 2. four types in storage structure of image data

- Unsafe conditions in macro images: It mainly includes the detection of entities and workers. And entities in construction site can be subdivided into dynamic and static entities. The position of static objects in the image is relatively fixed (such as scaffolding). Dynamic entities and workers positions are more complicated, so time series information needs to be added;
- Unsafe conditions in micro-images: The unsafe conditions in micro-images are also relatively static. Therefore, we only need to store them detection results and there is no need to add time series;
- Unsafe practices in micro-images: The identification of unsafe operations in micro-images requires high accuracy. It is difficult for ordinary two-dimensional images to achieve satisfactory recognition results, so depth image and posture information in detail is necessary;
- Unsafe practices in macro and micro images: the information required of Type K is similar to ‘unsafe practices in micro-image’, and both involve the accurate detection of objects and posture. Type L only focuses on the worker's posture and movement, and there is no other interaction with the on-site entities.

4. Case study

4.1. Establishment of image database management system

Based on the MySQL5.7 database management system, we utilize the classification and storage approach mentioned above to establish a macro-image and micro-image database. The database storage structure is shown in Fig. 3, where (W, H) is the boundary coordinates of detection results; T represents the time series; (R, G, B) and (X, Y, Z) are the pixel information and space coordinates of workers’ joint respectively.

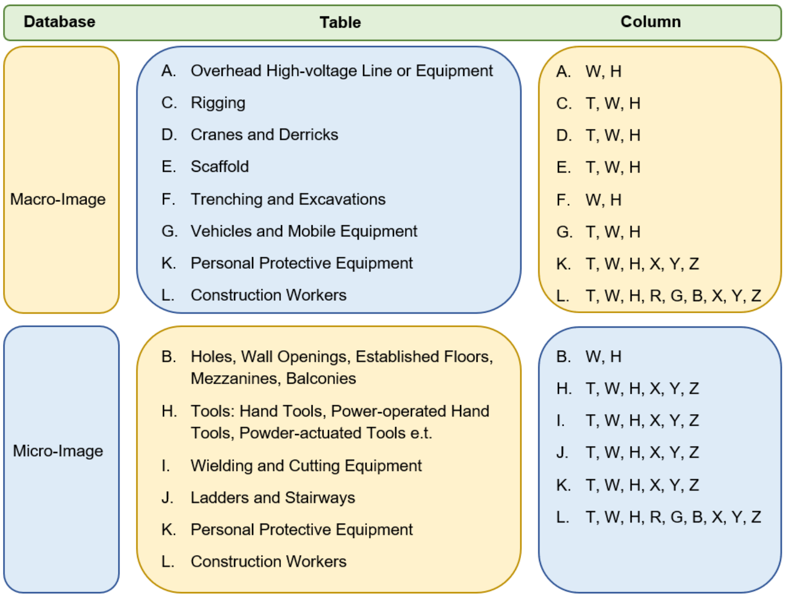

Fig. 3. conceptual model structure of image database

It can be seen from the analysis of construction safety requirements that the gesture recognition of workers is a crucial task. Therefore, this paper takes the storage process of workers' posture as a case study. In order to support the further interactive relationship analysis, the study chooses to use the joint data of workers, which can be collected by depth image and openpose algorithm. After labeling each joint, store the labeled data into the 'construction workers' table of 'macro-image' and 'micro-image' database. The process can be seen in Fig.4.

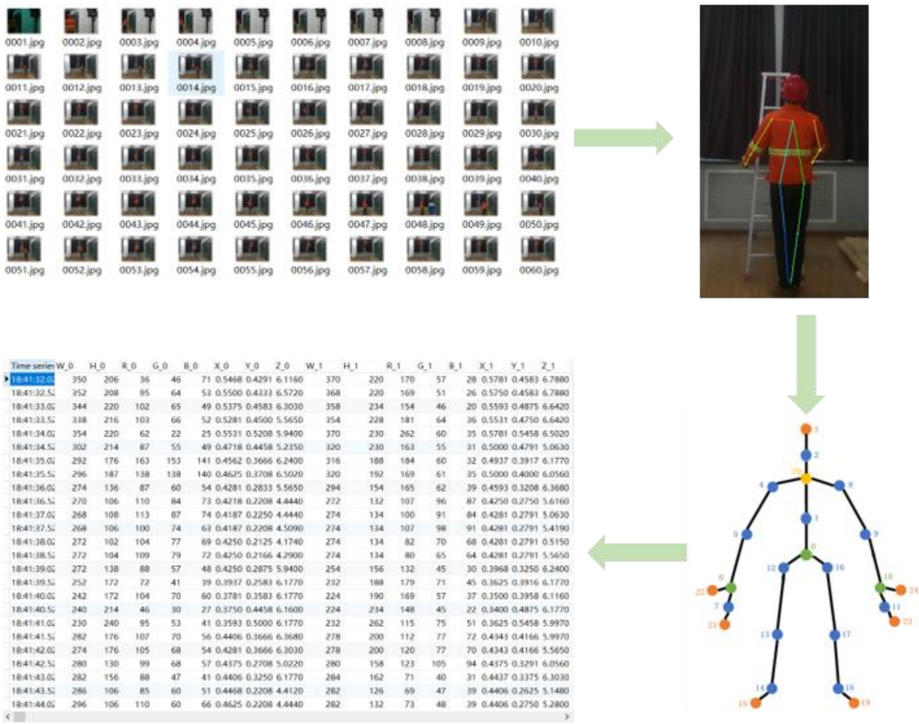

Fig. 4. the storage process of workers' joints

4.2. Findings and discussion

This case presents the storage process of workers' posture data by MySQL5.7. One noticeable finding is the 1.68G 3D point cloud data can be reduced to 0.75M, after extracting the 3D joint data and storing in rules. On the one hand, it greatly saves the storage space of the image data and increases the storage efficiency. On the other hand, the structured storage approach proposed in this study is not limited to special scenarios or types of work, which benefits boarder applications of computer vision in safety management.

5. Conclusion

In this study, the classification and storage approach of construction site image data is proposed. Satisfying the requirements of safety management, the key hazards that need to be identified from images are sorted out, and then classify them into macro and micro-images. Then, think of computer vision techniques, a structured storage method for images is proposed based on the classification result. Finally, the case study further confirmed the feasibility and effectiveness of the approach.

At the same time, there are some important issues for future work. The first is that the division of macro-image and micro-image needs to be clarified. From this point, a more scientific classification method can be proposed. Second, the storage framework of this study is based on the completion of object detection or action recognition, but the accurate identification of small entities still facing some challenges, such as the hooks of seat belts.

6. Acknowledgements

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A Lightweight BIM-GIS Integration Method for Rural Building Design and Construction

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Abstract

Building Information Model (BIM) and Geographic Information System (GIS) are both important data sources in the design and construction of buildings, and they have different emphasis on building information definition. A unified database that integrates BIM and GIS information is needed in many cases. However, most of the studies and applications of BIM-GIS integration are concentrated in urban buildings. Research on BIM-GIS integration in rural buildings is still rare. In fact, rural residences usually have different information characteristics with urban buildings. These characteristics need to be carefully considered to achieve effective information integration. A lightweight BIM-GIS integration method for rural building design and construction was proposed in this paper. The proposed method integrates BIM and GIS based on the Cesium platform, and realizes multi-scale lightweight algorithm based on the characteristics of rural houses. Based on a case study, the proposed method demonstrates its feasibility and efficiency in integrating BIM and GIS data. We believe it can assist with the design and construction of rural buildings.

Keywords: BIM, GIS, integration, lightweight algorithm, rural building

1. Introduction

Building Information Model (BIM) is a technology for storage, management, exchange and expression of building information based on three-dimensional models [1]. Geographic Information System (GIS) is an information system for storage, query, analysis and visualization of geographic data [2]. The integration of BIM and GIS is a promising task and has drawn the attention of researchers and practitioners. Some recent studies have applied BIM-GIS integration to support facility management [3], flood damage assessment and visualization [4], traffic noise analysis [5] and construction supply chain management[6], [7]. These studies have involved both building data and geographic data, and validated the effectiveness of the integrated BIM-GIS database in improving the efficiency of data acquisition and processing. However, most of the research in this field focuses on urban buildings or large public buildings. These buildings are characterized by their complex spatial topological information and numerous facilities. Almost none of these studies are involved in rural buildings. In fact, rural residence usually has different information characteristics with urban buildings which needs to be considered carefully.

Due to the vast area and sparse population, most rural buildings are designed as single-family houses with one or two stories and courtyards [8]. Compared with those high-rise urban buildings, the structure of rural buildings is relatively simple and the number of mechanical and electrical equipment is small. However, the village-level structure is often an important factor that needs to be considered in the design and construction of rural buildings [9]. This makes the information model of rural houses needs to integrate village-level spatial structure composed of tens to hundreds of buildings. At the same time, the surrounding environment and landform will have a greater impact on the building in rural areas, which makes a greater emphasis on the integration of GIS data. Moreover, high-performance computing devices are not common in rural areas, especially in rural areas of developing countries. Mobile devices are often the main source of information for villagers. As a result, lightweight algorithms need to be carefully designed to adapt to the performance of computing devices.

Ma and Ren [10] reviewed recent BIM-GIS integration studies and summarized the patterns of integrating BIM and GIS into three categories, including extracting BIM information into GIS, extracting GIS information into BIM, and extracting both BIM and GIS information into another system. Among them, integrating BIM into GIS is a common way and has been applied by many studies [3, 5]. Some commonly used platforms include ArcGIS [11], Google Earth [12] and Cesium [13].

A lightweight BIM-GIS integration method was proposed in this paper to assist rural building design and construction. The method implements information integration base on the Cesium platform [13], and the characteristics of rural buildings are fully considered. Cesium is a web-based light weight platform for GIS data visualization and analysis [13]. The platform is written in JavaScript and supports access from both desktop application and mobile devices. Some Cesium-based researches on GIS data visualization and analysis have been carried out, and the results have proved its effectiveness in processing massive GIS data [14, 15].

The proposed method in this paper will be implemented base on Cesium, and achieves information integration by extracting BIM information into GIS model. The remainder of this paper is organized as follows. The proposed BIM-GIS integration method is first presented. The lightweight algorithm for rural building is then introduced. The next section gives a case study to evaluate the performance of the proposed approach. Finally, the discussion and conclusion are given.

2. BIM-GIS integration methodology

As shown in Figure 1, an original BIM-GIS integration method is proposed in this paper. IFC is selected as the BIM data format for its versatility in building information exchange. The GIS information to be integrated involves several data sources. Among them, CityGML is selected as the storage format for 3D building geometric information. And 2D geographic data is represented in GML and GeoJson files. Multiple open source tools are involved in the proposed method. These tools are shown in blue italics in the fugure. Finally, all information is integrated into the Cesium platform.

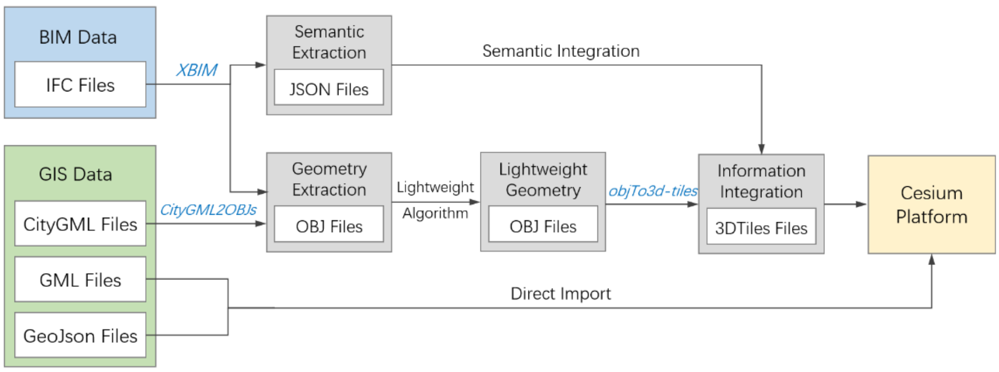


Fig. 1. BIM-GIS Integration Methodology

2.1. Integration with BIM

BIM files contain geometric information and rich semantic information of the building. An open source package xBIM [16] was applied in this paper to extract this information from the IFC files. The geometric and semantic information was decoupled and stored in different intermediate files.

As suggested by Chen et al. [17], the extracted geometric information was stored in OBJ files for that many open source tools for geometric format conversion are built around this format. A lightweight algorithm was then implemented. Subsequently, the lightweight OBJ files were converted to 3D Tiles format using the open source tool objTo3d-tiles [18]. 3D Tiles is a specification proposed by Cesium for streaming massive and heterogeneous 3D geographic data. It could be read by the Cesium platform to achieve the integration of geometric information.

The semantic information is mainly semantic attributes of buildings and components, such as names, materials, and topological connections. Among them, the material information was written into the MTL file, which is a subsidiary of the OBJ file, to support geometry integration. The remaining information was stored in JSON format. The geometric and semantic information of a building component is linked by its identifier in the IFC file. In addition, to integrate multiple buildings in the village, the geographical location of each rural house also needs to be provided. This information can be obtained from the corresponding CityGML file or specified manually. 3D Tiles have a Batch Table structure to record additional information about the model. All semantic data was written into Batch Table to achieve information integration.

2.2. Integration with GIS

Three GIS data formats including CityGML, GML and GeoJson are involved in the proposed approach. CityGML contains 3D geometric information of a building or building groups. In the proposed approach, this information is extracted by the open source tool CityGML2OBJs [19] and written into OBJ files. These files are merged with geometric information from BIM to perform the lightweight and format conversion process. For GML and GeoJson formats, Cesium provides Application Programming Interfaces (APIs) for reading files. This information can be integrated to the platform directly.

3. Multiscale Lightweight Algorithm

In order to display large-scale building models in mobile devices, lightweight algorithms are necessary. In this paper, a multiscale lightweight algorithm was proposed. This method consists of multiple lightweight algorithms, each of which is applicable to a display scale. Building information is organized into multiple levels according to its boundary scale, and lightweight algorithms are applied respectively. It has been proven that multiscale information model is an effective way to organize building data [20]. Specifically, building information are divided into three levels in this paper: single building interior, single building exterior, and the building complex level.

3.1. Lightweight algorithm for single building interior

The single building interior scale is displayed when observing the interior of a building. This scale contains information inside the building, including building components, furniture, and spatial layout of rooms. At this scale, only the part of the building where the camera is located needs to be displayed. And it is not necessary to show the information of the whole building and the building group. With this feature, a lightweight algorithm for filtering display information can be designed to improve visualization efficiency.

Octrees are applied in this paper to organize the geometric data. As shown in figure 2, the root node of the octree records all the spatial information of the building. The space of the building is then evenly divided into eight parts to generate eight child nodes. Building components inside or intersecting the space will be recorded in the node. The division of space proceeds until the divided space is similar in size to a room. For common rural houses, one or two divisions are appropriate.

When displaying the interior geometry of a building, not all nodes in the octree need to be displayed. In the case of a section view, only the nodes that intersect the section plane need to be shown. And in the case of perspective projection, the node where the camera is located should be first determined. Only this node and its adjacent nodes need to be displayed. The number of components that need to be rendered can be then reduced.

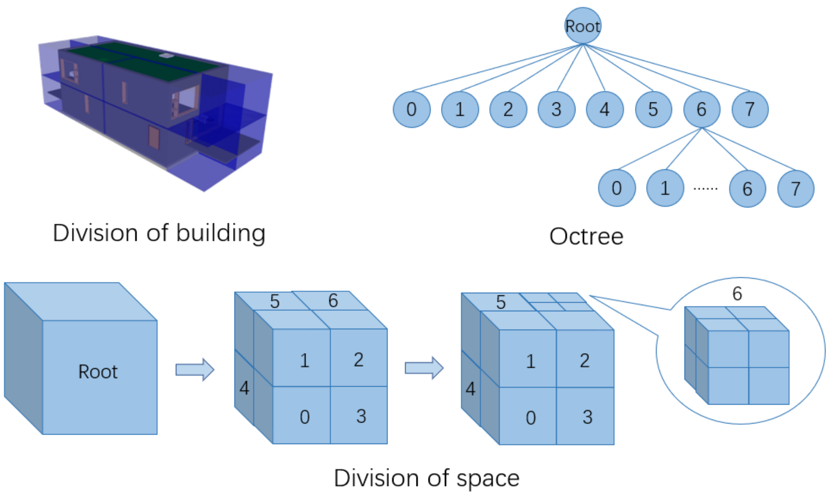


Fig. 2. Octree and the division of space.

3.2. Lightweight algorithm for single building exterior

The single building exterior scale is displayed when the building is viewed from the outside. This scale contains geometric information about the exterior surface of the building, including exterior walls, windows, and other external components. At this scale, geometric data inside the building does not need to be displayed. Therefore, a lightweight algorithm can be designed to filter out the information inside the building and reduce the size of models.

The algorithm also applies octree to store spatial data. Different from the algorithm in the previous section, the octree here needs to be continuously divided until the nodes do not contain any building components (In other words, all components have intersected some nodes). The leaf nodes will be then marked into three categories, including empty, boundary, and internal. The empty nodes are nodes that do not intersect any building component. A Boundary node is a node that is not empty and have no non-empty nodes on its outside. The internal nodes are nodes with boundary nodes on the outside. A depth-first-search process is carried out to mark each nodes, and only the boundary nodes need to be displayed.

3.3. Lightweight algorithm for single building complex

The spatial layout of the village needs to be considered in the design and construction of rural building, and the visualization of the building complex is required. The amount of calculation will multiply to render multiple building models in the same scene. At this scale, the location and orientation of the building are mainly displayed, and the geometric characteristics of the single building can be simplified. Light weight algorithms can be designed based on this feature.

In the proposed method, the exterior components obtained in the previous section are further filtered by their semantic information. Only building components belonging to the categories of walls, columns, slabs and roofs are retained. The openings on the walls for windows and doors are also ignored. The number of triangular faces to be displayed can be then reduced.

4. A Case study

A case study was performed to verify the feasibility of the proposed approach. Multiple BIM and GIS models were collected from the Internet and integrated into the Cesium platform using the proposed method. The introduction of the integrated files is shown in Table 1. And the integration of these models into the Cesium platform is shown in Fig. 3. Models from different sources and formats are integrated by the proposed method and displayed together in a Web browser.

Table 1. Introduction of the integrated files

File name	Format	File size	Data source
20191126AZUMA9	IFC (Model 1)	10.0 MB	University of Auckland (2019)
Duplex_A_20110907	IFC (Model 2)	2.3 MB	National Institute of Building Sciences (2019)
Clinic_A_20110906	IFC (Model 3)	17.3 MB	National Institute of Building Sciences (2019)
FZK Haus	CityGML	15.9 MB	Karlsruhe Institute of Technology (2017)
Region	GeoJson	1.69 KB	Created Manually

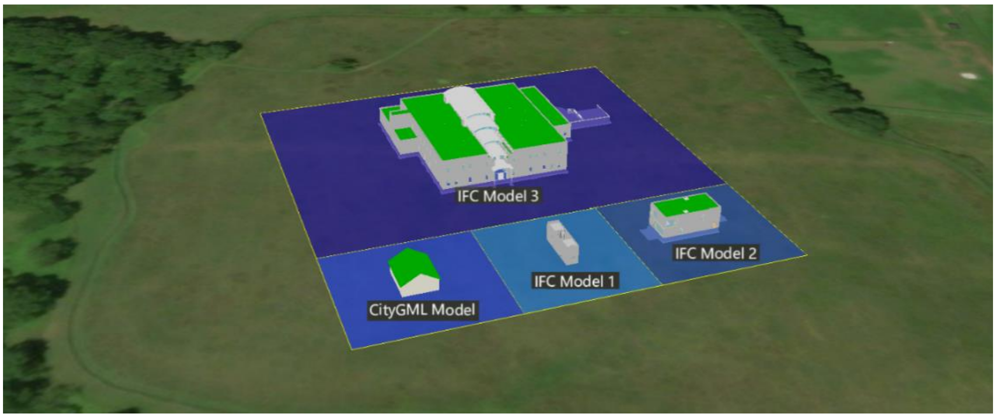


Fig. 3. Integration of the building models

The clinic model file is selected to estimate the effect of lightweight algorithm. The effect of the algorithm is illustrated in Fig. 4. Compared with the original model, the lightweight algorithms at three scales can all reduce the model size and number of triangles. Lightweight algorithms on the single building interior and exterior scales can reduce model size while retaining the appearance of the model. At the building complex scale, the proposed method can greatly reduce the model size, at the cost of rough model appearance. The cost is acceptable since the location and orientation of the building are mainly concerned at this scale.

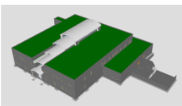
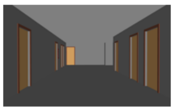
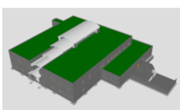
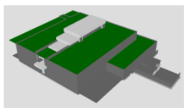
Model scale	Model view	Model Scale	Model View	Model scale	Model view	Model Scale	Model View
Original File		Single building interior		Single building exterior		Building complex	
File size	19.1 MB	File size	5.48 MB	File size	11.8 MB	File size	75 KB
Triangle count	533207	Triangle count	162413	Triangle count	334062	Triangle count	2016

Fig. 4 Effect of the algorithm applied to the model Clinic_A_20110906

5. Discussion and conclusion

The design and construction of rural building have different characteristics from urban houses. A lightweight BIM-GIS integration method for rural building is proposed in this paper to consider these features. Considering that the complex village-level spatial structure is required in the integration, an integration method was designed to integrate building models from different sources and formats in the village. A multi-scale information structure was proposed to achieve the model switching between single building and village scale. The integration and visualization platform are designed for web browsers considering that mobile devices are the main information acquisition tools in rural areas. Based on the multi-scale information structure, lightweight algorithms were proposed for each scale to address the lack of high-performance computing devices. Characteristics of rural building were considered in the lightweight algorithms to reduce the amount of calculation in the visualization process.

As a conclusion, a BIM-GIS integration method for rural building design and construction was proposed in this paper. The method is based on the Cesium platform and integrates BIM and GIS files in IFC, CityGML, GML and GeoJson formats. A multi-scale lightweight algorithm based on the characteristics of rural houses was then implemented. Algorithms applicable to three scales, including single building interior, single building exterior and building complex scale, were designed. The proposed method was validated by a case study, and the result proved its effectiveness. We believe it can support the rural building design and construction process.

6. Acknowledgements

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BIM-Based Cost Management Practices in the Quebec's Construction Industry

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Abstract

Construction projects are known for frequent cost overruns, due to different issues including the limitations of conventional cost management approaches. Building Information Modeling (BIM)supported cost management (5D BIM) consists in associating the cost variable with a BIM model in order to optimize the management of construction costs. Although several studies have been conducted in different countries to identify the benefits of, and barriers to, the implementation of 5D BIM, data on its implementation and associated practices in Quebec are missing. The objective of this study is therefore to present the general picture of the implementation of 5D BIM in the Quebec's construction industry. In order to achieve this objective, an in-depth literature review was conducted, and a questionnaire was developed and distributed to a sample of cost management specialists in the AEC industry in Quebec. The results suggest that that while 5D BIM is recognized to foster the production of better estimates, the automation of estimation is still far from being a reality. Excel is still the main tool for allocating costs to quantities extracted from BIM models and for estimates preparation. Thus, 5D BIM is mainly used for cost estimating, budgeting and cost control but much less for claims management.

Keywords: 5D BIM, construction cost management

1. Introduction

The Architecture, Engineering and Construction (AEC) industry is lagging in terms of technology adoption, compared to other industries. The traditional work in silos and the lack of collaboration greatly affect the productivity and the predictability of costs and schedules. Based on a study carried out on 258 infrastructure projects in 20 countries on 5 continents, Flyvbjerg et al. [1] concluded that almost nine out of ten projects are subject to a poor estimate of costs, with a probability of 86% for a given project being overestimated and 14% for being underestimated. According to the authors of the study, the real cost of construction is on average 28% higher than the budgeted cost. Ma and Yan [2] explained that one of the problems of cost management is that companies find it difficult to adapt to new technologies. These can allow an optimization of the construction processes, leading to a considerable reduction of costs and times while improving quality. They can also be used for gathering information on the real market in order to make adequate planning for the acquisition of resources and for monitoring cost information on site in real time. They finally can allow integration of cost management from the start of the project by extracting quantities precisely in real time in the different phases, for real-time dynamic monitoring of costs on the site, for updating the estimate during implementation, for noting deviations and for taking the appropriate measures to correct them. Khanzode et al. [3] estimate an accuracy of 3% between the budgeted cost and the cost at completion by integrating Building Information Modeling (BIM) approach at the start of the project.

However, the AEC industry in Quebec seems still reluctant, although this approach and its various tools to support cost management (5D BIM) have been around for a while and have been widely implemented around the world. In fact, only 31% of industry professionals claim to have adopted BIM [4]. No study has been specifically carried out on the implementation of 5D BIM in Quebec. The practices and issues specific to the use of 5D BIM in the Quebec construction industry are therefore not known. The main objective of the study reported in this paper is to present the general picture of the practices associated with the implementation of 5D BIM in the construction industry in Quebec. Specifically, the study aims at determining what are the current 5D-based cost management practices and the software used industry; and at identifying the perceived benefits, from the perspective of 5D BIM specialists in Québec.

2. 5D BIM adoption around the world

5D BIM consists in associating the cost variable with a BIM model, either by incorporating the cost data into the objects of the BIM model themselves, or by making a direct living link between a BIM model and an estimation software [5] [6]. Parametric modeling therefore facilitates the creation of a relationship between elements and includes the specification and properties of individual elements and objects, allowing the extraction of complete and precise information from the model which can be directly used for costing [7]. Indeed, the quantities can be extracted directly and instantly from the BIM model with a high level of precision. By assigning the unit cost to the quantities extracted, it is possible to automatically obtain an accurate and reliable cost analysis. As a result, modifications can be efficiently made in real time and an assessment of the impact of the change on the cost of the project.

According to Smith [8], the most comprehensive survey of quantity surveyors' use of BIM in the world was that of Royal Institution of Chartered Surveyors (RICS) [9] in the United Kingdom and the United States. The survey provides an overview of the level of adoption of BIM by quantity surveyors and the problems encountered which could well apply to many other countries in which quantity surveyors practice. Out of 298 participants, only 10% of quantity surveyor companies used BIM regularly, and 29% had limited engagement with BIM. As a result, 61% of companies had no engagement with BIM. For quantity surveyors using BIM, the most common use was construction planning (14%), followed by quantity extraction and facilities / asset management (8% each). Only 4% of companies regularly invest in BIM training and only 10% actively assess BIM tools with a view to their potential adoption [9]. This indicates that the profession of quantity surveyor in this region is not adopting BIM to the required level. However, since the British government's mandate regarding the use of BIM was introduced at the time of this survey, it would be interesting to see what effect this has had on the companies of quantity surveyors since then [8]. In the UK, a 2016 Software Advice survey of Small and Medium-Sized Companies found that 60% of users were looking for cost estimation software options and 24% of respondents wanted to increase transparency and the level of monitoring projects. However, 50% still use manual methods to calculate costs, prepare contracts and project management [10].

According to Boon and Prigg [5], 5D BIM is relatively little used in New Zealand due to a number of obstacles limiting its implementation in the industry. A survey of 20 quantity surveyors in New Zealand found that almost all of the respondents had participated in fewer than five projects using 5D BIM [5]. By comparing the implementation of BIM in Iceland and in the Scandinavian countries it emerges that the BIM utilization rate for cost estimate is 14% higher in the average of the Scandinavian countries. The data on tendering and extracting quantities is also interesting. In this case too, the Scandinavian countries are in the foreground with 9% and 18% respectively [10].

In Slovakia, 12.9% of companies use 5D BIM tools, but only for bill of quantities, and only 6.5% use it for bill of quantities and the budget itself. Interesting conclusions on the state of BIM implementation in Slovakia were presented by research by Mesároš, Selín and Mandičák [10], which aim was to identify cost management approaches in Slovak construction companies. The research has shown the influence of using BIM to reduce costs in small companies. This finding is mainly because BIM technology is mainly used by the designers who represented small companies in this research [10].

As we can see, 5D BIM is widely implemented around the world. However, data on its implementation in the AEC industry in Canada and more specifically in Quebec are lacking. The objective of this study is therefore to create an overview of the implementation of 5D BIM in the Quebec's AEC industry and to determine the professionals' perception of its benefits.

3. Research approach

A questionnaire survey approach was adopted because it allows reaching a large sample of a population. The target population of the study was professionals in the AEC industry in Quebec with a good knowledge of BIM in general and BIM-based cost management in particular. Our sample was a

convenience sample, of a non-probabilistic type, made up of subjects who freely and voluntarily consented to participate in the research in its entirety. All responses were kept confidential, and participants' anonymity was ensured. Ethics approval was sought and obtained from the ethics and research committee of authors' institution.

An in-depth literature review of previous studies on the implementation of 5D BIM, its Benefits and challenges was first conducted. We then formulated some questions and carried out an interview with the director and one manager of the preconstruction department of one of the largest construction companies in Quebec. This interview allowed us to better orient the questionnaire. Once elaborated, we submitted our questionnaire to an intermediate estimator working in another large construction company and having a good knowledge of BIM to test it before we distributed it. Invitations to respond to the questionnaire were sent by email to participants. 42 invitations were sent, and 17 participations were received.

The participants in the study are mainly in the estimation field (65%) which is completely normal given that our target audience were construction professionals with knowledge of BIM-based cost management. Then we have planners (53%), consultants (29%), designers (24%), and finally the others (29%) working in support and management.

Most participants (41%) work for large companies (more than 100 employees). 29% work for mediumsized companies (51 to 100 employees), 18% for small companies (6 to 50 employees) and 12% for micro companies (1 to 5 employees). This can be explained by the fact that large companies have more resources and are more open to the implementation of new technologies such as BIM.

4. Findings

4.1. Uses of BIM for cost management

Of the 14 companies that responded using BIM, five (5) responded that they did not use it for cost management (5D BIM), or 35.71%. An in-depth analysis revealed that out of these five companies, three (3) are large companies and two (2) are medium-sized companies. These figures tend to mean that large and medium-sized businesses seem more resistant to the use of 5D BIM, which is quite contradictory because they have the resources necessary for its implementation, which indicates that issues other than configuration costs are involved.

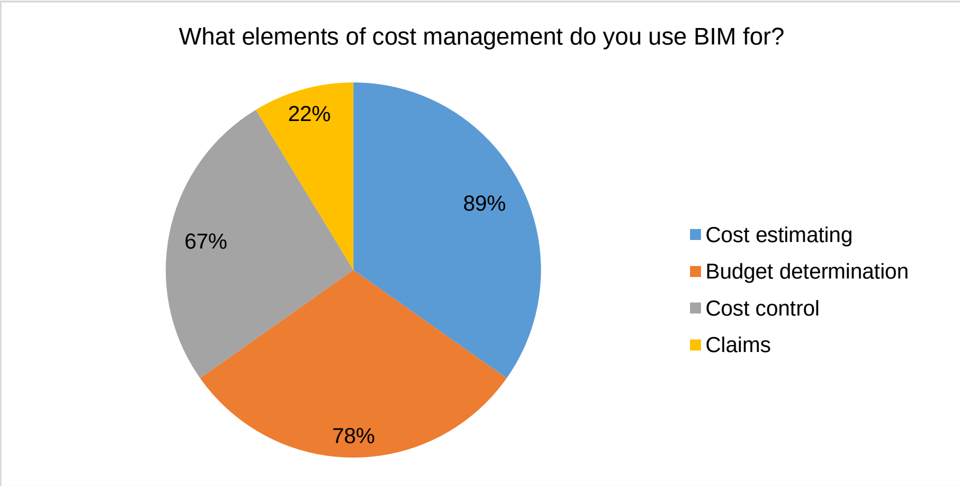

Fig. 1. Elements of cost management for which BIM is used

BIM is mainly used for cost estimating (88.89%), for budget determination (77.78%), for cost control (66.67%) and for claims management (22, 22%) as illustrated in Fig. 1.

4.2. The software used

For each element of cost management, participants had to specify which 5D BIM tools they use. The results are summarized in Fig. *2*.

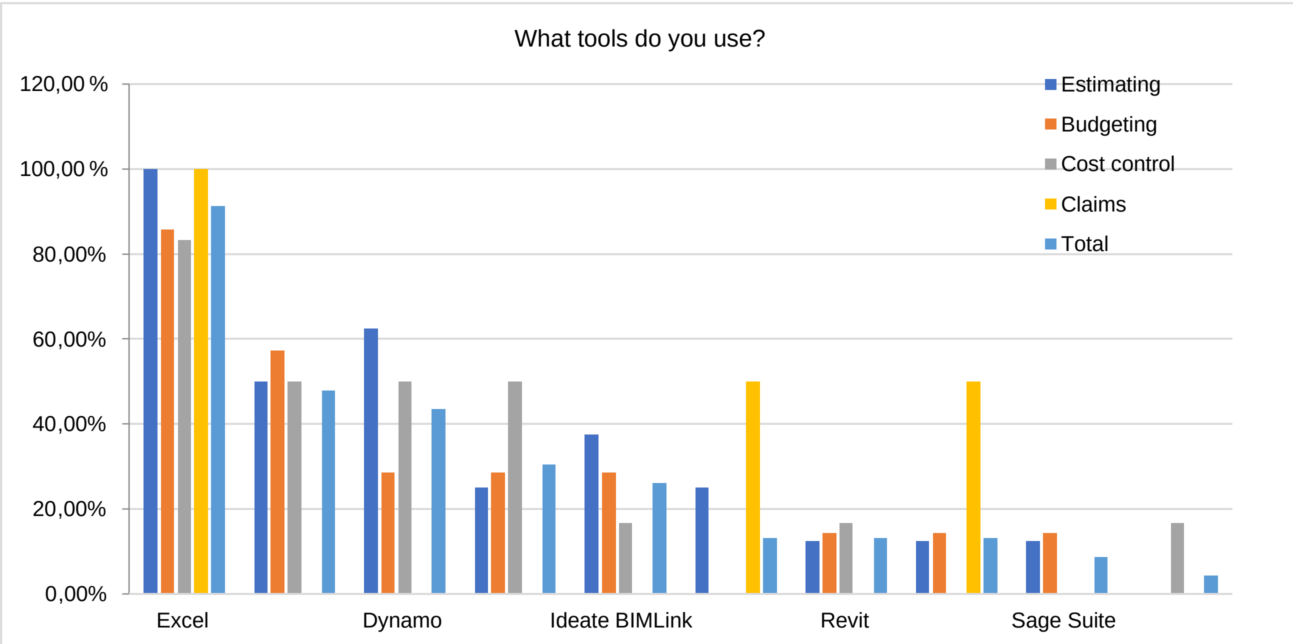

Fig 2. 5D BIM tools used

The three most used tools are Excel, CostX and Dynamo. Although Excel is not strictly speaking a 5D BIM estimation software, it remains the most used tool by participants regardless of the cost element. Next is CostX which is the second most used tool for budgeting, third for estimation and second with Dynamo and Navisworks for control. Dynamo is the third most used tool, it is second for estimation, third tied for budgeting and second for control.

4.3. Perceived benefits of 5D BIM

An analysis allowed us to assign marks out of 5 to each advantage and thus to rank in order to highlight the Benefits most perceived by professionals. The results are reported in Table 1.

Everyone agrees that BIM 5D produces better estimates thanks to the ability to model project options before and during construction. By considering project options early, fewer variations are likely to occur during construction [11]. Olatunji et al [12] suggest that BIM allows professional quantity surveyors to identify factors that have economic benefit or consequence on various design options in order to select the most suitable and cost-efficient proposal. Furthermore, early design advice "should lead to increased client satisfaction as they are receiving earlier economic feedback on the alternatives available" [13].

Table 1. Perceived benefits of 5D BIM

	[NB: 1 = totally disagree, 5 = totally agree]	1	2	3	4	5	Score /5
B.1	The estimation is improved thanks to the possibility of modeling the project options before and during construction.				1	6	4,9
B.2	Project visualization is increased, which reduces errors in drawing interpretation and improves decision-making.		1			7	4,6
B.3	Collaboration, communication and information sharing between project teams is improved.			1	2	5	4,5
B.4	5D BIM provides a business advantage over competitors.				4	4	4,5
B.5	Risk identification is done earlier: the detection of potential conflicts is improved, at an earlier stage than with traditional approaches.			1	3	4	4,4
B.6	Design changes can be identified more easily and quickly by overlapping previous BIM models with revised BIM models.			1	3	4	4,4
B.7	The ability to resolve requests for information in real time			1	3	4	4,4
B.8	Conceptualization of the project is made easier: 3D makes it easier to determine the cost of design options at the start of the design phase.			2	2	4	4,3
B.9	5D BIM allows more efficient preliminary estimates (by automatic generation of quantities from objects in the BIM model).	1	1		1	5	4,0
B.10	5D BIM allows more efficient detailed estimates (by automatic generation of quantities from objects in the BIM model).		1	1	3	3	4,0
B.11	The details of the provided preliminary bills of quantities more accurately reflect the scope of the work involved.			3	2	3	4,0
B.12	Automatic generation of quantities allows more time to be spent on other cost management services for the client (e.g. cost advice on more design options)		1	2		4	4,0
B.13	5D BIM enables more efficient production of bills of quantities (by automatic generation of quantities from objects in the BIM model).	1		1	2	3	3,9

5. Conclusion

This research presented the general picture of the implementation of 5D BIM in the AEC industry in Quebec. More specifically, current 5D cost management practices and tools are identified and the benefits of 5D BIM implementation are explored.

The survey shows that 5D BIM is mainly used for cost estimating, then for budgeting and cost control, and to a lesser extent for claims management. These results suggest that the automation of cost management is still far from being a reality. Even if quantities are automatically extracted from BIM models, Excel is still the main tool for manually allocating costs to them and for preparing estimates. The main perceived benefits of 5D BIM turned out to be improved estimates thanks to the possibility of modeling project options before and during construction, better visualization of the building, improved collaboration between project teams and the granting of a commercial advantage over competitors.

Even if the study provides an overview of practices in the industry, it is important to note that the small size of our sample may not allow us to extrapolate the results to the scale of the AEC industry in its entirety.

Indeed, the main difficulty of the project was to obtain participation in the survey, professionals being reluctant to answer it although anonymity was guaranteed. Nevertheless, the results obtained give a good overview of how professionals perceive 5D BIM, what uses they make of it and its advantages.

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BPMN 2.0 Modelling for the Management of the Inspection of Execution Processes in Construction

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Abstract

Nowadays digitalization is a growing challenge for the whole construction sector. Therefore, the need of supportive tools and procedures is becoming increasingly urgent in each construction project step and particularly for project supervision in the execution phase. This is a primary requirement especially for the public sector, since the legislative framework is becoming more and more focused on this aspect, in Italy as well as in the European and international context.

A formalization of the inspection procedures of project management in the construction phase is proposed through Business Process Modelling and Notation (BPMN) 2.0 language. The first key aspect of this proposal is to assume a model-based approach, which allows a more coherent information management, in contrast with the traditional document-based one. The second aspect concerns process modeling. In fact, the proposed method is based on processes, instead of BIM – based federated object-oriented models. Construction processes are modelled so that they can generate and feed the federated models themselves. In addition to this, Business Process Modelling and Notation can be used to create a collection of different procedures involved in the inspection management for construction projects. Also, BPMN model will allow an automatic feeding of an inspection management support system which will be developed in future studies, that will offer the full traceability of the procedures and the delivery of the quality certification of products. The case study of the inspection of ready-mix concrete cast-in-place process is analyzed and discussed.

Keywords: BIM, BPMN 2.0, digitalization, inspection of execution, process management

1. Introduction

The need of supportive procedures and tools for the digitalization of the construction field is increasing evident, especially concerning the public sector, since the legislative framework is becoming more and more focused on this aspect.

Building Information was traditionally gathered and communicated via documentation like construction drawnings, construction specifications, bill-of-quantities and written reports. Building Information Modeling (BIM) approach has shifted construction information from a document-based to a model-based system, where the complete building information is stored in a system of federated models that allows for collaborative working, for on-demand retrieval of information and digital data storage. BIM, with its centralized modelling environment, tries to answer to the need of intercommunication between the different project stakeholders, in contrast with the traditional approach of independently - developed systems and stakeholder requirements [1]. Nevertheless, despite the integration of BIM at the geometrical level has become widespread, it has not been the same regarding the development of transactional workflows to deal with interoperability issues. [2] [3]

The idea of adopting an approach based on System Engineering (SE) is the core concept of this paper. SE is an interdisciplinary sector that focuses on designing and managing complex systems during their whole lifecycle. In particular, SE provides languages and standards, which allow to represent the system and his operation, concentrating especially on the links between the processes and the products. [4]

Modelling of construction processes can be achieved through workflow charts. Flowcharts to represent process flows have been introduced by the Gilbreths in 1921 [5], and the current standard is ISO 5807:1985 [6], that has been widely used in the past especially in the ICT field. Flowcharting the process has different tasks, i.e. identifying inputs and outputs, identifiying the value chain, providing a visual representation of event and operationg sequences, identifying bottlenecks and controls. It is a graphical representation of a process or of a system, and many diagram techniques exist. [7]

In this contribution a formalization of the inspection procedures of project management in the construction phase is proposed using Business Process Modeling and Notation (BPMN) language. BPMN is a standard for business process modelling that is based on a flowcharting technique very similar to current flowcharts, that also provides an execution optimized business process language machine-readable [8]. Particularly, the inspection of ready-mix concrete cast-in-place process is analysed as sample case study.

2. State of the art

During the early 2000s, there has been a turning point for the evolution of SE field, consisted in the transition from a document-centric approach to a model-centric approach (Fig.1).

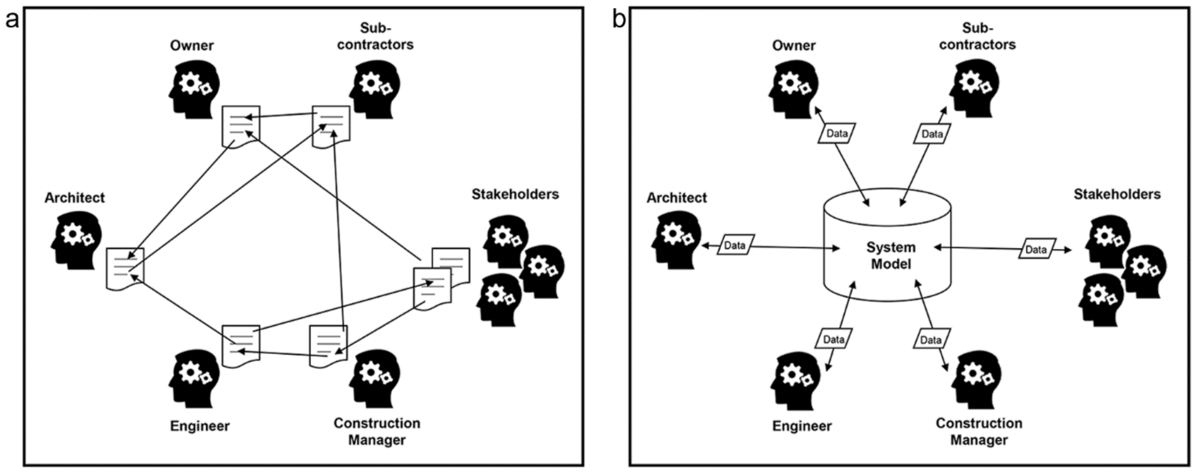


Fig. 1. (a) Document-Centric approach; (b) Model-Centric approach. [3]

However, despite the development of SE and BIM, the current practice of AEC sector is still grounded in the document-centric approach to exchange and develop building data [1]. This implicates the collection of information inside those documents, which, even if in the form of electronic files, restrict inevitably the interoperability of data exchanged between the different stakeholders. Moreover, the project data collected with this traditional method are often incomplete and inconsistent. The traditional document-centric approach describes a system literally, assuming the presence of a user between one phase and the other as a requirement, as an interpreter.

The model-centric approach responds efficiently to the lack of consistency mentioned above. In fact, many of the documents frequently required as intermediate deliverable can be generated automatically from the central model, which collects itself all the data. As Valdes et al. [8] states, “with the model-centric method, all objects depicted in different BIM or engineering tools are simply views of the underlying system model, they are not the model itself. In a united Model Based System Engineering MBSE-BIM model, as all modelling elements are programmatically and systemically integrated, any change that is produced will be automatically propagated to the rest of the model.”.

This paper proposes to apply this Model-Based approach to the process digitalization. In this way, process models will not have documents as inputs or outputs, but they will directly condition the central model (or database). Processes are modelled in order to feed the model, in contrast with the common practice to create models first and then verify if processes are compliant with them.

3. Proposed method

Business Process Model and Notation (BPMN) is a modelling notation defined by Object Management Group (OMG) [9]. This notation bridges the gap between business process description flow charts and machine-readable business process descriptions [10]. Basically, this notation allows to map the visual description of a process into the appropriate execution language.

The advantages offered by BPMN are:

- An intuitive notation to represent business processes (flow charts);
- Standardization, which facilitates communication
- A comprehensible representation of constructs defined in software-execution language

Camunda Modeler [11] is the software utilized to realize the BPMN process diagrams for the research underlying this contribution. The structure of a Camunda BPMN is sketched in Fig. 2.

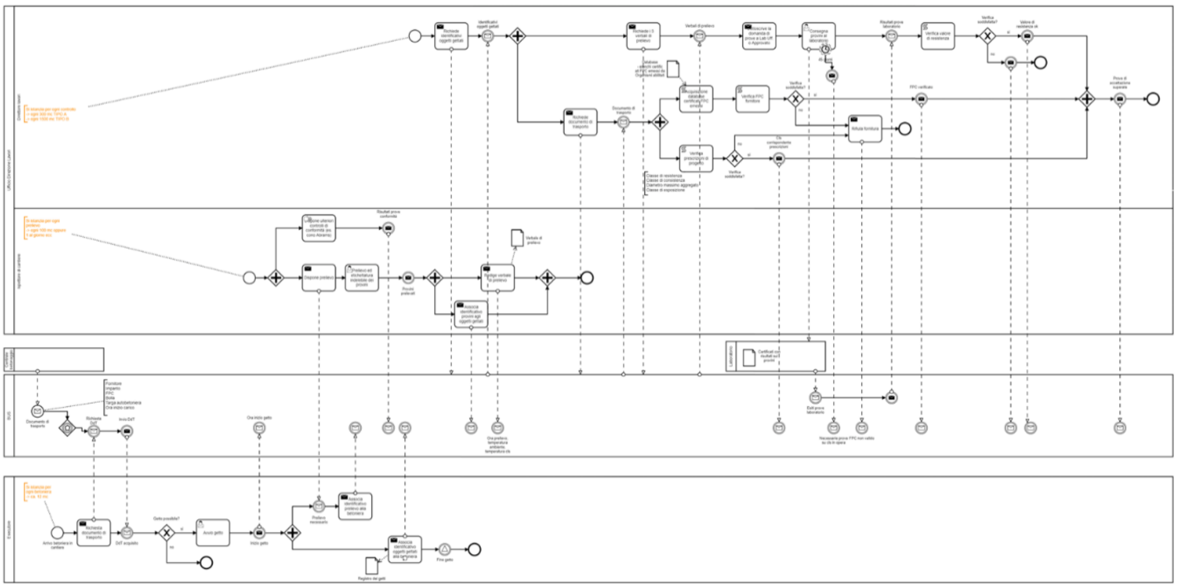


Fig. 2. Structure of a BPMN. The sample case study of inspection of ready-mix concrete cast-in-place process.

4. Sample case study

The inspection of ready-mix concrete cast-in-place process is analysed as sample case study. The cast-in-place of concrete in formworks is a very common construction sub-process, and the project supervisor must perform contract-based an regulation based quality tests. The inspection procedure is characterized by many correlated sub-processes, and implies a remarkable modelling complexity. Furthermore, the inspection of ready-mix concrete cast-in-place is a critical task for detecting a building structure quality and therefore needs to be assessd by several documents, following national standards, regulations and guidelines.

4.1. Stakeholders

BPMN diagrams describe and highlight the processes relations between the different stakeholders involved by organizing process operations and events by lanes of the chart. Each lane corresponds to one player of the process (fig. 2).

Besides the professionals designated for the inspection and the supervision processes, it was found that another lane needs to be designed to optimize the process flow. This additional lane, defined as System BUS, is intended to act as a communication channel, which will permit to the different stakeholders to interface and exchange coherent information.

This element can be conceived as a sort of database to collect data, which will inform the different parts during all the process phases.

4.2. Process instances

The inspection of ready-mix concrete cast-in-place process has been modelled as a series of nested-BPMs (Fig. 3). Indeed, basing on the Italian regulations, the procedure is characterized by instances of different levels:

- 1st level: instantiated by each inspection procedure (executed on 6 concrete sample collections)
- 2nd level: instantiated by each concrete sample collection (executed every 100 mc of concrete casting and at least one per day)
- 3rd level: instantiated by each concrete casting (executed from the moment in which the truck mixer leaves the concrete mixing plant)

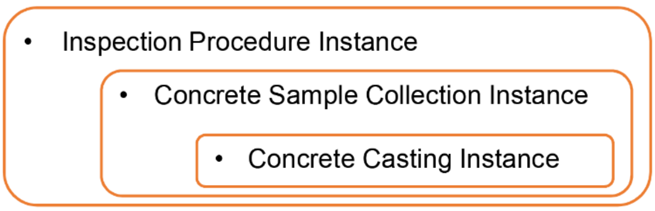


Fig. 3. Inspection of ready-mix concrete cast-in-place process: nested instances.

4.3. Model interaction

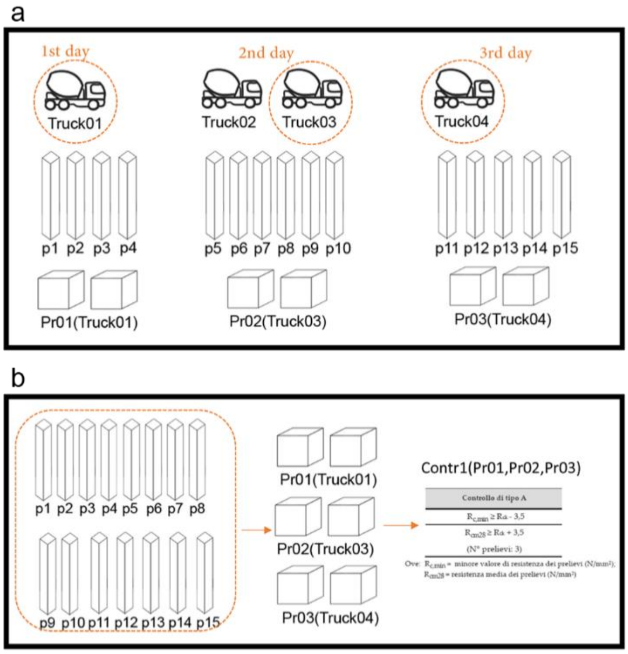
As mentioned above, the adoption of a model-centric approach is one of the key aspects of the modelling discussed in this paper. Particularly, the proposed BUS lane consists in a database aimed at collecting all the data directly from each stakeholder. In this way the information could be stored in a coherent, even automatic way. Consequently, the different stakeholders could just query the database to obtain the information.

Additionally, the proposed method does not ask the stakeholders to manipulate the federated model themselves. Otherwise, the instances are modelled in order to feed the database, which will inform the model itself.

Considering the sample case study, the following steps are fundamental for the interaction with the model:

- Concrete mixer ID – Concrete sample collection ID association
- Concrete mixer ID – Cast Object ID association
- Concrete sample collection ID – Cast Object ID association

Thanks to these bijective relations, once an inspection procedure is completed, it would be possible to automatically inform the model objects, for example by adding a Boolean field to the IFC object structure intended to record the result of the inspection (fig. 4).



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Object	Casting	Sample	Inspection
p1	Truck01	Pr1(Truck01)	Contr1(Pr1,Pr2,Pr3)
p2	Truck01	Pr1(Truck01)	Contr1(Pr1,Pr2,Pr3)
p3	Truck01	Pr1(Truck01)	Contr1(Pr1,Pr2,Pr3)
p4	Truck01	Pr1(Truck01)	Contr1(Pr1,Pr2,Pr3)
P5	Truck02	Pr2(Truck03)	Contr1(Pr1,Pr2,Pr3)
P6	Truck02	Pr2(Truck03)	Contr1(Pr1,Pr2,Pr3)
P7	Truck02	Pr2(Truck03)	Contr1(Pr1,Pr2,Pr3)
P8	Truck03	Pr2(Truck03)	Contr1(Pr1,Pr2,Pr3)
P9	Truck03	Pr2(Truck03)	Contr1(Pr1,Pr2,Pr3)
P10	Truck03	Pr2(Truck03)	Contr1(Pr1,Pr2,Pr3)
P11	Truck04	Pr3(Truck04)	Contr1(Pr1,Pr2,Pr3)
P12	Truck04	Pr3(Truck04)	Contr1(Pr1,Pr2,Pr3)
P13	Truck04	Pr3(Truck04)	Contr1(Pr1,Pr2,Pr3)
P14	Truck04	Pr3(Truck04)	Contr1(Pr1,Pr2,Pr3)
p15	Truck04	Pr3(Truck04)	Contr1(Pr1,Pr2,Pr3)

Fig. 4. Example of inspection of ready-mix concrete cast-in-place process: (a) sample collecting instance, (b) inspection procedure instance, and (c) database.

5. Results and conclusions

The research work has explored the potentiality of applying BPMN to the AEC sector with a positive ouput. In the same way, more BPMN based procedures concerning the management of the inspection of construction execution processes could be modelled in future studies, in order to create a collection of procedures ready to use by researchers and professionals.

The present contribution has permitted to outline the architecture of a product management system that could be the basis for the development of a tool to support the different stakeholders of building and construction projects, particularly in the execution phase. The use of BPMN – based support tools could guarantee a total traceability of the procedures, facilitating the supervision and preventing the risk of irregularities and quality non-conformities, often ecountered in the concrete cast-in-place sub-processes. Also, future research work could be aimed at developing a process-oriented digital quality assessment procedure for construction products and deliverable built with BPMN.

6. Acknowledgements

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Evaluating the Effectiveness of Virtual Reality Construction Safety Training and Lessons Learned

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Abstract

Virtual reality (VR) is often used as a training tool and research widely supports successful student performance in assessment scores when VR training tools are used. Experiential learning mimicked in virtual simulations has been found to significantly improve student's retention of new topics. However, some construction related topics do not improve when using VR. This study involved the creation of a construction excavation safety program that was administered using a VR headset. The researchers piloted the VR safety simulation as a controlled experiment to evaluate the effectiveness of VR reinforced learning as compared to presentation slides that are traditionally used for learning. A significant improvement was not evident in the results. The researchers undertook a further examination of elements of the virtual simulation to ascertain potential areas for improvement that could be used in future iterations of this study. The examination found that the participant's interactions with elements of the virtual simulation were essential as perceived by the participants. Furthermore, the study found that while realism was not a mandatory requirement for the VR simulation, the participant's interactions with characters in the VR training program did have some perceived negative impact. Additionally, motion (walking) within the VR simulation was a significant distractor for the participants. Considering these challenges, the researchers present their findings in this paper as a precautionary guide for further development of similar VR training tools.

Keywords: Virtual Reality, Mixed Reality, construction safety, training, gaming

1. Introduction

The use of virtual reality (VR) for educational purposes is well researches in many disciplines. It is especially topical for use in the construction industry which can be viewed as an industry that communicates visually through 2-dimensional construction plans or sketches and uses 3-dimensional parametric models. For this reason, preparing students with visually interactive content seems appropriate given that the industry communicates this way. VR content is immersive and interactive and can actively reinforce a student's learning [1]. This research study was conducted to examine the possible benefits of using VR to reinforce learned concepts about construction excavation safety by allowing students to interact in a fully immersive simulated construction project site. The simulation was designed to score the student's progress thereby casting an element of gamification [2] in the learning experience as well. This paper describes the experiment, its findings, and concludes with additional considerations for other researchers that want to undertake similar studies involving VR usage in the construction management classroom.

2. Background and research objectives

In this section, the authors review the circumstances documented in prevailing literature where the implementation of VR has demonstrated both significant and insignificant outcomes for the participant's learning. While the quantity of research seems to indicate that VR is a leading tool for innovative teaching, limitations do exist. The researcher's reason that by mitigating these limitations, future researchers can develop content that more effectively addresses the intended learning outcomes.

2.1. Challenges with using virtual reality for education

While VR has potential as an educational tool, some research suggests that for VR to work, there are some key relationships between people and their environment (i.e. real versus virtual environment) that may lead to "counter-intuitive" findings for supporting VR as an effective training tool [3]. Li et al. [4] conducted a systematic review of the literature concerning VR and augmented reality in construction safety and after filtering the available literature to 90 leading papers concluded that there are "challenges" for using these immersive technologies. The following list identifies some of those challenges:

1. Limitations of available hardware and software
2. Poor connectivity and interoperability with other learning management systems
3. The need for hybrid training (virtual and non-virtual)
4. Limitations in human-computer interaction
5. Symptomatic physical effects (dizziness and headaches)
6. Limitation of studies that account for non-technical factors (culture and personal background)

These are all serious concerns when dealing with a new pedagogy that can be viewed as technical and difficult to implement [5]. Furthermore, a limitation that can be associated with the use of technology in the classroom (VR is a technology) is cognitive overload [6]. As Kim & Irizarry [7] found in their research using augmented reality – students did not exhibit significant test score improvement when using augmented reality to improve their spatial skills despite their acknowledgment of Sweller's concerns for cognitive overload when preparing their research [7]. Therefore, experimentation using technology should be mindful of the variables (challenges) discussed in this section of the paper and must be controlled.

2.2. Benefits of using virtual reality for education

VR opens new spacio-experiential possibilities for students with their learning [5] by simulating real and potentially dangerous environments. VR has been synonymously associated with active learning, because it encourages learning by "doing" [1], allowing students to experience situations that would normally not be available to them [8]. Successful VR experiences include three primary factors that are present to convince someone that they are in a simulated environment; immersion [9]–[11], perception [12], and telepresence [13]. These three factors are available in varying degrees within all VR experiences offered today. Fig. 1 illustrates the most common modalities available and their magnitude of immersion, perception, and telepresence.

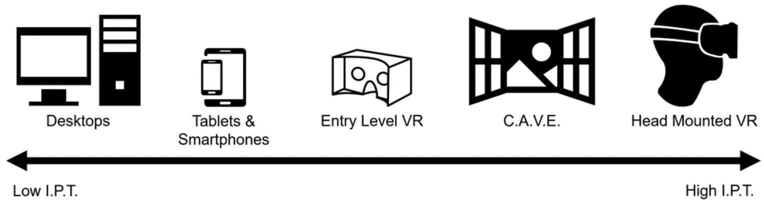

Fig. 1. Comparison of Immersion, Presence, and Telepresence (I.P.T.) in various modalities with today's VR technology [5].

VR has had a substantial impact on the gaming industry. According to a market sector research report in *Fortune Business Insights*, the VR gaming industry will grow from USD 4.15B in 2018 to USD 70.57B in 2026 [14]. This is an important statistic because turning learning into fun activities can support the learning experience [10]. Lastly, with the increased consumer availability of VR equipment at price points that are more reasonable for first-time users, it is no surprise that we are seeing more research and reading more periodicals that embrace the possibilities of immersive learning.

While many challenges were enumerated in the previous sub-section, some authors were successful with their methodology to positively affect the student's learning outcome. Behzadan and Kamat created a virtual user-discovery learning tool to help teach students about construction equipment [15]. Golovinia et al. [16] created a "serious game" to train about construction safety "close calls" and contact collisions. They chose to use a VR based platform for training where people can make mistakes without harming themselves or others. Lastly, Wolf, Teizer, and Ruse [2] approach training in VR with a low-cost solution that was prototyped to train workers in construction safety techniques. Despite these successful research studies aimed at positive student learning outcomes, there were some limitations concerning the content, whether in terms of the realism, the complexity, or the variability of the programmed environment that the user experience. To the authors of this research study, this centrally speaks to the need for properly-created content that is critical for a successful learning outcome [5], [12], [17].

2.3. Virtual reality content

The virtual environment is mostly digital, in the sense that it replaces the viewer's ocular and auditory perception of the world around them. Many other sensory replacements could also be mentioned, such as sounds, feeling, motion, temperature, and smell, however, most of the research in the construction education discipline currently focuses on sight and sound. Everything within the virtual environment is said to be symbolic of something within reality. Before VR was widely available to consumers, art historians examined the effect that these symbolic images had on our minds [18], by viewing art it was supposed that it could encourage emotion and learning through our visual senses. Similarly today, VR is in a sense intended to act on the viewer's perceptions in such a way as to cause experiences and potentially feelings to encourage different human behavior [19]. Despite the literature that supports or casts doubt on VR, there is an underlying notion that the content is what truly differentiates the VR experience [2], [13, (p.1249)], and potentially has some effect on the learning experience. Instead of merely creating a virtual environment and testing if the outcome had a benefit or not, there needs to be a more thoughtful approach toward measuring the content that is represented and its impact on the VR learning experience, currently the research is lacking in this dimension of the study.

2.4. Research objective

Previous research is peppered with successes and failures. The objective of this research was to ascertain, through a controlled experiment, the student's perceived efficacy when VR instrumentation was used to reinforce learned concepts, namely construction excavation safety. As was found, there was no discernable significance from this experiment, therefore, the researchers aimed to examine specific elements used to create the VR environment as potential causes for the lack of significance. It is surmised that these data will be useful in future iterations of this study and for those intending to author their VR simulations.

3. Methodology

3.1. Demographics

For convenience, the researchers requested participation from volunteers in a 4-year construction management program in the Southeastern United States. Graduates from this program commonly become construction management practitioners in the commercial construction sector. Most students were male (25 male and 3 female). The age distribution of the students was 26 students reporting *19 - 25 years old* and two students reporting *older than 25 years*. When asked about construction experience, 19 claimed to have *some experience* while nine claimed *no experience*. The population for the experiment was 28 students (n=28).

3.2. Controlled experiment

A controlled between-group single-blind experiment was conducted using a traditional passive teaching approach that included presentation slides (CONTROL GROUP) and an active learning approach that included a head-mounted VR simulation (TEST GROUP). Fig. 2 illustrates the experiment workflow. Students that volunteered for the study completed a pre-assessment. Following the pre-assessment, the students were asked to read a document containing learning material about construction excavation safety (*Safety Reading Document*). The students were split into two groups and each group reinforced their learning either by traditional passive learning that included presentation slides (CONTROL GROUP), or they reinforced their learning by using a VR simulation (TEST GROUP). Following the reinforced learning, all the students completed a post-assessment and a post-survey about their experience. The independent variables for this study were the reinforcement pedagogy used following the *Safety Reading Document*.

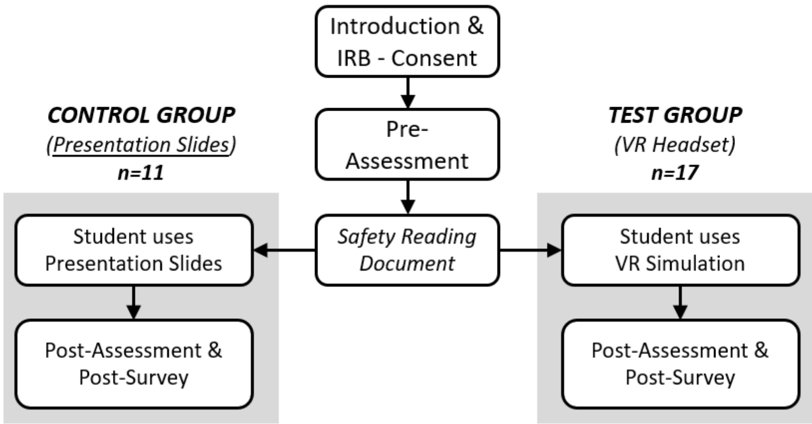

Fig. 2. Experiment Workflow

3.3. The Presentation slides (control group)

The presentation slides were created in Microsoft PowerPoint and consisted of an outline of the *Safety Reading Document* referred to in the previous section and within Fig. 2. Students were asked to view the slide deck on their desktop computers at their own pace.

3.4. The VR simulation (test group)

For the test group, a VR simulation was developed using Unity and C#. The VR environment was ported to an Oculus Go headset device that would be worn by the student volunteer during the experiment. The VR simulation begins at a construction trailer (see Fig. 4) and has some textual information dialog boxes for the student to read. These information dialogs instruct the student how to navigate in the simulation and what objectives must be completed. Once the student is ready, they virtually walk to each of the three objective points and are further instructed by a non-player character (see Fig. 4). The objective points are as follows:

1. Identify and place safety markers on construction activities
2. Assess the safety of a slope created by a trench excavation
3. Assess the safety of a slope created by a soil stockpile

At each of the objective points, the student checks in with the non-player character upon completing their VR task and are scored on the results. To conclude the simulation, the student virtually walks back to the construction trailer to receive their final score for the simulation. The VR simulation score was not collected and analyzed in this experiment.

4. Results

As mentioned, 28 students participated in the study. Eleven students reinforced their construction excavation safety learning using traditional presentation slides while 17 used the VR headset for learning reinforcement. Assessment scores for the control and test group were computed for both the pre-assessment and the post-assessment and an average was obtained for the change in score between the post-assessment and the pre-assessment. The average improvement for the control group was 23.64 points (*SD*=21.87) while the average improvement for the test group was 12.94 points (*SD*=23.71). To determine the significance of the improvement averages, a Two-Sample T-Test was performed. Assuming a *Confidence Interval* percentage of 95% (*CI*=95%) then $t_{(28)}$=1.174730, *p*=0.252382 (*p* X≤ 0.05), resulting no significant improvement for either group.

5. Analysis and discussion

5.1. No Significance and collection of lessons learned

The experiment resulted in no significant scoring improvement regardless of the type of reinforcing pedagogy that was used. Despite these findings, the researchers sought to learn from the experience and gathered additional data that would be helpful in future iterations of a similar study. Approximately a week after the experiments were conducted, the same group of student volunteers was asked to participate in another voluntary session designed to investigate the outcomes of the study. The same 28 students agreed to offer qualitative feedback to the researchers. All the students were allowed to try both methods of reinforcing their learning (presentation slides and VR) so that broad opinions and comparisons could be developed about both configurations. Three questions were presented to the students and the responses were collected and tabulated.

5.1.1. Question 1: If given a choice which method would you choose to reinforce your learning about construction excavation safety?

16 students preferred the VR headset while the remaining nine favored the traditional presentation slides. Despite a small sampling, students appeared neutral about their preferred method of learning reinforcement. Evaluation of the qualitative feedback also yielded results from both extremes (preferred vs. not preferred). One student recounted:

"VR seems more real to me and I can see things that the slides don't show…I can see things from different perspectives."

This statement reinforces a known strength of using VR for training [2], [15], [16]. Future iterations of this research could make use of this comment to strengthen the visual content in the VR environment. Adding annotations such as informational pop-ups, audio, or video content would be advised. However, at the other extreme, another student offered the following statement:

"I like to have something I can write on to take notes and I can't write while I'm in VR."

A comment such as this is an obvious shortcoming for using fully immersive VR (VR containing high I.P.T as shown in Fig. 1). A suggestion, in this case, would be the use of a less immersive form of VR (lower I.P.T as shown in Fig. 1), such as desktop VR that will allow students the freedom to take notes while using VR.

5.1.2. Question 2: For each learning method (presentation slides or VR), what were its perceived advantages as you were reinforcing your learning?

This question seeks to understand the advantages of one learning method compared to another (control vs. test). To illustrate the comparison, students were asked to contemplate seven different features of the reinforced learning used in the experiment:

1. Speed of learning
2. Memory retention
3. Preferred style of learning
4. Limited physical movement
5. Ease of use
6. Multiple visual perspectives
7. Ability for interaction

Next, they were asked to identify which of the seven features above were best represented in each of the reinforced learning methods (presentation slides or VR headsets). The responses were tabulated as frequencies for each of the reinforced learning methods selected by the students in Fig. 3.

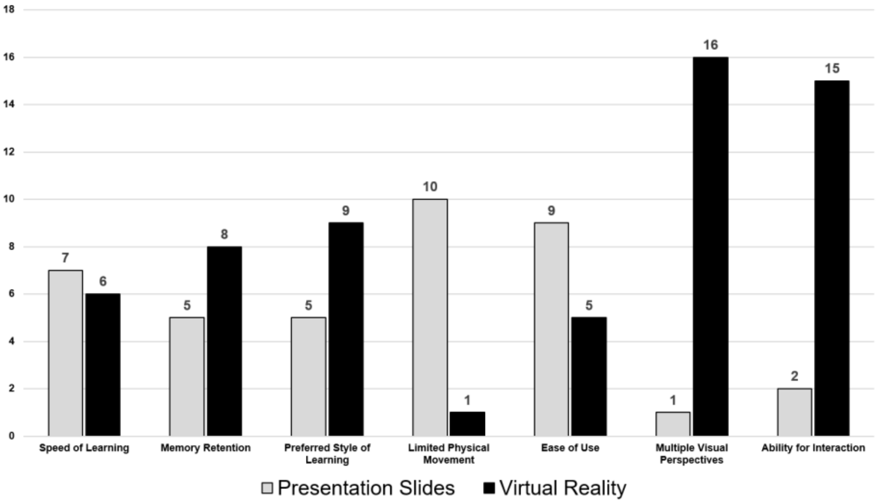

Fig. 3. Frequency of Perceived Advantages for each Reinforced Learning Method

The first feature, *Speed of Learning*, is consistent with the results of the pre and post-assessments. The students' learning seems to be unaffected by the method of reinforcement used and similarly, their responses are nearly identical in Fig. 3. There is a slight advantage in *Memory Retention* offered by the students' perceptions of the VR method. This difference is not conclusive and could be explored in more detail with future iterations of this study. The *Preferred Style of Learning* is not surprising since students in construction management disciplines tend to be "visual" learners [21] therefore the students' perceptions are supported by this finding. *Limited Physical Movement* was an expected advantage with presentation slides. This finding is supported by the student's feedback from section 5.1.1. of this paper where a student was concerned about taking notes while trying to reinforce their learning using the VR method. The motion required for *Multiple Visual Perspectives*, which was an advantage for VR, requires the student viewer to move constantly as they position their gaze in the VR simulation. However, it is this feature that also becomes a weakness as they do so and prohibits them from taking notes or anything else other than concentrating on the VR simulation. Lastly, VR is viewed as an interactive learning experience that also supports active learning in the classroom [5], [17], and is thus a significant advantage for the VR method of reinforcement.

5.1.3. Question 3: Upon trying both methods for reinforcing your learning, which do you prefer and why?

Most of the students preferred the VR method when reinforcing their learning – 18 preferred VR and 10 preferred presentation slides. When asked why students offered additional critiques about the VR simulation and identified some of its shortcomings. The qualitative feedback was coded for patterns and distilled to the following four factors:

1. *Realism* – Realism of the simulation was not an important factor for the students. They claim they were able to understand while handling abstract objects in the simulation. Fig. 4 displays the opening scene for the VR simulation and "floating" objects did not distract from the experience according to the students.
2. *Movement and Motion Affect* – The way that the students moved throughout the simulation was a significant distraction for the students. Several were affected enough to have to remove the VR headset for a moment before continuing in the experiment.
3. *Interaction with Non-Player Characters* – The concept of the "Uncanny Valley" as presented by Brenton et al. [12] is a degree of realism of a simulated human ("avatar") within the simulated environment that become eerie and unpleasant to the viewer. The students in this experiment also noted that interactions with the

non-player characters were uninspiring and did not aid them in their learning. One student offered that "…there is no need to have the people in the [simulation], they just stand there…I wanted them to talk".

4. *Surroundings and the Horizon* – An unexpected discussion point with the students was the position of the horizon in the simulation (see Fig. 4). Additionally, several students noted that they did not feel like they were on a construction site when the horizon continues into "infinity", as one student stated. "I want to walk to the end of the job site and I couldn't" noted another student. This element was perceived as unfinished for the students and it distracted them in the simulation, despite the student's earlier comments that realism was not that important.

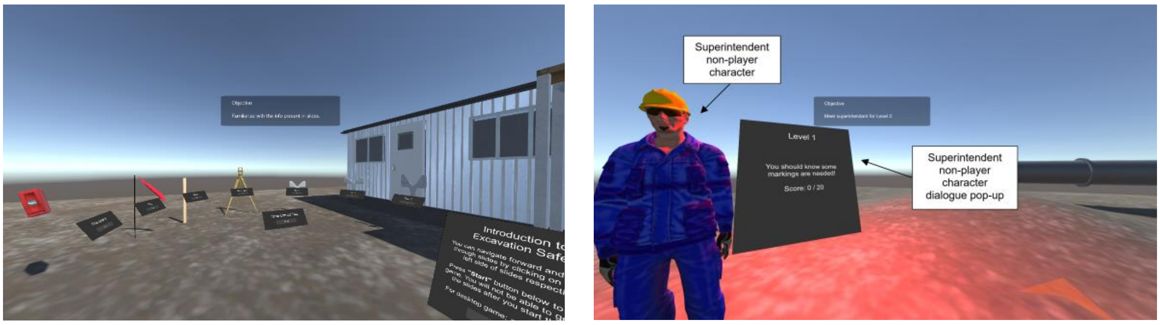

Fig. 4. Opening Scene for VR Simulation (left image) Superintendent non-player character (right image).

5.2. Limitations

While the researchers sought to minimize the conditions of the study that could adversely affect the results, upon completion of the experiment some elements became known that should be considered if the study were to be repeated.

5.2.1. Population

The population for this study was small, however, the researchers took the opportunity to gather as much post data from the experiment to make future iterations of the study more robust and revealing. The finding that the experiment is not statistically significant for either method of learning reinforcement is suspect. Upon completion of the Two-Sample T-Test, the researcher calculated Priori Power to assess the validity of the results based on limited access to a larger population, and at 0.2383, they are low enough to suspect that future iterations may yield different results when testing for significance.

5.2.2. Cognitive learning

Using technology to aid learning in the classroom is notoriously problematic. Sweller noted that cognitive load should be considered and if the load is too great the cognitive process degrades [6]. The researchers acknowledge based on feedback from the students that certain parts of the VR method were distracting (i.e. movement within the VR simulation, interactions with the superintendent non-player characters, and the effects of the surrounding environment). To assess these factors in the future, more scrutiny should be placed on isolating these as variables in the study to discover the effect they have on the results.

6. Conclusion

This study sought to ascertain the student's perceived efficacy when a VR method of learning reinforcement was used compared to the traditional method of using presentation slides. The data indicate no significant results either way which encouraged the researchers to investigate potential root cause issues with the study. Those results have been summarized in this paper along with the discovery of limitations that could be addressed in future iterations of this study.

During interviews with the students following the controlled experiment, most were eager to try the VR method, including students in the control group (those that used presentation slides for reinforcing), and openly offered that it seemed to have potential if some of the issues identified above were addressed. While the experiment did not result in a significant finding, the qualitative data obtained in this study did help the researchers align new goals for furthering the research with a larger population. A few important discoveries resulting from the inquiry following the experiment are as follows:

- Students are attentive to the content in the VR simulation. In some cases, they tend to want detail and realism to be high and in other cases, those elements were not important (see sub-section 5.1.3.).
- Relying on the strength of VR to allow for multiple visual perspectives while heightening student interaction (see Fig. 3) are important factors to consider for future successful implementation of VR as a learning tool for reinforcement.
- The development of the VR experience must be thoughtful so as not to cognitively overload [6] students with complexity during the simulation. A simple interface and clear objectives will keep things straightforward during the student's learning.

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Integrated Design Review Methodology for Critical Facilities Management and Maintenance

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Abstract

Critical facilities are expected to provide continuous performance in standard service conditions and in extreme events in particular. Continuity of performance is determined by the design redundancy, robustness and resilience. A framework for Integrated BIM based service life design review developed for planning of critical facilities. The framework aims at the execution of the design, construction, and commissioning of projects with whole life performance, operation, and costs planning. The methodology follows two phases: (I) Service life planning and (II) Design review. Service life planning is carried out through four stages: (1) Definition of the service regime; (2) Service Life Prediction of the building components; (3) Performance planning, and (4) Service Life Agreement. Design review (DR) is carried out for four building systems: structural safety and integrity, exterior envelope, interior finishing, and exterior infrastructures; and six electro-mechanical systems: Electric and power supply system, Water supply and sanitary, HVAC, Fire Protection, Elevators, and Communication and low voltage systems. DR follows four principles: (1) Durability; (2) Techno-economic service life planning; (3) Maintainability; and (4) Minimization of the Life Cycle Costs (LCC). A Design Review matrix developed for automation of the DR process: the DR matrix is composed of four leading key factors. Key leading factors are Durability, Maintainability, Service Life Planning and Design Guidelines. An integrated public-hospitality case study carried out and presented.

Keywords: BIM, briefing, critical facilities, maintenance, performance

1. Introduction

Integration between BIM and FM attains a potential for strengthening the core tasks of FM as well as delivering the BIM advantages to the commissioning stage. This includes: reducing the procurement costs, improving life cycle decision making, reducing costs due to waste, rework, and deterioration of components and systems, improving the safety and health of the occupants and the FM staff, and improving the end-users and stake holders satisfaction [1, 2]. Dixit et al. [3] researched 16 issues related to the integration of BIM and FM under four core categories: BIM-execution and informationmanagement, technology, cost and legal and contractual issues. The most significant issue for expediting the integration of BIM and FM was found to be involvement of FM in the project phases. Gurevich et al. [4] introduced a comprehensive BIM Adoption Impact Map (BIM AIM) as a four level gradual process composed of CAD (level-0), 2-D and 3-D (level-1), BIMs (Level-2), and iBIM integrating Life Cycle Asset Management (level-3). The authors found that comprehensive integration of BIM in the Life Cycle Management of a facility, implementation of BIM in the Design, Construction, Commissioning and maintenance of the facility can increase the probability of meeting the clients and end-users expectations of meeting the budget, the time, construction quality and performance of the facility. The study concludes that BIM can support a better project outcome by facilitating design review and acquiring improved performance in terms of lighting, ventilation, thermal comfort etc. Halmetoja [5] found that BIM can serve as an effective framework for building maintenance and operation, and that many of the services management can be delivered effectively when they will be implemented through the design and construction phases. This research also stresses that the integration of BIM into the life cycle management of the project will be effectively accomplished if FM will be integrated in the design phase.

2. Literature review

Kassem et al. [6] researched the implementation of BIM applications in FM through a case study of an academic campus. The authors figured out that BIM can improve FM processes due to improved information handover; improvement of the accuracy of FM data, improved accessibility of FM data and increase in the efficiency of work order execution. The authors found that the main barrier of BIM Implementation in FM are the lack of methodologies that demonstrate the tangible benefits of BIM in FM. This research indicates the need for BIM-FM methodologies such as design review. Ilter and Ergen [7] carried out a semantic review of the literature identifying BIM-FM input-output relations and exhibiting areas of focus as well as research gaps in the field. The authors recommended the development of BIMbased standard for the integration between FM and BIM databases. Development of specifications information exchanges in FM, as well as extending Industry Foundation Classes were also recommended to provide new properties related to FM. Matarneh, R. et al. [8] carried out a holistic review of the state-of-the-art on the current information exchange process between BIM and FM and concluded that software interoperability remains a significant barrier for BIM-FM application. This gap requires the standardization of practical processes to integrate between maintenance, health, safety management, and BIM data. In a follow up research [9], the researchers identified eight core BIM applications to FM amongst them: facilities information systems, maintenance management, energy management, space management, and health and safety management.

Pärn et al. [10] state that the BIM trajectory in facilities management must address long-term strategic planning, improvement of the data integration and interoperability, and advanced performance management. Singh et al. [11] developed a framework for BIM-server multidisciplinary collaboration platform. Three categories of core operational technical requirements were defined amongst them are: design review. Tan et al. [12] carried out three case studies on the effective knowledge and information flow between the building construction and facilities management in the procurement of construction projects. The researchers proposed three Key Success Factors (KSF): OCC (Open Communication Chanel), SLF (Soft Landings Framework), and BIM. The authors concluded that integration between the three KSF attains a strong potential for enhanced information flow in the construction process.

3. Research objectives

The literature review reveals a wide gap in the implementation of the life cycle aspects planning throughout the delivery of projects in general and delivery of critical infrastructures in particular. The research objectives therefore focus on twofold courses.

3.1. Integrated BIM and FM

Development of an integrated BIM and FM framework for implementation of life cycle design and planning of construction projects in general and for critical facilities projects in particular. This framework aims at the execution of service life performance, operation and life cycle costs planning of the design, construction, and commissioning of projects.

3.2. Life Cycle Costs, Facilities Management, and Design Review

The second objective focuses on the integration of LCC approach and the Facilities Management planning at the design process through a structured design review methodology for life cycle performance design. This objective aims at the integration of durability, performance, continuity of performance, maintainability, and LCC at the design and throughout the procurement process of Critical Infrastructures.

4. Research methods

4.1. Integrated DR and BIM

Integrated DR and BIM is developed in three phases: (a) The building characteristics including the building designed life cycle, its service regime and its environment; (b) the building parameters including its building and electro-mechanical composites, and (c) the last phase is the performance-based design principles for the selection of adequate solutions for each building systems. This inference adapts the design to the prevailing service conditions in accordance with the performance requirements and with IFC guidelines.

4.2. Design review methodology

The DR methodology is based on the connectivity linkages described in Table 1 presented here for the buildings' components (an elaborated matrix will be presented in the full journal paper). The building's components and systems are reviewed for the adaptation between the buildings design and FM considerations as follows: durability of the component with respect to the exposure and expected service regime, maintainability of the component, the design life cycle of the facility and the core design considerations referring to each particular component.

Table 1. Facility maintenance design considerations of building and electro-mechanical systems

System / Design Considerations	Structure	Exterior Envelope	Interior Finishing
Durability	The concrete's compatibility to the exposure conditions	Durability based on the building's surroundings, its height and execution deviations.	Compatibility to the service regime and to the planned life span. Durable elements to service regime and conditions
Maintainability	Drainage of the structure and the exterior envelope.	Replacement of elements and components.	Maintenance accessibility to elements.
Designed Life Cycle (DLC)	Compatibility with exposure, structural insulation based on the surrounding environment and the buildings criticality.	Predicted life cycle.	Adapting elements' life spans to the service regime and the service life, integrating the systems in the interior finishing.
Core Design Guidelines	Adaptability to exposure conditions, Adaptability of the geometry to maintenance and exposure conditions	Adaptability to exposure conditions, accessibility to maintenance, integration with the E.M. systems	Adaptability to service regime, maintainability

4.3. Architecture and reasoning of the DR model

4.3.1. Structure

Three principles guides the design review of the structure in this research:

(a) Adaptability to the exposure conditions, i.e. suitability of the structural elements protection to exposure conditions;
(b) Adaptability of the structure to the exterior cladding components: e.g. : fixing details geometry and measurements in structure and exterior cladding; (c) Drainage details such as: cornice drip-edge.

4.3.2. Exterior envelope

Three profound criteria guides the exterior envelope FM design review covering: durability, maintainability, and integration with the structure and electro-mechanical systems.

(a) Durability and adaptability to the exposure conditions: this parameter is assessed with respect to the predicted service life of the exterior cladding for the particular exposure conditions: marine environment, and air-pollution. The decision criterion can be either minimum LCC or maximum Predicted Service Life;

(b) Maintainability: assessed according to geometry of the exterior walls and accessibility for maintenance and repair using hanging or tube and coupler scaffoldings.
(c) Integration with the structure and electro-mechanical systems assessed by location of electromechanical equipment units such as location of chillers in roofs (safety and operational distances).

4.3.3. Interior finishing

The core criteria for the design review of interior finishing components are focused on durability in the service regime and maintainability as follows: Adaptability to the service regime (service regime is defined as light, standard, intensive, and extreme service conditions), this tool can be implemented for interior partitions, flooring (ceramic, concrete tiles, carpets, etc.), and interior doors. The second criterion is maintainability and is expressed in the case of interior finishing components by replace ability of the components.

5. Case study

5.1. Outline of the building

The case study in this research is an academic activity centre project located in Hsinchu in the north of Taiwan. The exposure conditions are standard. It is a RC structure with four above ground floors and two underground floors with a total floor area of 15,919 [sq.m.]. The seismic resistance of the structure is acquired by the elevators and the staircase cores. The basement floor of the case study is mainly where the parking lot and large electro-mechanical equipment units are placed. The ice water machine of the HVAC system and the generator of the power system backup are placed in the basement floor. The above-ground space includes restaurant, conference room, and guest houses, where are mainly equipped with air-conditioning pipelines, fire protection pipelines, water supply and drainage pipes, and hot water pipes. This study applies the proposed model to the case project examining the durability, maintainability and redundancy of the building components to demonstrate and validate the feasibility of the proposed model.

5.2. Integrated DR and BIM

The integration of BIM and DR can be discussed by the three aspects of Durability, Maintenance, Redundancy.

- Durability: the elevation of the pipeline in the power system is higher than that of the water supply pipeline, which can prevent damage to the power pipeline due to water leakage from the water supply and secure the durability of the pipelines systems.
- Maintenance: In the case study, due to the small area of some spaces, it may cause difficulties in equipment maintenance. With the help of the BIM model, sufficient space for maintenance personnel to maintain (such as the radius of gyration of electrical equipment) is reserved to improve the maintainability of building components.
- Redundancy: The basement tested in this case is where the electromechanical hosts are placed. If the various hosts are too close together, it will be impossible to expand other pipelines and equipment in the future. Therefore, the BIM model is used to assure sufficient expansion space in the design.

5.3. Building components DR

5.3.1. Structural safety and stability

The structural safety and stability is reviewed through seismic design, design for fire protection and for other scenarios should they be relevant. The review refers to seismic design (lateral loads) and resistance of the structural elements to fire events according to the classification of the building.

5.3.2. Exterior envelope

Through the BIM model, the details of the doors and windows assessed to check the size and details (waterproofing, drainage, durability, and maintainability) of the doors and windows parts. When the door and window components are damaged, the parameters of the components can be quickly inquired through the BIM model. Therefore, it is also possible to judge the cause of easy damage by the model, and select a more suitable material at the place to reduce the frequency of breakdown events.

(a) Durability: In the case building, there is space reserved for the exterior wall to repair the leaking space, so as to increase the service life of the exterior envelope.
(b) Maintainability: the exterior wall cladding of the case building is made of marble, it needs to be cleaned routinely according to its condition. Therefore, the working platforms of the cleaning staff is considered, and whether the cleaning staff has enough space for cleaning during maintenance.

- Roof drainage

Due to the long rainfall time (the average rainfall is about 1,164mm per year) at the area of the case building. When designing the case project, three drainage details are set on each part of the roof. The distance between each drainage is 4.4 m and the diameter of the pipe linking to the drainage is 100 mm. By checking the pipe diameter during maintenance through BIM, the cause of the blockage or insufficient capacity can be carefully and rigorously assessed. When the pipeline needs to be replaced, the maintenance engineer can also get the size of the pipeline and check whether the size is suitable for being placed there. Detail of roof drainage scheme is shown in Figure 1.

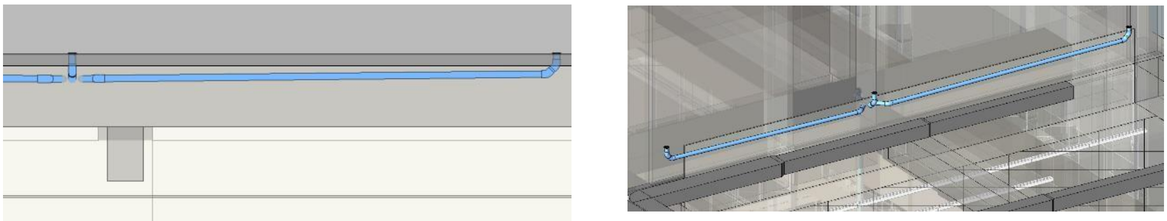

Figure 1. Detail of roof drainage scheme

- Exterior cladding

The curtain wall contains multiple pieces of information such as the crack resistance joints and the waterproofing details. In addition to the geometry of the curtain wall and the materials used, many parameters such as wind pressure resistance, earthquake resistance, air tightness, waterproofing, and deformation of the curtain wall affect the design principles. As the curtain wall project accounts for larger portion of the exterior envelope and the entire building, the parameters it contains also increase. If the information can be attached to the BIM model thorough the object classes parameters of the exterior wall object, it can assist in budget estimation, shorten the construction period, and find the most suitable repair plan and alternatives in subsequent maintenance. Facade detail of Curtain wall on the first floor is shown in Figure 2.

- Exterior wall

The exterior wall is reviewed according to the surrounding conditions of the building and the elevation, service life is assessed, and perform early detection of deterioration mechanisms to avoid excessive deterioration and avoid high maintenance expenditures. At the same time, consider the elevation of the exterior wall to learn about the maintainability of the place, and secure a maintenance accessibility to all exterior wall elements for proper and efficient maintenance.

5.3.3. Interior finishing

Through the BIM model, one can record the types of materials used in the interior decoration of buildings, such as interior partitions and paint colour numbers, door and window hardware materials, and so on. Through the information carried out in the proposed BIM model and framework, building parts can be quickly retrieved during maintenance in order to find a repair manufacturer. At the same time, through the function of BIM quantity calculation, when repaint or refurbish needed, one can quickly calculate the area for painting or decorating, in order to estimate the maintenance amount. Interior finishes of a typical guesthouse room are shown in Figure 3.

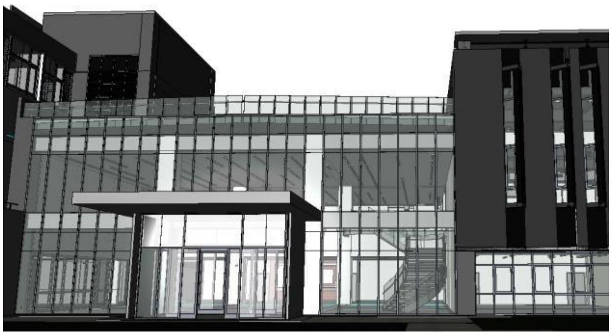

Figure 2. Facade detail of curtain wall on the first floor

Figure 3. Interior finishes of a typical guesthouse room

6. Conclusion

The proposed framework for BIM Facilities Management and Maintenance Design Review for Critical Facilities lays the ground for comprehensive development of the BIM tools towards an integrated interface between durability, maintainability and Life Cycle Management using IFC class. The proposed framework and methodology paves the way for the interoperability in BIM to integrate Knowledge based IT-based design review tools for project life cycle design.

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Transforming the AEC Industry: A Model-Centric Approach

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Abstract

The increased complexity of construction projects requires the involvement of a wide range of organizations throughout the project lifecycle – from conceptual planning to decommissioning. Construction project teams, therefore, differ from teams in other industries as they comprise individuals who are employed by organizations that conduct different businesses. These many separate organizations working together in a close harmony over the duration of the project is fundamental to the overall business of construction. Project success relies heavily on the management of the flow of information among players and access to the right information is vital to efficiently perform the work. Therefore, an efficient information access and effective information exchange methods internally and externally with other organizations needs to be achieved. The model-centric approach introduces a unique solution to solve the problems with the information jungle, inconsistency, and disintegration associated with the traditional document-centric approach. As such, a coherent use of information management is required to merge, co-manage, and semantically connect the information and artifacts generated throughout the project phases. Adopting a model-centric approach creates a single point of truth that centralizes information and facilitates access to it. A transformation plan is needed to outline the shift of the construction from document-centric to model-centric. This paper proposes a strategy to support the model-centric transformation of the Architecture, Engineering, and Construction (AEC) industry. Five strategic objectives are outlined and discussed in this paper highlighting considerations that need to be made to enable this transformation. This study describes the “what” necessary to enable and support a model-centric AEC industry.

Keywords: BIM, MBSE, model-centric, system engineering, technology shift

1. Introduction

The Architecture, Engineering, and Construction (AEC) industry is one of the most information-intensive industries where information needs to be readily available, accurate, complete, timely, and in a clear format that is understandable by the recipient. The increased complexity of construction projects requires the involvement of a wide range of organizations throughout the lifecycle – from conceptual planning to decommissioning. Project teams, therefore, differ from teams in other industries as they comprise individuals who are employed by organizations that conduct different businesses.

Project success relies heavily on the management of the flow of information among players. The multidisciplinary and fragmented nature of construction creates a challenging environment for successful project implementation. Even with the development of BIM and Systems Engineering, the current practice of construction still relies on the conventional document-centric approach to deliver and manage the data throughout the lifecycle. Joan Allen, a group product manager at Autodesk pointed out that 70% of construction projects are still using paper as the main medium of communication [1]. This approach emphasizes the generation of documents (physical or electronic with restrictive interoperable capabilities) which are exchanged among stakeholders and is prone to inconsistencies and incompleteness. Rezgui and Zarli [2] formulated the following vision statement in relation to transforming the AEC industry: "Construction in the knowledge society uses information and communication technologies as key enablers to meet main societal and industrial challenges. Sustainable construction is driven by total life cycle performance through knowledge intensive and functional integration of products and processes using a model-based approach to pave the way toward a knowledge driven industry." They highlighted that the document-centric information exchange dominating the AEC industry should be replaced with a model-centric approach [2].

Model-centric approach introduces a unique (and real-world practical) solution to solve the information jungle, inconsistency, and disintegration associated with the document-centric approach. The concept of Model-Based System Engineering (MBSE) was conceived by the International Council on Systems Engineering (INCOSE) to transform engineering by replacing the traditional document-based with a model-based approach [3]. Adopting a model-centric approach creates a single point of truth that centralizes data [3,4].

Model-centricity provides new opportunities for the development of an integrated platform for information exchanges that can cross the organizational boundaries and provide a unique opportunity for teamwork and efficient information exchange and knowledge-sharing among otherwise isolated entities. While a model-based approach offers flexibility, supports collaboration and communication, automates and centralizes data, it requires changes to the AEC business-as-usual process. Inspired from the five objectives set by the Department of Defense (DoD) in 2018 for the Digital Engineering Strategy [5], this study discusses a strategy to guide the transformation of the AEC industry into a model-based discipline. The five objectives that are discussed in this paper and are as follows: 1) Formalize the development, integration, and use of models; 2) Provide an enduring, authoritative single source of truth; 3) Integrate technological innovation; 4) Establish a supportive infrastructure and environments to collaborate and communicate across stakeholder; and 5) Transform the culture and the workforce to support the transformation. The description of each of the five objectives is supported with previous research endeavours undertaken to explore the transformation of the AEC industry into model-centricity. The objectives are then augmented with a set of considerations to be addressed before achieving model-centricity in the AEC industry.

2. Overview of System Engineering and Model-Based System Engineering

Before discussing MBSE and its current applications, it is important to understand what a *System* and *System Engineering* is. According to INCOSE, a system "is a construct or collection of different elements that together produce results not obtainable by the elements alone" [6]. Systems can be found in different products across different industries such as automobiles, shuttles, and airplanes. An aircraft, for example, is composed of various systems that are enclosed in a single body. These systems can be mechanical, electrical, and electronics. A F-35 fighter jet, for instance, has 8.5 millions of lines codes and thousands of electric circuit systems [7]. For an airplane to function and fly safely, these systems must thoroughly be designed, assembled and inspected. Additionally, systems must be coherently integrated – an integration that is achieved through System Engineering [8].

System Engineering as defined by INCOSE [6] is "an engineering discipline whose responsibility is creating and executing an interdisciplinary process to ensure that the customer and stakeholder's needs are satisfied in a high quality, trustworthy, cost efficient and schedule compliant manner throughout a system's entire life cycle". According to [9], a System Engineering roadmap can be summarized into the following five steps: 1) Stakeholders are first identified. Stakeholders can be individuals or groups who are participating in the system development; 2) Stakeholders' requirements and concerns are identified through questions of interest; 3) The system requirement, goals, external relationships and boundaries are later identified; 4) Budgets and schedules are established and maintained along with management and maintenance processes. Consequently, a baseline will be set to fulfill the stakeholders and system requirements; 5) User documentations, risk matrices, testing documents are finally created.

Researchers noted that there are numerous challenges facing System Engineering especially given the complexity of the design of today's systems [7]. System design complexity is increasing faster than it can be controlled, especially as it is assembled from different design parts and not from a common architecture. Moreover knowledge and communication are lost across the project lifecycle, and between different projects, resulting in products that are expensive to test, have low quality, and are risky to operate [10].

The increase of system design complexity forced engineers to reconsider the whole system development phase, and as a result, MBSE emerged. MBSE was first introduced by Wymore and is described as a paradigm that places the model at the center. [3] noted that although MBSE has been extensively researched in the past decade, it remains a mysterious concept that has different meanings to different stakeholders. INCOSE initially defined MBSE as "the formalized application of modeling to support system requirements, design, analysis, verification, and validation activities beginning in the conceptual design phase and continuing throughout the later lifecycle phases" [6]. [4] augmented on the definition put forth by INCOSE and defined MBSE as "the formalized application of modeling (static and dynamic) to support system design and analysis, throughout all phases of the system lifecycle, through the collection of modeling languages, structures, model-based processes, and presentation frameworks used to support the discipline of systems engineering in a model-based or model-driven context".

In MBSE, the "model" is the single source of truth promising increased effectiveness in developing complex systems [11]. A model is a representation of a system that evolves as the lifecycle of the system is progressing. A model can include design information, specifications, and testing requirements all stored in a central location [9]. These models will have different viewpoints, offering a flexibility in viewing model information [12]. For instance, the information viewed by the owner is different from the information viewed by engineer. The owner would be interested in cost information, project risk, on the other hand, the engineer would be interested in material delivery dates, progress, and upcoming weekly tasks. Therefore, model-centric design can capture different system aspects, while offering specific views through different lenses that highlight specific information in the model. In MBSE, models are created using modeling languages. One of the most prevailing languages is Systems Modeling Language (SysML), which is a graphical modeling language developed by Object Modeling Group (OMG) and INCOSE [8]. SysML can be used to analyze, design, and verify complex systems, whether it is software or hardware related.

One of the main reasons driving this shift to MBSE is to solve communication breakdowns that often occur as a result of the traditional document-centric System Engineering approach. In System Engineering, the data is stored in different formats using different software tools, which are deployed across different computers at the workplace. One of the main challenges arise when there are multiple versions of important documents being shared, which causes confusion between different stakeholders and can ultimately lead to conflicts. In addition, important design information is often not properly documented [7]. In a model-centric approach, on the other hand, the information is integrated into the model which is connected to the different requirements and design databases. The model can be then used to assess the performance of the system [13]. If changes in the requirements or design occur, it can be checked whether these modifications are safe to be implemented. If they are approved, they will be automatically updated into the main model. Therefore, the capabilities offered by MBSE help prevent design errors, by enabling a proactive check and analysis of the requirements and improving design feedback time [14]. MBSE is envisioned to transform a document-centric discipline into a model-centric discipline where data is maintained within a single repository and each stakeholder has a singular definition, with all needed attributes and relationships stakeholders are outlined [3].

3. A Model-Centric Transformation Strategy for the AEC industry

Trying to solve the challenges of complex systems, other industries adopted the application of MBSE [9]. The AEC industry is facing similar challenges while still operating in a document-centric manner. Even the great effort in researching multidimensional BIM in the last decades didn´t lead to a sufficient improvement in information flow [15]. The chance towards a model-centric approach becomes a necessity for the AEC industry to solve the long existing problems. To apply MBSE to the requirements of the construction industry a customized transformation strategy is needed, taking in consideration that there are currently no existing implementation frameworks. This paper discusses five objectives adapted from the Digital Engineering Strategy set by the DoD [5].

3.1. Objective #1 - Formalize the development, integration, and use of models

As mentioned in Section 2, a model "represents reality for the given purpose" [16]. Following the first objective of this study, the context of models in construction needs to be developed to create a common understanding and to evolve into a model-centric industry.

As models are a representation of something, they only have properties to the given purpose. Therefore, the purpose of the model and the relevant stakeholders must be considered [17]. Modeling construction information does not strictly refer to Computer-Aided-Drawings (CAD), Building Information Modeling (BIM), and reality models, but rather it references the representation of construction process (from conceptual planning to demolition) in data to facilitate exchange and interoperability of project information. Models could be 3D models, 4D simulations, drawings, specifications, Request for Information's (RFIs), cost, schedule, progress reports, as-builts [1]. A construction information model also consists of different repositories, which can then be accessible to different stakeholders [17]. Each model is tailored for its intended purpose and stakeholders and serves to understand the system, to optimize the behavior if necessary and / or design strategies for future operations [18]. Additionally, simulated models are used either because the real system is not yet defined or available or because it cannot be executed directly due to cost, time, resource or risk restrictions. These simulations, for example, enable design analysis on models and allow what-if analysis to be carried out [19].

It should be noted that while evolving technology enables more complex and capable models, it may not improve effectiveness if the human factor is not appropriately considered [2]. Humans have cognitive and conceptual limitations that limit the amount and type of information they can effectively comprehend and use to make decisions. Designing for humans requires understanding their capabilities and limitations and identifying their information needs so that the model intelligence can extend the overall system intelligence [16,20].

3.2. Objective #2 - Provide an enduring, authoritative single source of truth

Research efforts conducted during the past decades show that while modeling has already moved beyond the n-dimensional development of BIM, the degree of integration between different systems and stakeholders can still be greatly improved [15]. Given the various use-cases applied throughout the construction project lifecycle and their diverse requirements, there is currently little interoperability and automation potential to leverage the use of BIM [15]. Although the advances in vendor-independent formats such as Industry Foundation Classes (IFC) have a significant impact on the development of integrated methods for the exchange of construction data [15]. IFC provide the standards for model-based interoperability, similar to how SysML is becoming the standard modeling language in MBSE [25]. While taking into consideration industry´s stakeholders, subsets of the IFC scheme – so-called Model View Definitions (MVDs) – are created to meet the requirements of various disciplines [30]. Although these schemes are not yet fully developed, together with Information Delivery Manuals (IDMs), they support collaborative project management [30]. Research efforts show for example how Building Automation System (BAS) based systems which are used in facility management can be represented in an IFC structure [21]. While other researchers are still sceptical and consider that even with the further development of IFC, it does not seem feasible to switch from static BIM data to a dynamic web-based system [15]. Therefore, there are other approaches based on linking data which is kept in its original format [22].

Examining developments in other industries has led construction researchers to focus efforts towards a more holistic approach across the lifecycle of a construction project – the concept of Digital Twin. As the authors have shown in [23], the concept of the Digital Twin in the AEC industry goes beyond BIM. The authors classify the model-related body of knowledge in construction into three subcategories: Digital Models (most notably illustrated through BIM where there is no automated links between physical object and virtual representation is to be counted), Digital Shadow, and Digital Twin (highest level of data integration). Digital Twins in their full form have an automated bidirectional link between the physical and digital object [23]. The use of BIM in construction projects nowadays can thus be the starting point for the progression of sustainable Digital Twins that are enriched by data collected throughout the project lifecycle [15]. Regardless of the current maturity level of the Digital Twin concept in construction, the exchange of information continues to develop into more open, web-based platforms through the use of open formats such as IFC but also enabled by linking existing data. This direct access to information increases the importance of a single source of truth, which MBSE will offer if implemented.

[24] defined a single source of truth as an authoritative source of data that offers data services to other entities. In construction, a single source of truth is thought of as a Common Data Environment (CDE) and the practice of properly storing data such as plans, correspondences, specifications, Computer-Aided Drawings (CAD), 4D simulations in one place without duplications and with a clear path to locate, extract, and share the data throughout the lifecycle of the project – from design, to planning, construction and operations [1,25]. A single source of truth can be leveraged not only by the dynamic data that a Digital Twin manages, but also by the constant knowledge accumulated about the physical objects, which can lead to new insights and patterns with the use of data analysis [15,26].

[27] noted that a shared common data environment (CDE) or data repository is required to reduce miscommunication. Even though platforms that meet these requirements are less common in construction than in other industries, the use of CDEs is growing. Bentley offers such a platform with ProjectWise and Autodesk with BIM 360. Both of these platforms are constantly evolving, and their features, interoperability in particular, are being upgraded and tailored to meet the requirements of the AEC industry and its stakeholders [1,28]. With the ongoing development towards using a single source of truth in construction projects new challenges arise. Whyte pointed out that simulations based on wrong assumptions can lead to disasters, and thus, it must be ensured that the single source of truth is reliable and that verification and validation processes are put-in place and carried out throughout the lifecycle of the construction project [26].

3.3. Objective #3 - Integrate technological innovation

The construction industry is not an exception to the pervasive digital revolution. The industry is dealing with large volumes of data arising from different disciplines throughout the lifecycle of a capital project. As the Internet continues to evolve, and with the increased growth in the number of connected devices – coined as IoT, there is a massive increase in the accompanied data traffic volume. The vast accumulation of construction data, including BIM data and IoT data has pushed construction to enter the era of Big Data [29]. Big Data has three attributes; namely volume, variety, and velocity (a.k.a. 3V's) [30]. Construction data is typically large, heterogeneous (represented in various formats), and dynamic (resulting from the nature of data sources) [31]. The application of the major technologies of Industry 4.0 to a construction project generates multiple scenarios to be considered under the model-centric approach. For example, workers' wearables in construction linked to IoT allows the collection of ergonomic data. The gather raw data is stored in a database where data analytics is employed to infer information. This information is then accessed by the responsible person (decision-maker) to make decisions related to the behavior of workers. This decision is then communicated to the workers in the field, whose behavior will be adjusted accordingly, forming a closed loop under the model-centric approach. Visualization technologies such as Virtual Reality and AR and as well as web-based applications can also support the model-centric by leveraging the accessibility to, usage of, and interaction with information.

3.4. Objective #4 - Establish a supportive infrastructure and environments to collaborate and communicate across stakeholders

As outlined under the second objective, the collaboration between the various AEC stakeholders is centered on the idea of a single source of truth that is implemented on a web-based platform. Although the concept of the single source of truth is vital to model-centricity, the question pertaining to how the integration of the numerous stakeholders with their subsystems and their highly specialized applications in this single source of truth can be facilitated is subject of current research. The key to generate a reliable single source of truth is interoperability, which can be achieved by using open formats and also by linking existing data.

It should be noted that, even when interoperability is achieved within the single source of truth, there are other points to consider, such as the Information Technology (IT) infrastructure and the corresponding hardware and software tools needed to operate the web-based platform. This transformation should be also supported by a team of well-trained individuals and specialists to provide on-going feedback and assistance.

3.5. Objective #5 - Transform the culture and train the workforce to support the transformation.

Research indicates that the level of cultural change needed to transform an industry through MBSE should not be underestimated [32]. This transformation goes beyond the technical aspects of MBSE as it requires strong leadership involvement and commitment. Additionally, stakeholders need to be educated on model-centricity.

To overcome cultural challenges associated with the shift to a new system, Thales group which is a multinational aerospace company, has applied a rigorous plan related to MBSE implementation [33]. Owner and key players are involved early in the project to define and modify their needs. Then, research and training experts highlight operational needs and produce prototypes that are later validated. Moreover, a dedicated development team is responsible for enhancing the current modelling software. Additionally, dedicated support teams are put in charge to perform most of the analysis that require special attention. MBSE champions are also delegated to help operational engineers implement MBSE. Furthermore, local support teams are assembled and act as the liaison between operational users and support teams. Finally, operational engineers will oversee the implementation plan, and will regularly check and ensure that the current MBSE solutions are helping the engineers [32]. A similar process can be established for the AEC industry and tailored to the specifics of the construction project.

4. Considerations to support the Model-Centric Transformation for the AEC industry

The shift towards a model-centric industry is a necessity to continue to exist in the growing market, however the current state of the AEC industry is still mainly document-centric. The previous section discussed five objectives for implementing a model-centric approach. This section outlines several considerations that need to be addressed and should be carefully thought of when discussing model-centricity. These considerations can be summarized into the five themes illustrated in Fig. 1 (central figure) and are discussed in detail in the following sections.

4.1. Objective #1 - Formalize the development, integration, and use of models

As different stakeholders are involved throughout the lifecycle of a construction project, it is important to study and explore their relationships among each other. Their needs and requirements for the models should be well considered, defined and formalized. It is also crucial to define a common lexicon for models in the AEC industry to ensure consistency and buy-in from all stakeholders. After defining and agreeing on what the models are, the realization of those models on construction projects should be formalized. This ensures that the modes are complete, trustworthy, accurate and meet the specified requirements of the stakeholders. These models will be used to communicate and collaborate throughout the project. Another important aspect that should be considered is the Project Delivery System. Given the complex and dynamic nature of the AEC industry, it becomes critical to explore the feasibility of adopting a model-centric approach with the different Project Delivery Systems. While the adoption of a model-centric approach can be aligned with the Integrated Project Deliver System where communication, collaboration, and transparency are supported contractually, a significant number of construction projects are executed under other delivery systems such as Design-Build and Construction Management. Additionally, as the AEC industry prepares to become model-centric, models become valuable assets throughout the project lifecycle, requiring management and control (model curation).

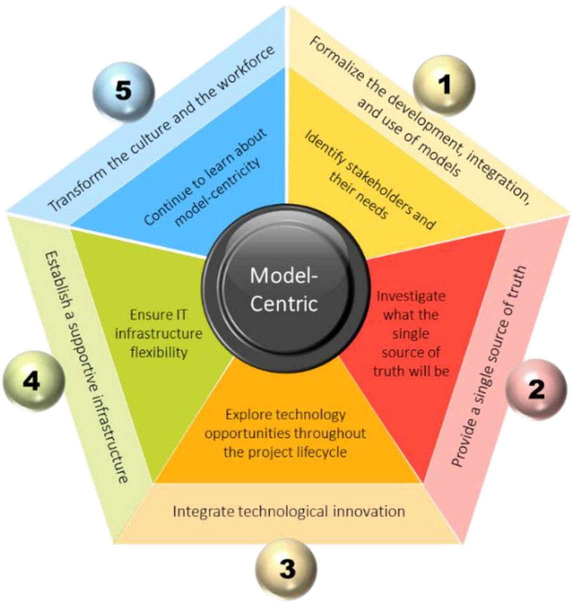

Fig.1. The AEC model-centric Tranformation Objectives and Considerations
(objectives are listed in outer pentagon and considerations are listed in the inner pentagon)

4.3. Objective #2 - Provide an enduring, authoritative single source of truth

After identifying the requirements of the different stakeholders, the single source of truth that will serve as the central reference point throughout the project lifecycle needs to be defined. With the existence of various types of models and software, the integration of models in a single source of truth is the main challenge. Main research efforts are undertaken to connect and link these models to apply the model-centric approach and establish a master model that will act as a hub for all other models.

To ensure the proper use of the single source of truth as the project moves forward, a governance plan must be established to trace and capture changes. It should be also noted that having a central model does not mean that everyone and anyone has access to the same information. Different viewpoints are crucial in order the channel the proper information to the right stakeholders.

4.3. Objective #3 - Integrate technological innovation

Shifting towards Construction 4.0 requires the adoption of MBSE into the AEC industry. However, the transformation is not linear as it depends on the use of advanced technology such as AR, IoT and Big Data. Technological advances are rapidly changing, and thus, it is important to make wise investments. When making technology-related decisions, it is important to ensure that knowledge is continuously captured, used, and leveraged, to provide the industry with a competitive edge to adapt and grow.

4.4. Objective #4 - Establish a supportive infrastructure and environments to collaborate and communicate across stakeholders

In order to integrate advanced technologies into a project or a process, a robust IT infrastructure must exist. Investing in technology and infrastructure is as important as investing in other decisions. Thus, the IT infrastructure can be thought of as the main “mechanism” to connect stakeholders and exchange information. Not having a robust and secure IT infrastructure will overturn all the advances in the construction lifecycle. Investing in establishing communication channels between stakeholder will help promote model-centricity by punching holes in the wall of silos of the AEC industry. Having subject matter experts guide and assist the development of an IT infrastructure and having leadership invest and support this initiative is crucial to this objective.

4.5. Objective #5 - Transform the culture and train the workforce to support the transformation

The human factor is as important as the use of technology. In order to exploit the full potential of technology not only the leadership level needs to be brought on board, but the workforce needs to be trained to navigate model-centricity. As this transformation requires collaboration and transparency among the stakeholders, it is important to ensure buy-in and support from all project participants. Project team leaders and model-centricity champions can also develop guidelines and organize workshop to educate and train stakeholders. Other industries, particularly manufacturing, have always been a source of innovation for the AEC industry. AEC professionals can learn from other industries that have benefited from a model-centric transformation and adopt and adjust best practices to fit the industry. Moreover, companies must realize that such a transformation is a long-term goal and efforts and investment in all aspects need to happen continuously and incrementally, over a long period of time. Such a transformation is not instantaneous, and although the cost of change is high, the return of investment will be higher.

6. Conclusions and Future Work

The increased complexity of construction projects along with the increased customer expectation has added more pressure on the AEC industry to re-examine its practices and revolutionize and modernize how it plans, designs, executes, and maintains its projects. The multi-party nature and uniqueness of the architecture, engineering, and construction industry creates a challenging environment for successful project implementation. Project success relies heavily on timely transfer of the correct information among players. Model-centricity provides new opportunities for the development of an integrated platform for information exchanges that can cross the organizational boundaries and provide a unique opportunity for teamwork and workflow automation among otherwise isolated entities. Characteristics of this new model-centric approach are centered on the concepts of ownership, accessibility, availability, and timeliness of information together with the notions of process digitization, integration, and optimization. This paper discussed five objectives that are envisioned to enable the transformation of the AEC industry to a model-centric industry, namely: 1) Formalize the development, integration, and use of models; 2) Provide an enduring, authoritative single source of truth; 3) Integrate technological innovation; 4) Establish a supportive infrastructure and environments to collaborate and communicate across stakeholder; and 5) Transform the culture and the workforce to support the transformation. On the other hand, these objectives cannot be achieved, without trying to mitigate the five identified constrains. First the stakeholders and their needs must be established, second a central model must be generated which provides different viewpoints to the different stakeholders. Advanced technology can be implemented to create and exchange knowledge and analyse data. Collaboration and integration will lead to change the silo culture in the AEC industry. Finally, the human aspect and training needs and support must be emphasized to achieve lasting change. While this research investigates the feasibility of a model-centric transformation in the AEC industry from a broad perspective, future research could elaborate on the objectives and considerations presented in this paper and provide a more focused and technical assessment of such transformation.

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