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Industry 4.0 Applications for Full Lifecycle Integration of Buildings

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Preface

Welcome to the 21st International Conference on Construction Applications of Virtual Reality (CONVR 2021). This year we are meeting on-line due to the current Coronavirus pandemic. The overarching theme for CONVR2021 is " Industry4.0 Applications for Full Lifecycle Integration of Buildings".

CONVR is one of the world-leading conferences in the areas of virtual reality, augmented reality and building information modelling. Each year, more than 100 participants from all around the globe meet to discuss and exchange the latest developments and applications of virtual technologies in the architectural, engineering, construction and operation industry (AECO). The conference is also known for having a unique blend of participants from both academia and industry.

This year, with all the difficulties of replicating a real face to face meetings, we are carefully planning the conference to ensure that all participants have a perfect experience. We have a group of leading keynote speakers from industry and academia who are covering up to date hot topics and are enthusiastic and keen to share their knowledge with you. CONVR participants are very loyal to the conference and have attended most of the editions over the last eighteen editions. This year we are welcoming numerous first timers and we aim to help them make the most of the conference by introducing them to other participants.

Middlesbrough, UK
December 2021

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Built environment has been perennially caught up in low productivity conundrum for a long time. This is despite its significant impact on industrial employment (i.e. over 6.6% contribution) and representation of 9.8% of the UK's Gross Domestic Product (Rhodes, 2019). Poor collaborative processes through effective information exchanges has been identified as a major reason for this (Crotty, 2013; Kumar, 2015). Besides, the knowledge gap between design and construction has also been cited as a major contributor to this discontinuity (Abrishami, Goulding, Rahimian, & Ganah, 2014; Fruchter, Herzog, Hallermann, & Morgenthal, 2016; Jack S Goulding & Pour Rahimian, 2019; J. S. Goulding, Pour Rahimian, Arif, & Sharp, 2015; Pour Rahimian, Chavdarova, Oliver, Chamo, & Potseluyko Amobi, 2019; Pour Rahimian, Ibrahim, & Baharudin, 2008; Pour Rahimian, Ibrahim, Rahmat, Abdullah, & Jaafar, 2011).

Over the years, leading experts from industry and academia (Egan, 1998; Latham, 1994) have contributed to the dissection of the drivers behind this and suggest solutions to address these issues. However, it has taken major developments in digital technologies like the internet, project extranets, building information modelling (BIM), IoT among others to generate the kind of optimism that the industry has never experienced before. Built environment is not alone in sharing the excitement around these technologies. These technologies have captured the imagination of just about every industrial sector. Of course, no technology can result in addressing the challenges of any industry on its own. A set of complimentary processes (Goulding et al., 2015; Kumar, 2015) need to be developed in tandem for the technologies to be effective enablers of change. Quite encouragingly, such processes have been developed recently particularly in relation to information management and collaborative working in the built environment sector. These are positive developments and whose veracity and effectiveness will be tested over the next few years.

Meanwhile, the wider world (including the built environment) is experiencing a kind of paradigm shift due to the emergence of the industry 4.0 revolution. Recent technological and other process-based advances and innovative technologies in the built environment mentioned above have a key role to play in this process. As widely reported in the popular and scientific media, the nine pillars supporting Industry 4.0 are 1) The Internet of Things, 2) Big Data, 3) Augmented Reality, 4) Advanced Visualisation, VR and Simulation, 5) Additive Manufacturing, 6) System Integration, 7) Cloud Computing, 8) Autonomous Systems, and 9) Cybersecurity.

In case of the built environment sector, these nine pillars can be said to be underpinned by BIM, widely regarded as the tool of choice to address key issues as industry fragmentation, value-driven solutions, decision making, client engagement, and design/process flow to name but a few. Therefore, it could be argued that the Construction 4.0 has ten pillars which includes the nine Industry 4.0 pillars and BIM. Exemplars from other industries such as automotive, aerospace and oil and gas currently demonstrate the power and application of these technologies. However, built environment has only just started to recognise terms such as "golden key" and "golden thread" as part of BIM processes and workflows. Construction 4.0 offers a portfolio of potential solutions to bridge the knowledge and information gaps between design, construction and operations (Newman et al., 2020; Sawhney, Riley, & Irizarry, 2020).

This has led to the emergence of a series of cutting edge technologies in the AEC realm including but not limited to virtual reality-based collaboration technologies (Pour Rahimian et al., 2019), artificial intelligence-based optimisation (Pilechiha, Mahdavinejad, Pour Rahimian, Carnemolla, & Seyedzadeh, 2020), data-driven decision support (Seyedzadeh, Pour Rahimian, Rastogi, & Glesk, 2019), smart data modelling (Pilechiha et al., 2020), blockchain and distributed ledger technologies (Elghaish, Abrishami, & Hosseini, 2020), and computer vision and graphics (Moshtaghian, Golabchi, & Noorzai, 2020; Pour Rahimian, Seyedzadeh, Oliver, Rodriguez, & Dawood, 2020). Where for example, these advancements are now able to assist decision-making to predict the cost and performance of optimal design proposals (Elghaish & Abrishami, 2020).

Advancements in cryptography and read-only data management optimisation are paving the way for fully-fledged distributed ledger technologies for digital twinning and asset lifecycle management. Previous research has demonstrated real-time centralised solutions for OpenBIM. Collectively, these developments are forcing a paradigm shift in design from asynchronous to real-time data exchanges which are impervious to repudiation, ultimately improving interorganisational perceptions of social presence (Oliver, 2019) and imbuing confidence in the design shift expected of OpenBIM.

This not only highlights the need to become more connected, dynamic, and customer-centric, but more importantly, mechanisms through which future AEC business will need to operate. This includes the need to think about new business strategies and models – from design to procurement and delivery, even the way goods are produced and delivered. Successful companies will be those that unleash their true potential, using business models that drive innovation and deliver evidence-based value. Those that do not do this will (more than likely) fall by the wayside. Therefore, AEC organisations will need to be highly competitive (perhaps more so than they are already), using factories and warehouses (physical and virtual) to leverage economies of scale (and expertise) to become much more streamlined, agile, and efficient. In doing so, they will be able to establish several new services and opportunities, especially through the deployment of cloud computing, big data, visualisation, artificial intelligence, machine learning, the internet of things, blockchain, etc. Data will undoubtedly be seen as the main asset not only to inform decision-making, but also to drive innovation and facilitate continuous improvement. This will also enhance customer-experience analytics, providing new end to end services and servitisation opportunities; where, for example, significant growth-driven potential has already been evidenced in other sectors. In summary, the inertia underpinning Industry 4.0 provides AEC with many powerful opportunities to explore, nurture, and exploit. Some of these opportunities are presented throughout the following papers.

CONVR is one of the world-leading conferences in the areas of virtual reality, augmented reality and building information modelling. Each year, more than 100 participants from all around the globe meet to discuss and exchange the latest developments and applications of virtual technologies in the architectural, engineering, construction and operation industry (AECO). The conference is also known for having a unique blend of participants from both academia and industry. The overarching theme for CONVR2021 is " Industry4.0 Applications for Full Lifecycle Integration of Buildings."

This proceeding brings together twenty-two papers related to industry4.0 applications in construction. In part one of the proceeding, an introduction has been given. In addition, papers have been presented. (Disney, Johansson, Roupé, Sundquist, & Gustafsson, 2021) explored the applications of AR in the construction project life cycle. (Disney et al., 2021) investigated the prerequisites for – and outcomes of – implementing the Total BIM concept, where commonly found individual and isolated BIM uses is turned into an all-inclusive approach to achieve a more efficient design and construction process. (Bokde, Johansen, Wandahl, & Teizer, 2021) proposed the concept of a Digital Twin framework to track, monitor, predict, and reduce construction emissions (DTCE). (Mudiyanselage & Luo, 2021) focused on developing a comprehensive construction safety knowledge assessment for students of construction-related disciplines. (Mahamadu et al., 2021) reviewed the existing research evidence regarding application of eye-tracking technology in Architecture Engineering and Construction industry (AEC) through a systematic review. (Rashidi, Yong, Fang, & Maxwell, 2021) uncovered unique experimental findings by integrating 4D-Building Information Modelling to Virtual Reality (VR) technology during construction planning among construction professionals at Light Steel Framing (LSF) projects in Malaysia. (Ozorhon, Ozcan-Deniz, & Gurunlu, 2021) investigated the critical success factors (CSFs) for BIM implementations in the design phase by using a project-based framework. (Adebowale & Agumba, 2021) reviewed areas that Augmented Reality technologies (ARt) could contribute to productivity growth in construction projects. (Agarwal, Nirjhar, Behzadan, & Chaspari, 2021) investigated the effectiveness of personalized, adaptive, and bio-behaviourally aware in-the-moment feedback, administered in a virtual training environment, for mitigating speaking anxiety and achieving successful interpersonal communication. (Schiavi, Havard, Beddiar, & Baudry, 2021) introduced a system allowing the semi-automatic creation of operating procedures scenarios in virtual reality through the exploitation of 4D BIM and procedural knowledge. (Godfred Fobiri, Musonda, Muleya, & 2021) explored the extent of research on reality capture applications in the built Environment to establish the roadmap for further investigation. (Hosseini, Hodkinson, Jupp, & 2021) offered an account of the initial stages of a research project with the aims of developing a proof of concept (PoC) for an automated roadmap generator, to assist Australian companies in their transition from traditional methods of asset management to digital ones – enabled by BIM and DE – DAM. (Alieh, Hosseini, Martek, & Jupp, 2021) assessed both the current status of BIM competencies among university graduates and explores how BIM education at Australian universities may be further improved to deliver BIM Work Readiness (BWR), as required by the industry. (Alani, Trejo, Dawood, Hafeez, & Dawood, 2021) used Semantic Web Technologies to address product information capture and validation by proposing a common-model semantic library for phase-specific data exchange. (Pidgeon & Dawood, 2021) explored the current availability of BIM measurement systems, processes, and toolsets as well as their limitations and opportunities for development through the utilization of a two-phase data collection and analysis approach. (Ogunseiju, Gonsalves, & Akanmu, 2021) presented the use of eye-tracking and think-aloud data to demonstrate the potentials of machine learning for detecting learning stages and interaction difficulties from eye-tracking data during the usability study of laser scanning in the mixed reality environment. (Gonsalves, Ogunseiju, & Akanmu,

2021) investigated the potential of automatically recognizing construction workers' actions from activations of the erector spinae muscles. (Chauhan, Elghaish, & Brooks, 2021) developed a workable and simpler framework for BIM professionals and developers to use Alexa as a voice assistant for data manipulation in a BIM model and information retrieval from it. (Ehab Sayed, Kumar, & Greenwood, 2021) considered the industry's readiness for such transformative technologies and business models. (Reyes-Veras, Renukappa, Suresh, & Algahtani, 2021) identified the strategies that would allow the adoption of Big Data in the construction industry of the Dominican Republic. (Burfoot, Naismith, Ghaffarianhoseini, & Ghaffarianhoseini, 2021) conducted a BIM-based acoustic simulation for the first time using the novel intelligent passive room acoustic technology (IPRAT) in classrooms.

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Application of Augmented Reality in the Life Cycle of Construction Projects

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Abstract: *The construction industry plays a significant role in relation to other industries, and thus it vividly reflects various advancements in other areas. Increasing complexity in projects require construction companies to employ innovative solutions to grow. These techniques and tools, including simulations, augmented reality (AR), virtual reality (VR), drones, and image processing, have revolutionized the construction industry over the past two decades. AR is used as a new and emerging technology in various stages of construction projects. Several researchers in multiple contexts have defined AR. However, there is a gap that integrates these definitions and their applications. The purpose of this study is to explore the applications of AR in the construction project life cycle. Throughout the project life cycle, seven major groups of AR applications were identified, including a shared work environment, integrated simulation, automated processes, technical controls, management controls, and analysis tools. Each of these groups was further mapped out in a matrix to display the detailed use of AR along with relevant entities following the RIBA, FIDIC, and PMBOK standards. The structured AR application model provides construction educators and professionals with a road map to plan for training, logistics, and communication throughout the life of construction projects.*
Keywords: *Augmented Reality, Project Life Cycle, Construction*

1. INTRODDUCTION

Over the years, AR has been defined by several researchers in various contexts. One of the definitions accepted by Azuma states that AR has three basic characteristics: (1) it combines both reality and virtual content in the real world; (2) it is executed in real time; (3) it is recorded in three dimensions (Imad A Khalek, 2019). Technologies in the construction industry have greatly improved the efficiency of projects and are constantly growing. In the information and technology industry, construction companies need to improve their productivity. AR as a new and emerging technology produces several items. Opportunities arise through the use of AR in the manufacturing industry. Increasing productivity, improving coordination and cooperation, as well as the quality of work and safety of workers in each country occurs at the stage of the life cycle (Imad, 2019). Construction is a large, complex, and time-consuming process that involves many parallel activities. From the initial design stage to the demolition of the structure, many activities are carried out that waste resources, time, money and damage the environment (Elshafey C. S., 2020). Technologies are always emerging and facilitating engineering. One of these technologies in the field of construction is the use of AR and modeling of construction information, which have several advantages in the project life cycle, for example: 1) Reducing decision time in Design stage; 2) Better understanding of documents in the planning stage; 3) Monitoring the implementation of the project and its compliance with the intended purpose. AR technology introduces new ways to present knowledge. AR can enhance the user’s perception of a real situation (Hernandez B. , 2018).The design process consumes a lot of time and money, but by modeling construction information, all stakeholders can be in the same environment and can be simulated with the help of AR and VR Advanced (Lina, 2018). AR has many applications in architecture and engineering. The implementation of AR on building information models has many applications. Inaccuracy in the project will increase time and cost, which is due to not using a proper method to control the progress of the project (Christian Koch M. K., 2014). There is a lot of competition in the market right now, so construction companies and other people involved in the industry need to use new methods and technologies in their projects. Methods that are both appealing to their clients and retain numerous benefits for them. In the last few years, AR has attracted a lot of attention. Against this backdrop, the present article aims to categorize the advantages of AR and show the advantages and applications that AR has in the life cycle of construction projects (design to demolition). In this study, about 60 articles have been evaluatedand the seven general advantages of AR are identified, then the opportunities that arise through these seven advantages are explored. These advantages have many applications in the life cycle of construction projects, such as conceptual design, identification of defects and shortcomings, change management, etc.

2. LITERATURE REVIEW

2.1. AR in lifecycle of project

AR and VR technology during the project, including design, implementation, and maintenance information (temperature, light intensity, humidity, etc.) are taken from objects and use an AR environment (Natephraa, 2019). One of the most important steps in construction is the operation and maintenance phase, which is the longest and most expensive phase. Engineers must provide a comfortable living and working environment for residents and prevent possible breakdowns. There is a way to do this easily with the use of AR (Koch, 2014). Modeling building information on the site by AR platform has a tremendous impact on increasing communication and information sharing (Wang L., 2012). The use of AR and modeling of construction information is effective in the piping repair and maintenance phase. Two-dimensional drawings of the work performed are different and it is also not possible to inspect behind the walls, so by modeling construction information and using it in AR helps a lot in the maintenance phase (Shih, 2019). The results show good user acceptance and strong potential for the use of construction information, modeling data, and AR augmented solutions in building maintenance as well as other building life cycle applications (Woodward D., 2014).

2.2. AR and visualization

The evolved 3D model enables stakeholders to have a higher understanding of the project and make better and more informed decisions, and is also a useful tool for monitoring project progress as well as evaluating project quality (Vincke, 2019). AR helps to implement and visualize the model at the project site. Implementation and visualization of large-scale models are used on the site and the interior design system, as well as visualization of past buildings in the historic site. AR can also be used to maintain buildings (Woodward D., 2014). To provide a platform for modeling information and AR and its acceptance by stakeholders, providing pre-use training will be significantly effective (Elshafey S. A., 2020).

2.3. AR and information

AR allows you to query and update building information. VR is the visualization of 3D models with VR screens to simulate different scenarios and is therefore used in the AECO industry (Chen, 2020). AR and VR help a lot in the development of structured information modeling because in all project’s stakeholders are side by side and maybe from different countries. VR helps them navigate the project environment and analyze issues together. It is also effective in increasing worker safety, as it allows workers to be trained and experienced before entering the project environment, so project performance and management are very effective (for example, how to position themselves during welding). Trainees show to be 23% faster than usual and develop better muscle memory and patterns. AR can significantly reduce the cost and time of the project, as well as the activities related to the project site and control (Salem, 2020). The information of a building is constantly increasing and we are facing an increase in information, so we need a tool for visualizing information and easier access (Hakkarainen, 2018). Errors occur during the construction project. There is a large amount of information that may be lost or misinterpreted. Information modeling and AR work very well in sharing information and improving communication (Berto, 2014).

2.4. AR and manage

AR can be used to manage the site. It is also used for easy access and interactivity. With AR, accurate features and specifications can be specified on the project site, which makes the decision easier and better. The design is done by modeling the construction information, i.e., the specifications of the geometry, etc. are determined and then it will be determined by the AR of the connections (Wang P. L., 2017). Quality management during the project can be done by AR and modeling of construction information and many implifications are eliminated. There is a common digital environment between stakeholders so that those involved in project quality management have constant access to up-to-date information. This environment reduces time, reduces reprocessing, and makes easier decisions (Mirshokraei, 2019).

2.5. AR and decide

In their research, they point out that integrating construction information modeling with XR (AR, VR, MR) is not only helpful in project design but can also be used and useful in the maintenance phase. It is also very remarkably effective in reducing time, cost and increasing safety and quality. (Alizadehsalehia, 2020). AR is used to plan the layout of the site, which makes it easier to decide on the layout of temporary facilities. This system goes beyond the visualization of three-dimensional space and helps a lot in the planning process. AR and Information Modeling Platform is a convenient platform for virtual design and planning, allowing the inexperienced to use the experience and optimizing layout allocation (Singh, 2018). Decisions made early in the design phase can have a major impact on facility maintenance. AR allows users to follow up to determine why an area is difficult (Khalek, 2019). Using AR and modeling of fabrication information, the thermal environment can be simulated, making comparisons and decision-making easier (YokoiI, 2017).

3. METHODOLOGY

The purpose of this study is to answer the question of what are the benefits of AR in the life cycle of construction projects. To find the answer to the research question, various AR articles and their applications in construction industries were searched. The first articles with keywords: AR, Application of AR in Architecture, Application of AR in Civil Engineering, Application of AR in the Life Cycle of Construction Projects, AR Benefits, were searched. The articles found in the search were read as abstracts to identify the relevant articles. The relevant articles were then identified and the contents of the articles were analyzed and classified. These findings were then analyzed and discussed based on the benefits and opportunities of AR about 60 articles have been reviewed.

3.1. Criteria for search in the journals

To make the selection of articles that were as relevant as possible, the following criteria was used when searching the journals:

- Articles published in the period 2013-2020
- Articles with key word: AR, Application of AR in Architecture, Application of AR in Civil Engineering, Application of AR in the Life Cycle of Construction Projects, AR Benefits.
- After initial search the abstract of all articles was read, articles which did not relate to AR although it was mentioned were removed from the list.

3.2. Classification of parameters found in the articles

Selected articles were thoroughly read to identify the benefits of AR. Seven benefits of AR were identified, and then these benefits were further analyzed to identify the opportunities that arise through them in projects.

3.3. Search for construction project lifecycle standards

Finally, according to the review of these articles, seven main advantages for AR were defined, each of which creates opportunities in the project. Then, using the standards of RIBA, FIDIC and PMBOK, a life cycle with full details (activities of each stage) was defined and it was determined that according to recent research, in what stages of the life cycle is it used.

The life cycle of construction projects

Project phases and life cycle from PMBOK

According to the PMBOK (Project Management Group) guide by the Project Management Institute (PMI), the project management life cycle consists of five distinct stages, including initiation, planning, execution, monitoring, and closure, that turn a project idea into a product. Table 1 shows 5 basic phases of project management from PMBOK.

Table 1. Basic phases of project management (PMBOK)

1) Define project goals 2) Create a business case 3) Completion of the project charter	Initiation
1) Define scope 2) Create a project plan 3) Set a budget baseline 4) Definition of roles and responsibilities	Planning
1) Resource allocation 2) Resource management 3) Build a process or product 4) Meet often and fix issues they rise	Execution
1) Track effort and cost 2) Monitor project progress 3) Ensure adherence to plan 4) Prevent any chance for disruption	Monitoring and control
1) Handover deliverables 2) Review project deliverables 3) The result of the project 4) Document project learnings	Closure

Project phases and its life cycle from RIBA

The Royal Institute of British Architects (RIBA) is an association of architectural professionals operating both in the UK and internationally. The institute was founded in 1834 by several prominent British architects and its mission is to support buildings, associations and environments related to architecture. Figure 1 shows a plan of work from RIBA. Table 2 shows life cycle stages from fidic.

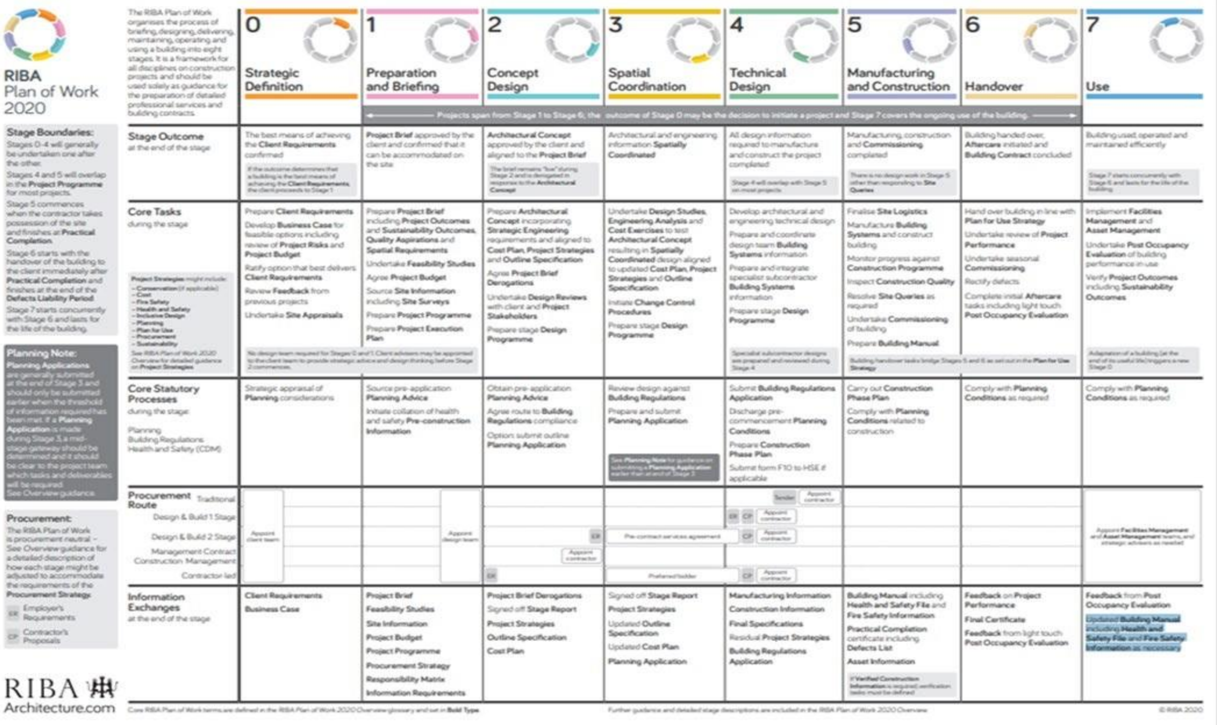

Figure 1. Plan of work (RIBA)

Project phases and life cycle from FIDIC.

Table 2. Life cycle stages from fidic

1. Definition of Services	8. Construction
2. Concept and Predesign	9. Commissioning and Facility Acceptance
3. Schematic/Preliminary	10.Full Occupancy and Utilization
4. Developed Design	11.Operation
5. Construction Documentation	12. Maintenance
6. Permission/Permits	13. Refurbishment
7. Procurement Contractor Engagement	14. Decommissioning

4. AR BENEFITS

In this table (table 3), level one is the advantages that are created if AR is used in the project, and the second level is the opportunities that are obtained through the advantages:

4.1. Shared work environment

AR can create a shared platform that helps manage and exchange all project-related data. This platform can be supported and used on all mobile devices. Building information models can be obtained on mobile phones and tablets via AR to help construction shareholders improve the quality of work during the construction process (Elshafey S. A., 2020).

Table 3. AR benefits

First level	Second level
Shared work environment	Information sharing
	Reduce redundancy
	Telecommuting (physical)
	Increase coordination
Integrated simulation	Review of executive-design changes
	Visualization of information
Automated processes	Real-time data retrieval
	Easy access to the model
Technical control	Advanced Report Tracking
	Project Control
Management controls	Reduce time
	Reduce cost
	Improve quality
	Improve communication
	resource management
Safety	Education
	Increased experience
	Proper planning
Analysis	Easy decision making

Information sharing

Modeling information-building on site by AR platforms has a huge impact on increasing communication and information sharing, for example information exchange between architects and engineers on site (Berto, 2014) (Wang L. , 2012).
AR allows us to provide an environment where we can share visualized designs remotely and collaborate in real time. (Lee, 2020)

Reduce redundancy

There is a lot of information that may be lost or misunderstood. AR works very well in sharing information and improving communication (Berto, 2014). There is a common digital environment between stakeholders to have constant access to up-to-date information. This environment reduces redundancies (Mirshokraei, 2019).

Telecommuting (Physical)

In all projects, the stakeholders are side by side and may be from different countries, but with the AR platform, they can collaborate and make decisions regardless of their distance (Salem, 2020). AR uses knowledge such as graphics, audio files, and videos to exchange knowledge between remote professionals (Nassereddine, 2020). The remote expert system connects an on-site technician with one or more specialists sitting in their office. The person at the construction site has a small pair of glasses and a video camera (DOKA), and specialists have remote access to a live video stream from the construction site and can transmit written or audio recommendations (Nassereddine, 2020).

Increase Coordination

There is AR as an effective visual platform to increase collaboration and coordination between team members. The effectiveness of AR in improving team collaboration is demonstrated and team interaction created. The proposed models help to minimize verbal explanations and discussions among team members, thus reducing the communication gaps that typically exist in such processes (Singh, 2018; Khalek J. M., 2019).

4.2. Integrated Simulation

AR consists of three main elements: 1) 3D recording; 2) Composition of reality and virtual reality; 3) Interaction with real-time. 3D recording is the process of adding virtual objects to the real environment in a precise position, which is the basis of AR technology. The exact process of placing the model in the correct position at the construction site is a three-dimensional recording. And the process of integrating the builder and model site into this virtual space is a combination of reality, which provides a new environment for the user to experience more realistic visual effects and more abundant scene information (Ren L. Z., 2016).

Review of executive-design changes

AR can help identify and validate areas where 3D design information does not integrate well with existing structures or construction information. For example, when mechanical and electrical design overlap (M&E) does not properly match steel structure (Ren L. Z., 2016). Users can try and change different options on the project site using the object server. The use of AR in projects makes it easier to make corrections and make changes (Lee, 2020). Using AR, the constructed structure is visible before the workers start working. Employers and architects can view the entire building from any angle and in real dimensions, and find design problems, and can quickly and easily make changes to the design without causing financial or physical damage to the construction operation (Tretyakova, 2019).

Visualization of information

AR in the implementation and visualization of the model on the project site (site) helps to see the result before the start of the project and visualizes the needs of the building and better understanding of the stakeholders (Nassereddine, 2020; Woodward K. P., 2014; Singh, 2018; Ahmed, 2017; Seung Kim, 2013).

4.3. Automated processes

The platform consists of four modules: Information Integration Module, Display Module, Positioning Module and Manipulation Module. The information integration module is used to transfer information from the model to the images to enable on-site retrieval. The location module enables users to enter their location and automatically search for the images they need. The manipulation module can evaluate users' movements from the touch screen and accelerometer on the devices and then use image cropping to eliminate unnecessary information. The module display, which connects directly to the projector, can continuously calculate the images processed by the previous three modules and scale the images accordingly. (Yeh & Kang, 2013)

Real-time data retrieval

AR has the potential to improve on-site information extraction, on-site retrieval of information is one of the problems of construction projects. With the AR platform, information can be generated automatically and used in real time (Nassereddine, 2020; Yeh & Kang, 2013). AR can eliminate paper designs and the builder will be fully mechanized and automated so that workers are rarely present at the site (Ren L. R., 2016). Improving the integrity of information, smart documents, access to distributed information and retrieval of building data are added to the benefits of reality (Wang P. L., 2017).

Easy access to the model

AR can change the way a building is built. Workers can use headsets like the DAQRI Smart Helmet at work and keep an eye on the construction plans they need to run and easily place materials and equipment in the right place without the need for paper drawings, which eliminates the need for paper or digital maps and project site specifications. Using this platform prevents engineers from carrying large building plans to the site and spend less time finding the plan they want (Yeh & Kang, 2013).

4.4. Technical control

AR is presented as a mechanism to increase the process of extracting information from the building. Comparison of manual information retrieval methods (control group) with information retrieval through artifact (non-control group). The results showed that participants were approximately 50% faster using artifacts, and made fewer errors than the manual method (Chua, 2017).

Advanced report tracking

Using AR combined with visual equipment and related intelligence, inspectors can navigate to their target locations and find their target easier, safer, and cheaper. Inspectors can add virtual photos or notes in one place, as well as share them across multiple devices, making it much easier to monitor progress (Salem, 2020; Nassereddine, 2020).

Project Control

Due to AR, the control is much easier by the employer because he can compare digital images with real images. In other words, it can compare the status of the project with the planned status (Tretyakova, 2019).
The advantages of AR include the discovery of design errors and the analysis of spatial conflicts and scheduling before construction, assembly, and installation (Wang P. L., 2017). First, the project manager must capture a true picture of the current work situation and upload real site data such as noise, site images, animation data, and so on. They are sent to a web server which is augmented by VR and AR data. If the project manager receives this data, at this time, the differences between the planning data and the actual data can be seen in an AR object. It can be useful for site engineers to understand current progress by comparing scheduling (Kim, 2017).

4.5. Management controls

Given the benefits of AR, its use creates managerial opportunities throughout the project life cycle.

Reduce time

The time difference is one of the main concerns in construction. Due to various and complex factors, the construction process usually deviates from the planning. The use of AR can help to solve this problem; for example: reducing the time of decisions in the design phase, constant access to up-to-date information, reducing complexities will reduce time (Singh, 2018). There are errors during the construction of the project, such as miscalculation, misreading of drawings, etc., which can be avoided by using AR. As a result, there is no time to correct the error, which saves time (Seung Kim, 2013; Forren, 2019; Mirshokraei, 2019; Hernandez X. B., 2018).

Reduce costs

The use of AR in cost management is also very effective; for example, many redundancies are reduced, project safety is increased, the amount of paperwork is reduced. Also during the design, the maintenance phase can be considered, which will reduce costs. For example, a number of factors such as accessibility, cleaning and replacement of components, and determination of parts are all influenced by the decisions made in the design phase (Alizadehsalehia, 2020). With AR, the cost and time of the project can be significantly reduced (Salem, 2020; Dallasegaa, 2020).

Improve quality

Quality management during project implementation can be done by AR and many simplifications are eliminated (Mirshokraei, 2019). Investigating quality and controlling it by comparing physical components as constructed components with AR models as programmed components. Construction workers are guided by AR through the construction of real buildings, helping to improve the quality of their work,better quality control, and faster daily reporting (Wang P. L., 2017). Quality assurance starts with the customer defining his needs andis the basis for the design team to define the specifications. To understand elements that are made with quality and compliant with standards, characteristics, quality parameters, and quality control activities must be determined along with when they should be controlled. All this information leads to a quality control plan that is the basis of quality control. After integrating the qualitative information, a quality model will be obtained that will be distributed among the project stakeholders, which will be the basis of on-site inspection by AR technology (Vincke, 2019).

Improve communication

In reconstruction projects, design communication is also difficult because most works are presented in two dimensions. AR, unlike VR, makes visualization possible on the site. AR can be used on the project site to present work realistically. Users can try and change different options on the project site using the object server, so communication is done visually and interactively (Lee, 2020; Berto, 2014). Each worker can play their role by drawing information from a model through AR and can examine their work interaction with others and see the support of effective communication (Wang P. L., 2017).

Resource management

The construction life cycle is a large, complex, and time-consuming process that involves many parallel activities. From the initial design stage to the demolition of the structure, many activities are carried out that lead to a waste of resources. The use of AR in projects reduces human resources, so any mistakes and carelessness are eliminated. It also makes informed decisions about resource allocation (Wang P. L., 2017; Tretyakova, 2019).

4.6. Safety

Before starting, a worker with AR can visualize environmental safety instructions (e.g., altitude checklist, machine operation safety) (Wang P. L., 2017). The allocation of storage space, which is an important safety concern, must be planned in advance and specified in the building design diagrams. Due to the complex arrangement of mechanical equipment and the limited access to the adjacent open space, the access space to the pipes may not be large enough. To prevent unexpected damage, a path with clear signs and free of unforeseen obstacles should be provided with proper visibility of the updated location of the storage space. AR, using complex geometries facilitated and integrated with information and reality, can turn 3D models into an environment for project workers to maintain. (Shih, 2019)

Education

AR is used successfully in workers' education. AR is also used to train architects and engineers, and specialists for complex maintenance in construction systems (Wang P. L., 2017).

Experience

AR provides a more advanced and accurate real-time experience (Jishtu, 2020). AR can also help inexperienced workers. For example, DOKA molding company is developing a mold validator for its Farmi system. This system checks the components and if they are done correctly, they are displayed in green and if not, in red (Nassereddine, 2020). The AR platform is a convenient platform for virtual design and programming, allowing the inexperienced to use the experience and optimizing the layout allocation (Singh, 2018). The use of AR helps architecture students to learn better and gain experience (Abdullah, 2017).

Proper planning

If conflicts are not resolved in a timely manner, the plan will not go well and work will gradually gather to affect the project safety plan (Singh, 2018). The allocation of storage space, which is an important safety concern, must be planned in advance and specified in the building design diagrams. Due to the complex arrangement of mechanical equipment and the limited access to the adjacent open space, the access space to the pipes may not be large enough. To prevent unexpected damage, a path with clear signs and free of unforeseen obstacles should be provided with a proper view of the updated location of the storage space, which is done by AR (Shih, 2019).

4.7. Analysis

Changes in the external environment usually lead to a domino effect, AR will solve this problem effectively. It will optimize model-based simulation analysis. In addition, it will maximize the life cycle of data flow, enhance information usage and improve productivity at various stages, and provide users with smart analysis and decision making (Ren L. R., 2016). AR helps to analyze information and data. Detection of design errors and analysis of spatial conflicts and scheduling prior to construction, assembly, and installation (Wang P. L., 2017). AR has the ability to add or remove mediation processes; for example, the use of AR can replace data processing and analysis of manual processes (Nassereddine, 2020).

Easy decision making

The evolved 3D model enables stakeholders to have a higher understanding of the project and to make better and more informed decisions (Vincke, 2019). AR combines digital information with the real world to allow better plans and decisions to be made. Ar has the ability of analytics to make decisions and improve information analysis. The use of AR improves decision-making and reduces its time (Nassereddine, 2020). Decisions made early in the design phase can have a major impact on facility maintenance. AR allows users to follow up to determine why an area is difficult (Khalek, 2019). AR-based design increases customer satisfaction because design decisions are made according to customer needs and user support is one of the keys to design satisfaction even in the early stages of design (Lee, 2020). With AR, the actual scale of a 3D model can be moved to its final proposed location, giving all project stakeholders an appropriate interpretation of the scale of objects. This information can help support decision-making processes that actually make cost savings on construction and building materials components a reality (Khalek, 2019). AR is used to plan the layout of the site, which makes it easier to decide on the layout of temporary installations (Singh, 2018). AR can be used to simulate the thermal environment, making comparisons and decision-making easier (YokoiI, 2017).

5. AR IN PROJECT LIFE CYCLE

At this stage of the research, using the standards mentioned above, a life cycle with activities related to each sector has been defined, which has been evaluated by reviewing AR application articles in each of the sectors.

5.1. Project Planning

In the project planning part, a worker has received safety training before entering the site by AR. AR can also be used to analyze what kind of building materials, how much is delivered, how much is stored, and when it is stored (Wang P. L., 2017). By integrating AR with other technologies such as scanning and GIS technology, the project team can gain accurate information about the project, such as volume and location. Information accuracy in conceptual planning will be extracted from the domain defined in this step as detailed design drawings, cost estimation, planning and cost control (Ren L. R., 2016). In the field of design,AR experts gather together and achieve the desired physical form, and also the interaction of materials with each other contributes to the ecological concept of design (James FORREN, 2019). The final design of the project site can give customers a better spatial understanding of how the design fits with the existing facilities and change it with customer satisfaction. Detection of design errors and analysis of spatial conflicts and scheduling prior to construction, assembly, and installation. Construction and pre-construction processes make short-term planning more precise, leading to a shorter construction process with reduced delays and lower demand for material buffers. AR turns architectural and structural drawings into a three-dimensional image, and it is on a real scale that helps to identify errors quickly and efficiently (Wang P. L., 2017). AR is used to plan the layout of the site, which makes it easier to decide on the layout of temporary facilities. This system goes beyond the visualization of three- dimensional space and helps a lot in the planning process and optimizes the layout allocation (Singh, 2018).

5.2. Project implementation

Attempts to create mental models can be reduced through AR because models are imaginable. For example, executing the resulting program (work tasks), and reprogramming activities can all be performed using AR. AR can be an active approach in which the potential negative effects of any action can be identified and mitigated beforehand, or easily avoided (Singh, 2018). AR eliminates errors caused by technical and human errors during construction (Agarwal, 2016). Also, AR makes informed decisions about resource allocation and dynamic regulation and on-site discussion and coordination between different parties on the site before immediate construction. For example, on-site exchange of information between architects and engineers (Wang P. L., 2017). The use of AR increases the efficiency of construction execution and reduces cost and time, increases quality and reduces resources, and also creates sustainability factors in the project (Dallasegaa, 2020). Collisions occur during the actual construction process due to reasons such as changes in building elements, site facilities, and the movement of construction machinery. The challenge is to determine the real-time dynamic collision detection of the site due to changes in the construction sequence, timing, components, and methods. Thus, the use of AR enables the site administrator to display conflicts on the site by retrieving and visualizing all the features and details of the building elements, such as, Mechanical Revit and Power Plant (MEP) (Singh, 2018).

5.3. Monitoring and control

AR can significantly improve overall performance bymonitoring the status of the site through documentation activities. AR can be integrated with the factory before construction. This can improve logistics efficiency, on-site material control, and overall tracking of project progress (Singh, 2018). Modifications (change management): When we are on a site and we want to remove a wall, we measure and compare them with the main programs. When we are physically present, we can easily engage with what we see on the site and feel better about continuous improvement. AR may be the closest we can get without laying a brick. This gives an extra degree of flexibility at the planning stage. By making major changes, such as removing the wall, AR allows users to view the interior and exterior views of a structure, so that engineers can find the components and move them around with just a few taps on their devices (Vincke, 2019; Hernandez B. , 2018; Chen, 2020).

5.4. Operation

AR information can be used in building life cycle applications such as maintenance. The three-dimensional representation of the building can act as a platform for linking various other information, for example building management systems (Hakkarainen, 2018). The use of AR is effective in the piping repair and maintenance phase. Two-dimensional drawings of the work performed are different and it is also not possible to inspect behind the walls, so modeling and using it in AR helps a lot in the repair and maintenance phase (Shih, 2019).

Most studies focus on the construction phase, followed by design evaluation, monitoring process, maintenance and operation (Chen, 2020). Among the various construction stakeholders, engineers/architects make the most of AR. Most used in design, pre-construction planning, construction and conceptual planning (Nassereddine, 2020).

6. DISCUSSION

AR can be used in the construction project as one of the construction information modeling cases. AR technology can be used to create a real construction model by overlapping virtual object data against the real background of the project site on a computer. AR visualizes building information needs, thus providing better coordination and understanding among project stakeholders. The use of AR is expected to reduce errors and save time (Jishtu, 2020). Opportunities are created through the construction of information and AR modeling during the planning, design, construction, and maintenance phases that will improve the AEC industry. AR can lead to the elimination of paper designs, and the builder will be fully mechanized and automated so that workers are rarely present at the site (Ren L. R., 2016). The use of AR in projects makes: 1) Work control by the employer much easier because it can compare digital images with real images. 2) Human resources are reduced so any mistakes and carelessness are left out. 3) Apply changes and make decisions and make corrections easier. 4) The possibility of higher productivity. In general, AR improves construction technology (Tretyakova, 2019). AR is used successfully in construction project planning, progress tracking, worker training, safety issues, time and cost management, quality and defects. VR is used as a tool for visualization, worker training technologies, safety management tools and quality and defect management tools in this study. AR and VR are also used to develop a network that allows conferences to be held with people who are geographically distant from each other. This study can be useful to explore the potential areas for the use of AR and VR technology in the construction industry effectively as time and savings in tool costs. (Shakil Ahmed H. H., 2017). The use of AR increases the efficiency of construction, reduces cost and time, increases quality and reduces resources. Students of project management and construction (future workforce) have problems in construction processes that lead to a lack of understanding of them. The use of AR in understanding construction processes helps to significantly increase productivity (Issa P. R., 2014).

AR is to be used as a tool in construction projects. This tool is used throughout the project life cycle and solves many project challenges, for example, in design, eliminates the need for visualization and allows the designed project to be seen on the site in real scale before execution. This issue causes a significant reduction in time and cost. Also in the process of implementation process causes a very high level of safety. For example, workers can see the necessary training before starting and is also very useful in monitoring and control.For example, you can put the model next to the amount of work done digitally and measure the progress of the project. It also has many applications in the transfer phase, for example, the performance of the project can be measured. In the stage of repairs and maintenance by AR, we can easily see parts of the project that can not be seen, for example, parts related to project facilities and also in renovation, AR has many applications.

7. CONCLUSION

In the project life cycle (design to demolition) there are many challenges in the project including reducing time, reducing costs, improving quality, and increasing coordination. Therefore, new technologies must be used to solve these challenges and carry out projects as well as possible. Few articles have examined the application of AR in the life cycle of construction projects. Therefore, in this research, the applications of AR and the opportunities created by it in the life cycle of construction projects have been discussed. Based on a review of previous research, AR has 7 advantages (Shared work environment, Integrated simulation, Automated processes, Technical control, Management controls, Safety, and Analysis) and through these advantages, opportunities are created in projects. In this research, a project life cycle is defined by FIDIC, RIBA and PMBOK standards and includes the phase of studies and planning, implementation, supervision and transfer, completion and delivery and operation. Each of these steps involves activities that can be used by AR. In the studies and planning stage, AR is used to determine the layout of the workshop, site design, conceptual design, spatial coordination, technical design and definition of roles and responsibilities. In the implementation phase, AR is used in document presentation, resource management and procurement. In the monitoring and control phase, AR is used in change management, project progress monitoring, quality monitoring and identification of shortcomings. In the completion and delivery phase, AR is used in fault monitoring, project performance evaluation, final delivery and temporary project delivery, and finally in the exploitation phase, AR is used in repairs, renovations and demolition. Therefore, AR has many applications in construction projects. Further studies include the application of AR and corresponding methods used in different stages of project life cycle.

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TOTAL BIM PROJECT: THE FUTURE OF A DIGITAL CONSTRUCTION PROCESS

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ABSTRACT: *Although the construction industry strives to implement Building Information Modeling (BIM) to improve efficiency and quality, adoption in the actual construction phase is still limited. However, in Scandinavia, recent years have seen the rise of an idea known as Total BIM - An approach where the BIM is the legally binding construction document and no traditional 2D-drawings are used on-site. In this paper we present a case study of a successful Total BIM project. We investigate the prerequisites for – and outcomes of – implementing the Total BIM concept, where commonly found individual and isolated BIM uses is turned into an all-inclusive approach to achieve a more efficient design and construction process. Our analysis shows that the success was contingent on factors from within several different areas, including strategy and innovation, organizing, and technology, but also on the commitment shown by the construction management company responsible for the project. In addition, three key elements were identified; BIM as the legally binding construction document, cloud-based model management, and user-friendly on-site mobile BIM software.*

KEYWORDS: *building information modeling, Total BIM, digitalization.*

1. INTRODUCTION

Building Information Modelling (BIM) can be seen as a strategic methodology that can innovate the construction sector (Fox 2014; Renz et al 2016). Indeed, the growing use of BIM has led the construction industry to move towards a digital construction approach by which it is possible to work on 3D data providing complete information to the stakeholders. The use of 3D models and BIM is widely reported in research, identifying numerous benefits (Azhar 2011; Volk et al 2014; Kumar et Bhattacharjee 2020). In particular, previous studies identify that using 3D models instead of 2D drawings facilitates communication ensuring clearer information, such as clash detection (Zaker & Coloma 2018). Nonetheless, barriers in BIM implementations still exist, such as issues surrounding the legal status of the BIM in construction projects (Englund & Grönlund 2018).

With BIMs often having unclear legal status, it is instead common to see the BIM methodology applied as a parallel process to conventional 2D drawings. BIM is far from becoming a standard because the current rules, regulations and contracts still require 2D drawings as the legally binding documents. As such, despite extensive resources being spent on providing 3D models, the potential in implementing them is not realized and the simultaneous provision of 2D drawings hinders the leap forward to a more extensive utilization and a digital process in the construction phase.

In this paper we present a case study in which the demand and requirement of 2D drawings as legal document is finally superseded. Indeed, a "Total BIM" concept where BIM (recognized as the contractual document) was used in all phases of the project by every actor. This paper offers a unicum in the literature where 3D models are fully implemented and is also used on-site by the construction workers where on-demand information and measurements are created and extracted directly from the BIM. The paper aims to investigate the prerequisites for and outcomes of implementing a Total BIM concept where the 3D model is legally binding and used in the construction phase on-site.

2. BACKGROUND AND THEORETICAL CONSIDERATIONS

Previous studies present some examples and attempts at pushing towards a full implementation of BIM, but no project seems to have reached the objective to eliminate the 2D drawings from the construction phase. Already in 2014, Czmock and Pękala (2014) reported a case study of an office complex in Warsaw based entirely on BIM, while 2D CAD drawings were secondary. The design process was estimated to be 10% faster and 80% more accurate. The authors concluded that BIM promotes simplification and saves money and time. Nevertheless, the use of BIM was limited to the design phase, because on the construction site they used paper drawings, which were required by Polish law. In 2017, in the Thames Tideway Tunnel project (a large sewage system in London) the designers assumed a challenge to eliminate 2D drawings and to work with information derived uniquely from the BIM model (Gaunt 2017). Indeed, they considered the 2D drawing production process unsuccessful, but in any case, it was legally binding for the project. Limited to the design phase, they prepared both 2D drawings and a 3D model to identify the benefits of a 3D model-based method and discovered that BIM could save money. Thus, even if in the cases presented the use of BIM could be translated into advantages, the request to produce parallel 2D drawings caused additional effort for the stakeholders that nullifies the business value of BIM. Indeed, currently most designers create 3D data models rich in information that does not reach the construction site.

Recently in Scandinavia some projects were realized using the 3D model as the legally binding document on the construction site. In the Norwegian Randselva Bridge project (due for completion in 2021), IFC models were uniquely used, defining it as a “drawingless” or “drawing free” project. The information was derived from the 3D model and used on the construction site. However, at the same time 2D drawings were requested from the client to have “an overview of general information”.

In the case of the Röfors bridge, 2013 – a project realized entirely without traditional drawings – additional agreements were established that gave the BIM the same status as “specifications”, thereby placing it above “drawings” according to the General Conditions of Contract. Construction workers then had direct access to the BIM on tablets for an easy overview and understanding of the project. However, due to limitations at the time in the BIM-viewer software, it was difficult for construction workers to extract accurate measurements and specific information from the model. In order to solve this issue, the project regularly had a structural engineer on-site to create so-called Production-Oriented Views (POV) from the BIM in consultation with the construction workers. These views were essentially enhanced screenshots typically containing color-coded elements, specific measurements and dimensions, object information, 3D-sections, or any other information the construction workers considered was necessary to perform the actual work on site (see Figure 1). After creation, these views were uploaded as images to a shared model repository and could then be accessed and used as a complement to the complete BIM on the tablets.

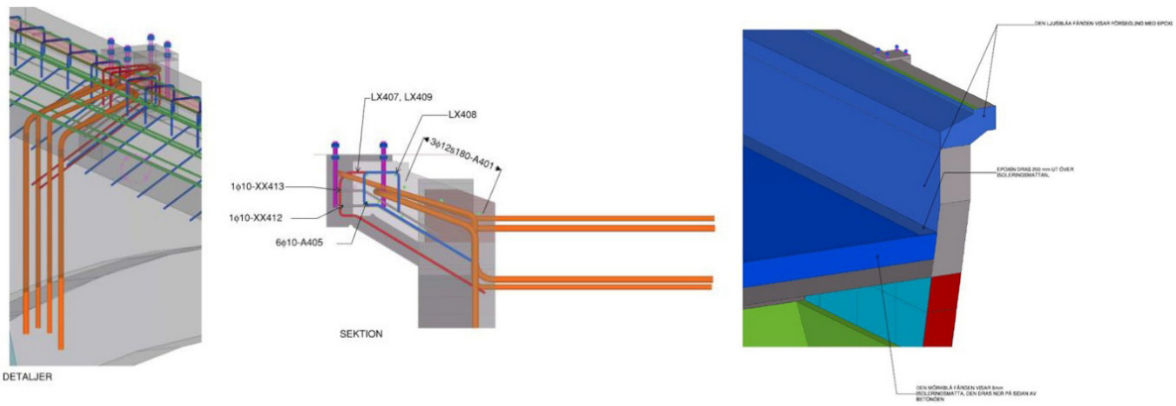

Fig. 1: Illustration of Production Oriented Views (POVs) in the Röforsbron case (Johansson & Roupé 2019)

In the Norwegian Oslo airport expansion project, completed in 2017, due to a large number of estimated paper drawings they decided to use a BIM approach on site, but only for placement of the reinforcing bars (Mershbock & Nordahl-Rolfsen 2016). It is noteworthy as this also occurred in the Röforsbron project where they decided to use the POVs to facilitate the work on site.

The Slussen project, in Stockholm, is the rebuilding of the junction between Södermalm and Gamla stan (Cousins 2017). The project started in 2019 and the completion date is scheduled for 2025 (Nohrstedt 2017). It was decided to use only 3D models in the project and to not use 2D drawings because the creation and handling of the latter wastes time.

In the Smisto project, a hydropower station in Norway, the consulting firm collaborated strictly with the contractor to reach the goal of only using the 3D model. They also used the model-based approach in the construction phase (Gaunt 2017) and only delivered one 2D drawing. The drawingless execution increased progress monitoring and interaction among stakeholders both during the design and the construction phase (Multiconsultgroup 2016).

Considering the cases found in the literature, to understand how BIM could be fully implemented even in the construction phase, it is necessary to highlight both its social and technological nature.

The BIM approach is based on technological and processual factors (Mondrup et al 2012) that influence information management along the supply chain and the overall business concept (Sundquist et al 2020). Nonetheless, the ability to tackle and manage complexity in the project has encountered many challenges due to the different needs and incentives of various stakeholders. Furthermore, the BIM environment has not been mature enough to adopt a Total BIM approach. In fact, different maturity models have been proposed to assess and evaluate the level of BIM implementation within organizations (Sacks et al 2018). Using these models, the level of BIM maturity (that could find its maximum stage in a Total BIM approach) can be evaluated accordingly to a socio-technical perspective, considering the simultaneous application of technological (e.g., 3D model) and social factors (e.g., synchronous collaboration).

Finally, because BIM entails interdependencies between technological, process and organizational aspects, to capture the implementation of a Total BIM approach, in this research we apply a holistic method where ecosystem, strategy and innovation, organizing, and technology categories are used (Sundquist et al 2020). By applying a socio-technical holistic point of view, this paper wants to investigate and analyze a project that has embraced the Total BIM approach during the entire project from design to construction phase.

3. METHOD

Due to the nature of the research, a qualitative approach was employed. The data consists of qualitative semi-structured interviews with the Virtual Design Construction (VDC) manager and the VDC on-site coordinator for a total duration of 10 hours. The semi-structured protocol allowed the interviews to be organized according to a pre-established structure and to keep open-ended questions as to collect more comments from the respondents (Dicicco-Bloom & Crabtree 2006; Yin 2009). Before commencing the interviews, the VDC manager provided an extensive project presentation. According to the framework firstly proposed by Bosch-Sijtsema et al. (2016), (see Figure 2) data was grouped according to the following categories.

- Ecosystem: Environment of new developments; standards, laws, regulations; requirements.
- Strategy and innovation: Business value of BIM in terms of costs, productivity, performance.
- Organizing: Methods, processes, and ways of working with BIM; Cooperation with BIM between firms.
- Technology: Technological components of BIM, interoperability (type of software), technological platform and framework for collaboration, standards (structure info, naming the objects, BIM guidelines).

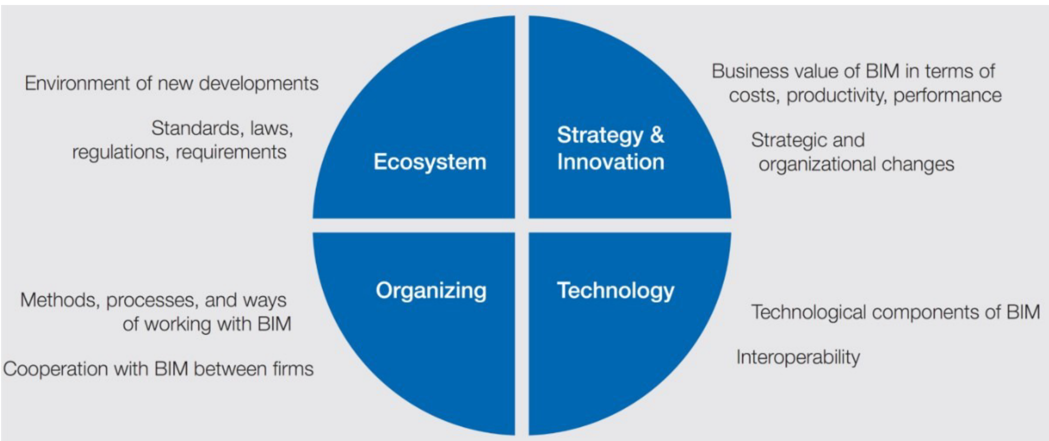

Fig. 2: Holistic research framework to BIM implementation. (Bosch et al 2016; Sundquist et al 2020)

3.1 Total BIM case study

The Celsius building located in Uppsala Science Park, is in an attractive area for new innovative science companies in Sweden (See Figure 3, Right). Design work on the project started in 2017, construction began in

2018 and work was completed in November 2020. The project is a new construction of an advanced laboratory built by a leading Swedish real estate company, consisting of 12 000 square meters over 7 floors. The project budget was roughly 45 million Euro, and the building has been certified with LEED Platinum, with highly advanced energy, water and waste systems. The CM company behind Project Celsius won the 2020 international buildingSMART award for their innovative and digitalized process in construction. In the design phase BIM-models were live-linked between BIM-applications and firms to produce high-quality open BIM models, that eased communication between stakeholders to solve more issues in this phase than previously possible. The bidding process was streamlined by providing bidders with custom IFC-models and extracted quantity data, with only information that was relevant to them, which was aimed at reducing their workload and attracting more bids. In the construction phase the 3D IFC model was the legally binding construction document. The model had to be used by all workers during construction as no paper drawings were produced. Everything was built on-site from the 3D model by using mobile devices and large screens operating StreamBIM to view the model and for tasks such as taking measurements, checking object attributes, and communicating administrative items (see Figure 4).

Fig. 3: Left: Use of StreamBIM on-site. Right: View of the Celsius project during construction

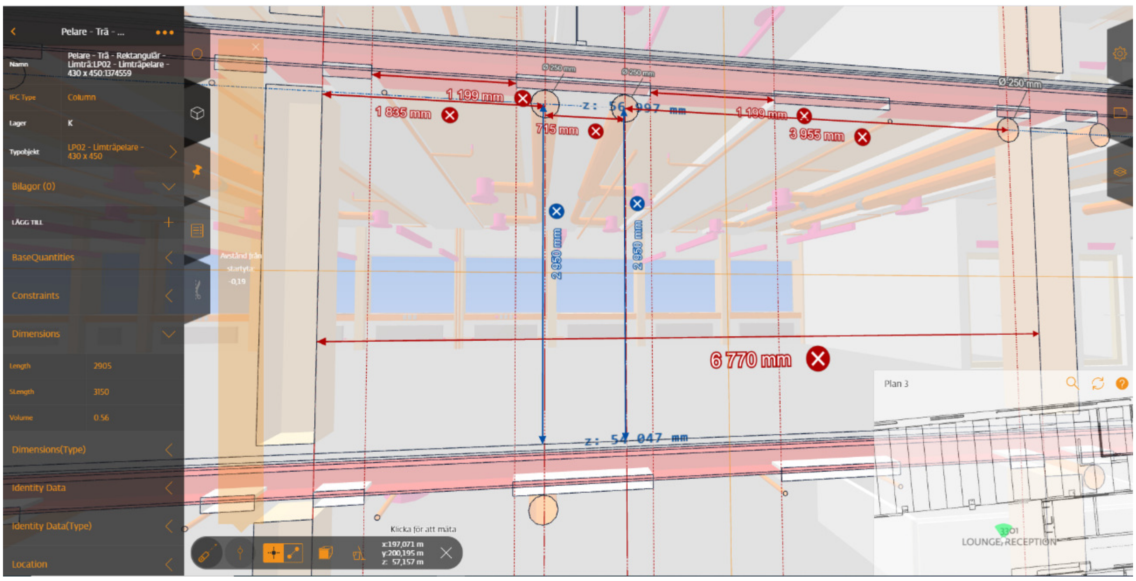

Fig. 4: In the Celsius project the construction workers took their own measurements and extract information directly from the BIM using StreamBIM the phone or tablet on construction site.

4. RESULTS

In the Celsius project, the CM company was responsible for implementing digitalization and BIM by using a model-based approach where BIM carried all the information, thus, no drawings, i.e. a Total BIM project. The project strategy is unique and novel in the sense that the vision was to utilize digitalization and BIM to enable a new approach and way of working with digitalization of construction, and in so doing achieve a more efficient construction process by simplifying and improving project quality, information handling, communication and administration (self-monitoring, case/issue management, quantity take-off, bidding and cost management, etc.). The gains and outcomes of this implemented strategy in the Celsius project are categorized in Table 1 in accordance with the previously presented category framework.

Table 1: Gains/outcomes in the Celsius Total BIM Case Study

		Total BIM Case Study, Celsius **Gains and Outcomes**
Ecosystem	*Standards*	**Standardization for codes/names** in BIM (e.g. BIM object) added in design and used in pre-production and production phases. Flexible way of information flow and working for enabling innovations and feedback from production and design.
		BIM and digital model as information carrier.
	Laws, regulations, requirements	**BIM legally binding** and forcing sub-contractors to use digital tools. Legally 3D BIM is richer about what is to be done.
		Clear structure of who is responsible for supporting BIM on the construction site and a change order process for production where the BIM and StreamBIM is used for error-handling, e.g. design change for hole punching during construction.
Strategy & innovation	*Costs*	**More design cost:** the implementation of Total BIM costs more money than a traditional design process. The focus was to create high-quality BIM and production orientated model-based design that are more thoughtful instead of making drawings.
	Productivity, performance	**Eliminated unbudgeted changes:** high quality BIM and use on the construction site eliminated unbudgeted changes.
		Single source of information and efficient process: the vision was to achieve an efficient process by removing any duplication work and use of a single source of information that emanated from BIM stored in the cloud. Information in description and drawings is not an efficient process e.g. interpretation errors, search for information and guess work of the design.
Organizing	*Methods and processes*	**Education and technical support:** local VDC and technical support on site from the management for construction workers/sub-contractors. Clear structure of who is responsible for supporting BIM on the construction site.
		Cost for BIM education taken by the construction process, support provided and knowledge transfer for new construction workers/sub-contractors on the construction site.
		No conflicting information: as all information delivered from or linked to the model. 3D-model is the construction document in the project and 2D PDF is handled as a complement for details that are hard to describe in 3D.

		By not giving the workers the opportunity to use traditional drawings, they were forced to use the new digital working methods.
		High quality of the model and the linked information, as it was the construction document and used on the construction site. A templates system was used to organize the data contained within the BIM-model.
		Bidding process using BIM: the project was a Design-Bid-Build process with 40 sub-contractors in the project. Sub-divided IFC and quantity take-off lists from BIM were used for the bidding process. Possible losses of some sub-contractors during the bidding process due to competencies when moving to digital models.
	Cooperation with BIM between firms	**Information transparency** among different contractors as everything was derived from cloud-based BIM, which gave better coordination on the construction site.
		Engagement of users using Total BIM through the process: StreamBIM supported mobile phone and camera, which simplified and improved question-answer handling, communication, coordination, information handling, administration, self-monitoring, case/issue management on construction.
		The CM-company helped the clients on how to implement BIM and stated demands and BIM-guidelines.
		Cost taken by project: StreamBIM license cost connected to construction project which supported new users and sub-contractors (+300 users in the project).
		Clearer routines and BIM-guidelines focus on constructability and the use of the digital models on the construction site. The detail level in the model was flexible and developed according to the construction site needs.
Technology	*Technological components*	**Cloud-based BIM** that supported a single source of information, which was accessible from mobile devices.
		WiFi Support: installed construction site WiFi to support internet connectivity.
		StreamBIM in the construction phase supported a user-friendly interface for measurement, sectioning and creation of 3D-views in mobile devices, which supported single source for information on the construction site.
	Interoperability	**Interoperability through cloud-based BIM:** using Autodesk 360, which supported automatically synchronized BIM-coordination and information.
		Sub-contractor discipline and custom fitted filtering of information for BIM objects depended on the sub-contractor's interest.

4.1 Ecosystem

BIM was the legally binding construction document in the project, and the only information carrier from design to construction as no printed drawings were used. To develop a high-quality detailed model was thus crucial. Standardization for codes/names of objects in BIM were added in the design phase and used in both pre-production and production, with a strong focus on how the information would be used, thus usability was a key concern. Clear routines and structures, but at the same time maintaining a flexible approach enabled development and innovations when it came to BIM and its information uses. Since the 3D model was legally binding and no paper drawings were produced, subcontractors were also forced to use the digital tools provided to carry out construction. The CM company was responsible for supporting and transferring knowledge to subcontractors on site about how to use BIM and StreamBIM, which were also used for error handling in cases such as a design change for hole punching during construction.

4.2 Strategy and innovation

Working with a Total BIM concept changed the focus from the delivery of drawings towards creating high quality BIM and more thoughtful design in 3D, which in turn led to a more production orientated model-based design. In this way, “information islands” and disconnected information sources that often occur in traditional construction design and production projects became obsolete. To accomplish this, extra human and financial resources had to be allocated to BIM and IT, adding to the overall design cost. However, the high-quality BIM greatly reduced the number of unbudgeted change requests on the construction site, thus invested money in the design phase improved production performance at site. As the vision for the project was to only have one single source of information that emanated from BIM stored in the cloud, the construction workers had to align to model-based production. Information was delivered via BIM as this was a more efficient process than when descriptions and drawings are used, and errors and guess work are common.

4.3 Organizing

Due to the model being the legal construction document and being used for construction it was ensured that a high-quality model was created, and all the information required by the subcontractors was linked. Templates were generated to organize the data in such way that users could quickly find the information relevant to them with just a single click. On the construction site local VDC and IT-support was present. The CM-company was responsible for BIM implementation and education of all new construction workers/sub-contractors. Workers arriving at construction site for the first time were introduced to the digital model-based work method and tools with an introductory education. The cost for this was covered in the budget for the construction process, as well as software licensing costs. The CM company also guided the client on how to implement BIM. The bidding process for subcontractors to work in the project also involved BIM. The project was a Design-Bid-Build process where 40 contracts were tabled. Each contract was sub-divided into IFC and quantity take-off lists, created from the BIM and distributed to the bidders. The result was a greater number of bids than in comparable projects with less variance. However, some sub-contractors may have lost out due to lacking competencies when moving to digital models.

There was no conflicting construction information as the BIM was the construction document, but 2D-PDF was used as a complement to 3D when details were hard to describe in 3D. By using a single source of information that emanated from BIM stored in the cloud, the construction workers had to organize their work based on the model and use the new digital methods. The creation of “drawings” was pushed to the construction site, as the construction workers themselves created their own “drawings”/production-views from BIM in StreamBIM (e.g. measurements and information). By doing this, time was saved as only relevant drawings were created instead of the common approach of drawing overload that has no function on the site, and the construction-workers got the measurements, information and views they need to conduct their work. The workers turned out to be positive to this change and did not want to revert to the traditional way of working. Also, by doing this, all the information became transparent among stakeholders, as everything was derived from the cloud. Commonly, the respective sub-contractor only has "need to know" for their own discipline and cannot easily understand other sub-contractors' work or information. Here, coordination on the construction site between the different sub-contractors was improved significantly.

At the beginning of the construction the project invested in buying BIM-kiosks with large TV screens, which were placed on the construction site. However, as the project continued the construction workers started to use mobile devices, such as tablets and mobile phones, instead. As the mobile phones had cameras they also started to communicate and document with photos in StreamBIM’s case/issue management tools. Using this approach facilitated improved communication and coordination between the different sub-contractors.

4.4 Technology

To accomplish the project vision, it was recognized early in the design phase that a cloud-based design process would be used. As most of the members in the design team worked and designed in Autodesk Revit, they recognized Autodesk 360 as interoperability and collaboration platform. Consequently, almost any file-based exchange was carried out during the design phase and automatic processes for merging, color-coding, cleaning and publishing updated IFC-models to StreamBIM were developed. The updates were done during nights and saved a lot of time compared to a traditional file-based BIM-coordination process. For one of the designers working in Trimble Tekla (e.g. pre-concreate fabrication), the model was exported once a week into an IFC file. The file was then subsequently imported into Revit and Autodesk 360 to facilitate coordination with the design team. During the construction phase the model was kept up to date and accessible by mobile devices from the cloud, thus, providing users with a single source of information rather than having to locate the most recent drawings. For this to work WiFi had to be installed and made accessible across the construction site. This single information source was supported by StreamBIM, which provided a user-friendly interface for measuring, sectioning and creation of 3D views in mobile devices. Information in StreamBIM was custom filtered so that subcontractors could immediately locate the data relevant to their discipline without having to browse through multiple tabs/windows.

5. DISCUSSION

When looking at the Celsius case from an individual/isolated BIM usage perspective (e.g. model-based quantity takeoff, shared cloud-based model repository, etc.) there are few applications that are fully unique to this specific project. Although many of them are certainly exotic, such as having the BIM as the legally binding document as well as excluding traditional 2D-drawings (both physically and digitally), there are previous examples from practice of such applications, although still mainly within Scandinavia. Instead, what specifically sets the Celsius case apart from other projects is that the CM company has managed to incorporate all of these applications within a single project, thus embracing the Total BIM approach to its fullest. In relation to this, it is generally accepted that each consecutive step on the "BIM-ladder" (e.g. going from BIM-Stage 2 to BIM-Stage 3) is an increasingly challenging task for all involved stakeholders (Succar 2009). Furthermore, it is commonly advocated, and the de-facto standard, to mix traditional – albeit digital – 2D documents and BIM to ease the transformation. This is also reflected and operationalized in mobile BIM-viewers, such as Dalux and BIM 360, where 2D documents and BIMs are used together. However, by essentially going all-in on BIM, the project can focus solely on a single representation, instead of having the burden of keeping two representations continuously up to date – the BIM, as well as the traditional 2D construction documents. Not only will this have an effect on the design organization, but also during actual construction, where conflicts between two different representations are no longer an issue. Taken together, this approach does put a higher relative cost on the design phase, which in the Celsius case was increased from approximately 11 to 13 percent of the total cost (compared to previous projects of a similar type), but at the same time these investments also allowed for other applications, such as automatic quantity takeoffs, ultimately simplifying the bidding process and cost estimations in general. Obviously, this high-end BIM use requires more from the design organization, but at the same time it allows the designers to focus on and prioritize a single representation to deliver. As such, it stands to reason if a Total BIM project is more challenging than a (semi–Total BIM) "mixed-mode" BIM project.

Furthermore, concern is often raised that small firms might get excluded in high-end BIM projects, due to lack of general BIM competence as well as resources to put on various BIM software and technology (Lam et al 2016). This may still hold true for the consultants (i.e. designers) in the Celsius case, considering the high demand regarding model quality. However, for the subcontractors, the opposite applies. In fact, more bids were actually received compared to other similar projects, therefore inclusion rather than exclusion is present with the Total BIM approach. Still, this should not really come as a surprise. Instead of having to spend time and resources on extracting quantities from 2D-drawings, before even being able to place a bid, the subcontractors were given detailed lists of quantities provided by the CM company. Moreover, with the on-site software as well as training and support provided by the CM company, subcontractors essentially had no extra costs in relation to the BIM-use.

The results show how the CM company have managed to transfer and redistribute costs and resources differently from traditional as well as BIM-based projects. Although the design phase was more expensive, it allowed for automatic and accurate quantity takeoffs to be used during procurement, which in turn made the bidding process less expensive for the subcontractors. With the task of extracting quantities from 2D documents being far from non-negligible, subcontractors typically must be strategic on which project to bid on (which was made easier in this case). Similarly, instead of having to make strategic choices around internal education, software investments, or digital innovation in general, the subcontractors could take part in this highly innovative project simply by taking advantage of the software and support provided by the CM company on site. Thus, in many ways, the Celsius case challenges the general understanding on how high-end BIM projects affect the different stakeholders.

In comparison to more traditional BIM projects, perhaps the most daunting concept employed by the CM company was to use the BIM as the legally binding construction document. Although this has been done previously on a few projects in Scandinavia, there are still no turn-key solutions as far as contract and legal aspects go. This meant that additional resources had to be spent on (realizing this) modifying the standard contracts. However, this part appears crucial (for the Total BIM concept), as it essentially makes it impossible for the project to fall back on traditional, non-BIM ways of working, which is otherwise common during times of high pressure. In fact, similar conclusions can also be drawn from the Röforsbron case, where the legally binding properties of the BIM ultimately led to new and improved working methods. Still, it must be acknowledged that this concept might not even be legally possible in many countries due to local regulations. On the other hand, the Celsius case does highlight the need for these issues to be raised and reconsidered by authorities. In order for BIM to be taken to the next level, and hence, making it possible to embrace the Total BIM concept, and allow for more efficient and less inaccurate construction, it must be possible to make the BIM the legally binding construction document.

Another key component for the success of the Celsius project can be seen in the use of the StreamBIM software on-site. As discovered in the Röforsbron project, functionality and user-friendliness is crucial in order to be able to actually build directly from a BIM, and it is typically not sufficient to only be able to “view” the model. What mainly sets the StreamBIM solution apart from other available software solutions is the simple, but powerful, filtering and measuring functionalities. Thus, in many ways, a similar concept to that of the production-oriented views could be adopted, but instead created on-the-fly by the construction workers themselves (see Figure 3). In addition, StreamBIMs issue management system was used to handle and keep track of all the issues throughout the project.

All in all, important success-factors are identified within each one of the four categories of the BIM holistic research model. Although some of them (e.g. BIM as a legally binding construction document, ecosystem), may appear more crucial than the others, it is, in fact, when taken into consideration the strong interdependencies among them that enables reaping the benefits. The Total BIM approach is thus only as strong as its weakest link. By being strategic and investing more resources (up-front) during the design, the bidding process and the cooperation with subcontractors was improved, at the same time as production costs where reduced. Still, without clear methods, processes, and routines in place for support, responsibilities, information management, and issue management (i.e. organizing), it becomes difficult to utilize BIM cost-efficiently throughout the project. Furthermore, without access to a user-friendly and powerful BIM-viewer software (i.e. Technology), a high-quality BIM would become difficult or even impossible to use and build after on-site. Consequently, we see that all these factors and BIM-uses have merits on their own, but it is the fact that they are all used and incorporated together that makes the Celsius case so successful.

6. CONCLUSIONS

In this paper we have presented and analyzed the Celsius case, a rather unique project that has embraced the Total BIM concept to its fullest with a number of successful outcomes. In many ways, the high-end BIM use has put additional demands regarding commitment and competence on both the CM company as well as the members of the design team. However, contrary to what one might expect, it has actually fostered inclusion rather than exclusion with regards to the subcontractors.

By applying a holistic, socio-technical view we identify strong interdependences among factors of ecosystem, strategy and innovation, organizing and technology and a successful Total BIM project is thus contingent on the alignment between them. In fact, when looking at isolated BIM uses and applications there are few of them that are as unique as this case. Instead, the strength comes from combining all of them within a single project, thereby finding even more “leverage” from each one of them.

Still, we identify three main factors that have played a crucial role in the project’s success:

- BIM as the legally binding construction document
- Shared cloud-based model management
- User-friendly and powerful mobile BIM-viewer application on-site

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A DIGITAL TWIN FRAMEWORK FOR EQUIPMENT EMISSIONS FROM CONSTRUCTION SITE OPERATIONS

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ABSTRACT: *The construction industry has been embracing digitization for several years to remove wasteful activities in its site operations. Construction sites generally offer dynamic workplaces that are rich of data but still lack in many applications the availability of suitable Internet of Things (IoT) solutions to gather and process data. The most recent trend towards deploying Digital Twins has further benefited the interest in intelligent site monitoring and decision-making technology to optimize its workflows. However, a unified framework and a cohesive approach towards tracking and reducing emissions from construction site operations have reached little attention in research to date. Besides, construction sites are known to cause a variety of emissions, for example, greenhouse gases, dust, noise, and vibrations. In total, construction sites contribute to a significant share in the world's total emissions. Our research aims to minimize emissions from construction equipment using digitization. A cohesive and unified Digital Twin framework is desired that guides as a stepping stone in the process of transforming an industry towards greener operations. In this paper, we propose the concept of a Digital Twin framework to track, monitor, predict, and reduce construction emissions (DTCE). While we discuss the components of the DTCE in depth, early results from a case study implementation add a promising outlook of using sensor technology that generate the required data sets that will be needed.*

KEYWORDS: *Digital twin, construction sites, emissions, equipment, planning, monitoring, analysis, prediction.*

1. INTRODUCTION

In the growing industrial societies including agriculture, transportation, forestry, manufacturing, and construction human activities are responsible fora large number of emissions (Lamb et al. 2021). Examples of emissions are Greenhouse Gases (GHG), dust, and noise. A significant amount of GHG emissions (around 10%) originates from construction site activities, which cover emissions from heavy equipment (for now, still reliant on the use of fossil fuels), power tools, lighting, heating, and several other activities (Akan et al. 2017). In the general trend towards greener industries, sustainable building standards, guidelines, and policies have been implemented worldwide to improve the building sector's energy utilization and reduce emissions. In 2015, for example, the Nationally Determined Contribution (UNFCC 2021) was established under the Paris Agreement committee and the United Nations Sustainable Development Goals. It intends to reduce the carbon footprint of the building sector.

In the era of Construction 4.0, many construction sites are today dynamic workplaces and rich in sensors and IoT data. This makes the construction sector one of the few which can heavily benefit from information-driven knowledge management. Numerous activities are foreseeable for implementation regarding site monitoring, data analytics, decision-making, and other processing to reduce waste, optimize the construction flow, and reduce emissions. However, these actions lack a unified and cohesiveness framework to integrate information-driven processes. The outcomes are inefficient construction site operations and unleashed potential for efficient and sustainable construction (Sacks et al. 2020).

In order to utilize the full potential of digitization in the construction sites and interface it with the physical construction site with cohesive and unified framework, the Digital Building Twin (DBT) technology can be a practical solution. In this paper, we have propose a conceptual digital twin framework to track and monitor emissions from construction site operations. We introduce and discuss our Digital Twin for Construction Emissions (DTCE) concept as it adds value to various users and stakeholders and helps in tracking and monitoring emission levels in construction equipment operations. We are introduction several components of DTCE in detail and demonstrated its application with a preliminary case study.

For common understanding, we define the term Digital Twin. In the evolution of Construction 4.0 sites with data-centric operations, the "Digital Twin" concept is generally seen as an up-to-date digital representation of the physical work with functional properties of a system that support rapid decision making, for example, by predicting and analyzing potential future scenarios (Tao et al. 2019). For the domain of construction:

- the "physical twin" includes construction site events, activities, workers, vehicles, and artifacts in the real world (e.g., the emissions from equipment).

- the "digital twin" is the digital counterpart (e.g., a virtual model of the construction site events, activities, etc.) used to generate simulations for predicting, e.g., areas or activities with excessive emissions).
- the "digital twin platform" provides the formal connection between the two twins (e.g., data, information, and knowledge exchange)

2. BACKGROUND

2.1 Current state of emissions reduction process and level of information technology

Emissions tracking, monitoring, and reduction at a construction site are part of any successful sustainable agenda in construction, like, e.g., the fossil-free construction site. These steps, in combination, fulfill important roles in making construction site operations greener. Over the years, planners, public authorities, and governments have established and implemented approaches for reducing emissions from construction operations (e.g., demanding construction fleet managers to change to biofuels or even electric-powered construction machines) (EPA 2021, European Commission 2021). However, very few of these approaches target the practical reasons and processes responsible for emissions at the construction sites. Managing construction emissions is more difficult due to the highly dynamic nature of construction operations. For instance, these operations consist of several processes such as a frequent change in construction site layouts and plans; update in production schedule; variability in machine availability, size, type; uncertain and changing weather conditions; diversity in the kind of construction activities (e.g., pile driving, excavation, etc.). These processes are typical construction management issues where Lean Construction is adapted to reduce waste, improve flow, and make construction more sustainable in general (Wandahl et al. 2021). Moreover, these reasons make it challenging to formulate solid practical policies to reduce the emissions in constructions significantly.

With the advancement in analytical and modeling tools, simulative approaches have been utilized by the construction industry for optimizing and improving operation and process, such as finding a trade-off between crew size and on-site winter heating or improving choices of construction material (Mohamed & AbouRizk 2005, Iddon & Firth 2013). However, such studies have not discussed and addressed the actual sources and operations responsible for construction emissions. Long back, it has been predicted that construction equipment and processes will be responsible for significant emissions (Winther & Nielsen 2006), and several precaution measures and policies have been proposed and implemented. However, the existing construction emissions reduction approaches are labor-intensive, time-consuming, and error-prone (Li et al. 2017). Even with the emergence of Building Information Modeling (BIM) methods, investments, and present strategies for construction emission, reductions follow manual, time-consuming, and error-prone processes (Cheng et al. 2020).

2.2 Digital Twins and data acquisition within typical construction project constraints

Construction is often referred to as one-of-a-kind products with being highly unique dynamic. However, construction tasks, methods, and associated risks are fairly well-defined at a decomposed level and, thus, predictable. However, the large number of subcontractors, suppliers, and stakeholders in general, work with or generate their own information about products and construction processes. Under current conditions, few stakeholders are motivated to collaborate intensively, which often leads to a fragmented use of digital tools with multiple data formats that are not exchangeable.

As Sacks et al. (2020) point out, in the effort to establish Digital Twin information systems, federated building models that represent as-designed and as-planned states of a project are not digital twins. As such, building information models as the digital representation of buildings or infrastructure lack the frequent as-built and as-performed states essential to understanding and optimizing construction workflow. These building information models often include planning (4D) and cost (5D) information. To make matters worse, construction sustainability (possible 6D) is far behind and often not included in BIM. Likewise, numerous data acquisition technologies that support sustainability goals are rarely implemented on construction sites.

There is a significant opportunity for Digital Twins that are explicitly tailored for reducing emission from construction site operations to provide new kinds of decision support to key stakeholders. Primary stakeholders are the contractor and sub-contractors but include all others responsible for making construction greener (e.g., engineers, planners, construction managers, workers, and even the client). This potential has slowly stimulated construction engineering and management research, although many research efforts often only target the use of a singular technology without integrating the technology and subsequent analysis into a broader, more comprehensive framework for identifying and reducing construction-related emissions (Teizer & Wandahl 2022). Therefore, this paper aims to create a thorough workflow for planning, monitoring, reducing, and learning for construction emission using digital twin information systems. Certain aspects concerning user interfaces are reflected in the research as well. The method is conceptual analysis (Laudan 1978) as a way to establish the foundation of a concept that is based on elementary parts and interdependencies (Beany 2018). Furthermore, a preliminary case study performs a proof of concept.

3. DIGITAL TWIN FOR CONSTRUCTION EMISSIONS

This section describes how a Digital Twin for Construction Emissions (DTCE) can be created and utilized to track, monitor, and reduce emissions from construction site operations.

Figure 1 shows the overview of our Digital Twin for Construction Emissions (DTCE) (shown in the lower-left corner of the diagram). The DTCE is dependent on other DTs, and those should be interconnected in a network that lets them exchange information and knowledge of interest. The DT should also be able to perform tasks for each other. For example, we envision that the Digital Twin for Production Planning (DTPP) requests DTCE to enable emissions (e.g., GHG, noise, dust) reductions and assessments to an alternative production plan or a batch of those. It is chosen to concentrate mainly on the DTCE, which means some details are missing from some of the surrounding components, e.g., the greatly simplified DTPP, where user interaction, creation, and simulation have been kept out of the diagram. In the following, we will elaborate on the inputs, interactions, and outputs of the individual components of the DTCE.

3.1 Construction Site (CS)

The construction site refers to the actual workplace (i.e., the physical twin), either planned, under construction, or constructed. It contains the production factors used to transform input to output. These factors are mainly; (1) equipment, machines, power tools, and other tangible fixed assets; (2) labors, e.g., construction workers, operators, site managers, HSE and BIM coordinators, etc.; (3) energy use for equipment, lighting, heating, dehumidifying, etc.; (4) construction materials; (5) services and information like construction schedule, site layout, work descriptions, etc.

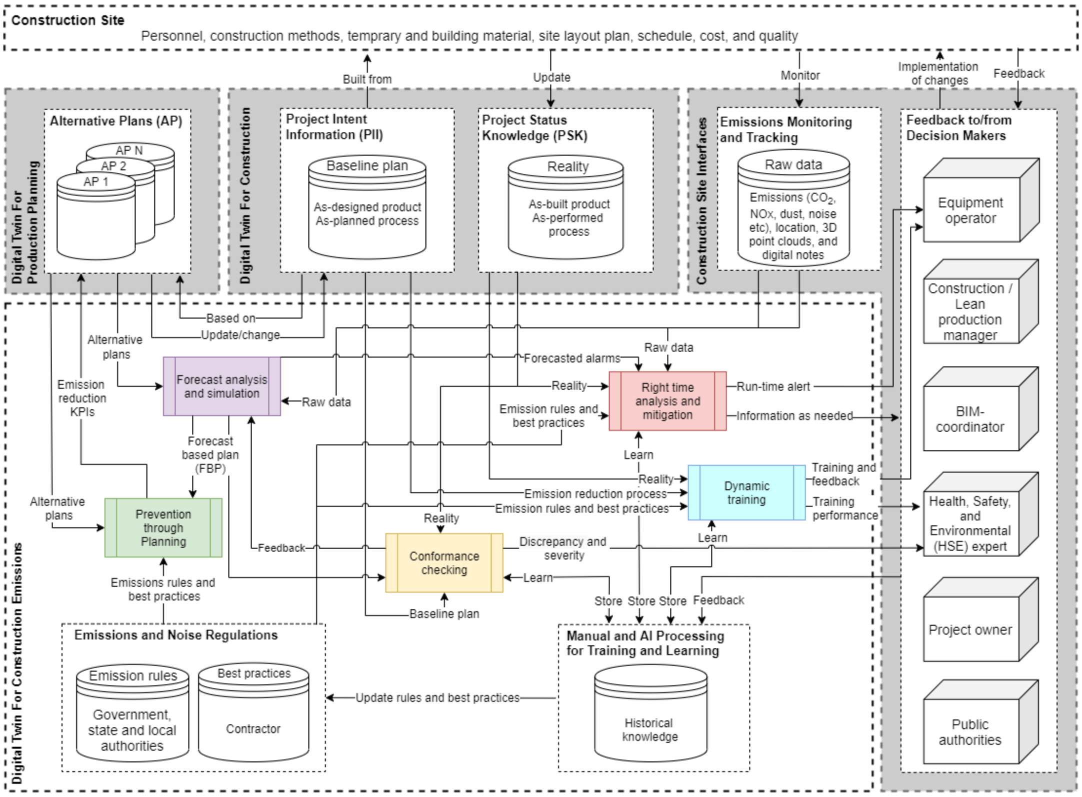

Fig. 1: Overview of the Digital Twin for Construction Emissions (DTCE) and relationship and interaction with the other important Digital Twins (e.g., production planning), physical construction site, and construction site interfaces (e.g., monitoring and decision-makers), education and training (e.g., operator behavior).

3.2 Digital Twin for Construction (DTC)

DTC is a digital representation of the construction site (i.e., the "digital twin" of the physical world, where the physical world itself is referred to as the "physical twin"), which contains both the future potential reality, called Project Intent Information (PII), the past reality, and the present reality, captured in the Project Status Knowledge (PSK) (Sacks et al. 2020). The construction is *built from* the PII, namely the Baseline Plan (BP), containing both the as-designed product (how it *should* be) and the as-planned process (how and in which sequence it should be constructed). The PSK is then *updated* from the physical world (e.g., semi- or fully automated through a combination of raw and processed field data, i.e., real-time location sensing and three-dimensional point cloud data of resources or structures, respectively, of which both are present or appear on the construction site). The PSK also captures the state of the product (as-built product), which is tightly coupled to the product's design. An example of the state is the set of the equipment or machines that have already been in operation and information on whether they have been operating correctly compared to the as-designed product. Furthermore, the PSK captures the performed process of the construction (as-performed process) that can be compared to the as-planned process. Comparing the two sets of information (i.e., as-designed vs. as-built and as-planned vs. as-performed) generates knowledge about the discrepancy that may be avoided through different planning strategies in future projects.

The DTC gives knowledge that can be applied to future planned construction activities and projects through information gathering of historical decision-maker feedback and preferences and the information from the comparison of planned activity vs. reality. For example, this knowledge can facilitate optimized construction site-related emissions and noise in task-specific coordination in schedules, the budget associated cost in more detail than available before, and ensure higher quality.

3.3 Digital Twin for Production Planning (DTPP)

As mentioned, the Digital Twin for Construction (DTC) contains a Baseline Plan (BP) used to build the physical construction. The DTPP also generates Alternative Plans (APs) with the BP as a starting point, along with the decision maker's preferences (i.e., based on experiences or internal guidelines). It creates some number, *N*, of APs, that slightly differ in the process, cost, quality, etc. The measures, aka. Key Performance Indicators (KPIs) of the individual plans are gathered through simulation affected by the historical knowledge that is a part of the digital twin. Each of the APs is given to the DTCE to enhance and assess emissions and noise reduction policies. The KPI facilitates the selection of the AP. The decision-makers should be presented with the APs (including the related KPIs), from which the decision-makers select an AP on an as-needed basis that aligns with their overall goal and vision. This may happen daily (i.e., morning meetings), weekly, or as otherwise defined in the planning method. Through this process, the BP is updated/changed continuously with newly collected knowledge. This may well be integrated with ongoing look-ahead scheduling used in construction production planning.

3.4 Construction Site Interface (CSI)

The CSI serves to provide, get feedback from, and give feedback to the different decision-makers present on the construction site, thus including different interfaces. The interfaces are illustrated as different boxes for the individual decision-makers, although some may overlap or extend. The emission and dust monitoring components provide the DTCE with raw data that must be interpreted into information that can then generate knowledge. It is envisioned that the raw data can contain different sensor data, which can be used in collaboration to create information that is not visible in one sensor output exclusively (aka. data fusion). Here, digital interfaces (i.e., wearables) that are simple to use for personnel on the construction site may provide an additional means to record data or receive communication.

An example is an interface for an equipment operator interface that would be different from the ones the construction management uses. The equipment operator can be alarmed if emission or noise levels exceed the permitted thresholds. It would not be sufficient if the operator needs to interpret a comprehensive emission report first before being notified of excessive emissions or unbearable noise generated on the construction site. The vision is to rather give a (run time) alert through sound or light emitters. Likewise, construction management and/or HSE can be informed via an application, a daily e-mail notification, or a live dashboard available online. If needed and in case to understand how to react correctly, a push notification allows the user to see alternative plans or corrective measures. Likewise, historical data can be processed and predict potential strategies to avoid such situations in the future. The solution can be the creation of new alternative plans for the equipment of operations.

3.5 Digital Twin for Construction Emissions (DTCE)

With the components mentioned above, we are now ready to describe what happened in the DT for construction emissions in greater detail. The DTCE consists of three main components, i.e., Prevention through Planning (PtP), Conformance Checking (CC), and Right-time Analysis and Mitigation (RAM). First, we introduce the overall interaction of these with their surroundings, and subsequently, we describe their contents. The alternative plans are received from the DTPP for emissions and noise reductions, which means the new policies are added to the model. There may exist more than one way to make a better plan, which will result in an answer set of different solutions. The solutions are created based on the rules and regulations (government and local authorities), which holds information about emission thresholds provided by the government, the state, and local authorities (e.g., EU regulation 2016/1628 for Non-Road Mobile Machinery) (Europea Commisssion 2016). Another component of the emissions and noise regulations is best practice, which should hold the decision maker's preferences (e.g., the contractor's own rules might be stricter than government/local regulations. Or, the client may require more stringent policies than regulation requires). Each AP is given a collection of KPIs informing the HSE about the cumbersomeness of, among others, a new plan for site logistics and construction schedules. The rules and regulation data storage should be updated based on the actual performance of the chosen AP and the decision-makers' feedback stored in the historical knowledge database.

Based on a conformance checking of the new plan and the actual construction site's reality, it should be possible to locate discrepancies. These are classified into three levels of severity (i.e., high, medium, and low), provided to the project manager and responsible actors, and *stored* in the historical knowledge database. The project manager should then act appropriately to the severity, solve the flagged rise in emissions or noise, and implement changes to the physical construction site. When an event has been solved, the project manager should provide feedback to the system (comparable to data labeling) for future improvement, i.e., *learning* from the output (both information & classification) and recommendations.

Right-time analysis and mitigation provide two kinds of output, i.e., the run-time alerts for the equipment operator and information as needed for the remaining decision-makers. It is envisioned that an equipment operator in the construction site should be alerted as soon as possible through an appropriate user interface. The information as needed is more elaborated information and includes appropriate mitigation strategies, where further analysis has been performed. This is envisioned as there may not necessarily be time, or necessity, for elaborate mitigation actions in a close call situation. For example, the equipment has exceeded the emissions or/and noise level above a hazardous level. Hence, the equipment operator and all other employees available on the construction site should be aware of the exceeded emissions or/and noise situation and solve the issue collaboratively. Information and mitigation proposals can be compiled and handed to the HSE and BIM coordinator for future avoidance of similar occasions. For example, avoidance measures may consist of a better execution plan for equipment usage and better coordination between several types of equipment on the construction site. Once again, it is envisioned that the output is *stored* along with the decision-maker feedback, from which the component can *learn* to provide better information and mitigation actions.

3.5.1 Prevention through planning (PtP)

The left side of Figure 2 illustrates in brief how the alternative plans are generated based on the decision maker's preferences and the current baseline model. The APs are handed to the PtP component of the DTCE (right side of Figure 2) and enhanced with emission measures (e.g., schedule changes) based on the emissions regulation that applies to the construction site. The system analyses the emissions-prone spaces in construction sites and processes identified responsible for excessive emissions. The APs are returned to the DTPP for decision-maker selection, consequently updating the baseline plan from which the construction site is built.

3.5.2 Conformance checking

The conformance checking should find and classify discrepancies between the plan (created in PtP-module) and reality (captured by sensors) (Figure 3). For example, a diesel engine-driven equipment producing excessive emissions than the regulated thresholds would result in a relatively high severity. This information is stored, and when the HSE personnel knows about the problem, they can provide new information on the correctness of the output (in terms of both understanding reasons and its severity). This information provided by the HSE should be used to reduce chances of future occurrences and to update the best practice.

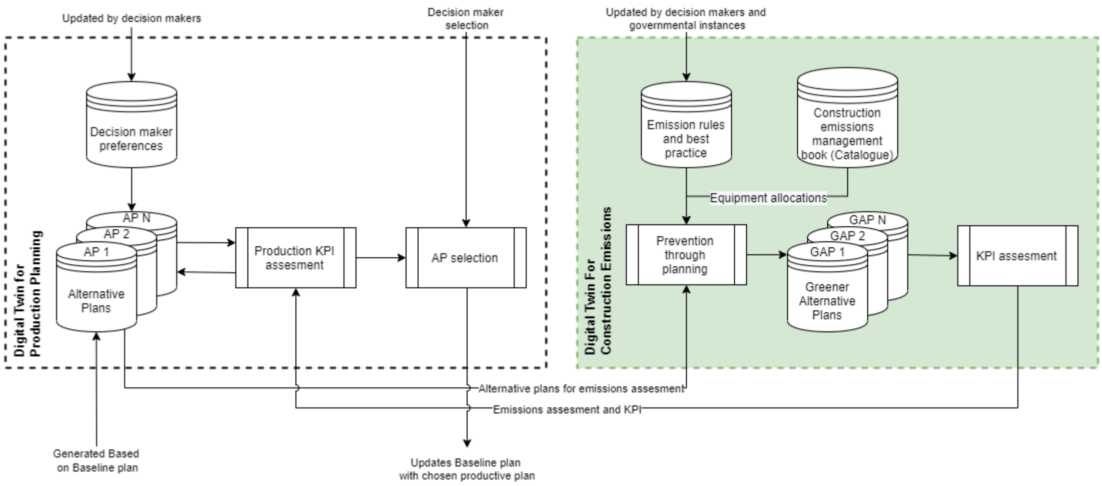

Fig. 2: Internal operation of the prevention through planning component. As the in- and outputs are highly connected to the Digital Building Twin for production planning, it is chosen to include these in the diagram.

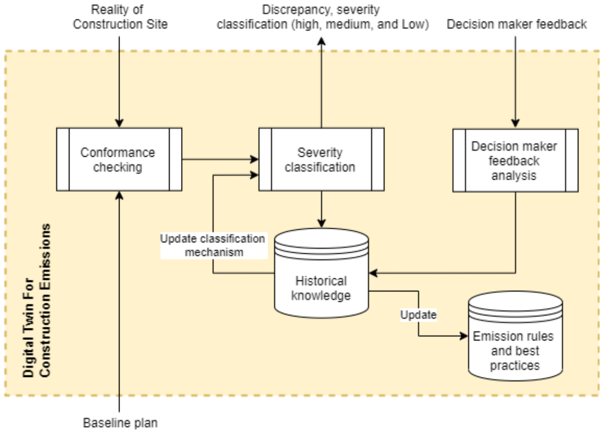

Fig. 3: Internal operation of the conformance-checking component.

3.5.3 Right time analysis and mitigation

Based on the reality of the construction site, the raw emissions monitoring data, historical knowledge, and emission regulation module perform complex event processing, from which the equipment drivers and construction managers are alerted to prevent emissions-oriented alarming situations (Figure 4). The module subsequently performs an investigation, where the incident's root cause can be determined and prevented in the future. In addition, in this module, the feedback to and from the decision-makers are stored and used in processing and investigation mechanisms. The new rules are also included in this diagram. These are updated and used in the prevention through planning module (i.e., the first component of the DTCE), conceptually closing the loop of the digital twin for construction emissions.

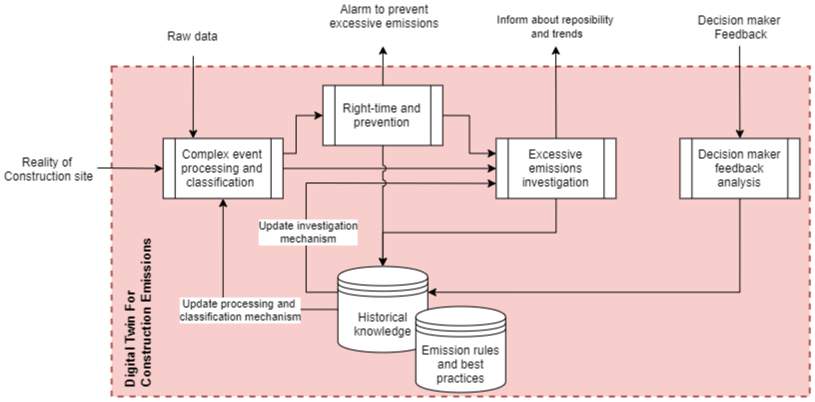

Fig. 4: Internal operation of the right time analysis and mitigation component.

3.5.4 Forecast analysis and simulation (FAS)

The FAS component (Figure 5) is dedicated to emissions forecasting (time series analysis) and simulating greener construction plans for future construction operations based on the forecasted emissions. The components of DTCE discussed so far are related to the real-time operations on the construction site. Whereas the FAS component works in the back-end and simulates plans (based on the forecasted emissions, baseline and alternative plans, and other available resources (e.g., equipment history)) that can help explore the possible emission severity in the near future at the construction site. For instance, we have historical CO_2 emissions time-series from the construction site for the last two weeks; the emission history and schedule of all equipment; and baseline and alternative plans for tomorrow's construction activities. The FAS will explore all resources, and based on this analysis, it will simulate different plans (from baseline and/or alternative plans) and estimate the possible emissions in the following days (near future). The simulated plans with the lesser emissions potential will be noted as 'Forecast Based Plans (FBP).'

The FBPs will help prioritize the available plans along with their information about emission reduction potentials. Besides, the FAS will be able to track high severity events corresponding to all FBPs, and preventive measures can be thought of accordingly in advance. The FAS component can enable DTCE to look at the future and plan in real-time to reduce the chances of high severity events at the construction sites.

The FAS component will coordinate with other DTCE components for different purposes. It provides FBPs to the PtP component and helps to prioritize the alternate plans. The FAS will share FBPs with the conformance checking component, which compares the discrepancies between reality and FBPs and return the feedback (e.g., the accuracy of FBPs) to FAS. The FAS will interact with the 'right time analysis and mitigation' component whenever it predicts a chance of possible high emissions event (based on FBPs) in the near future.

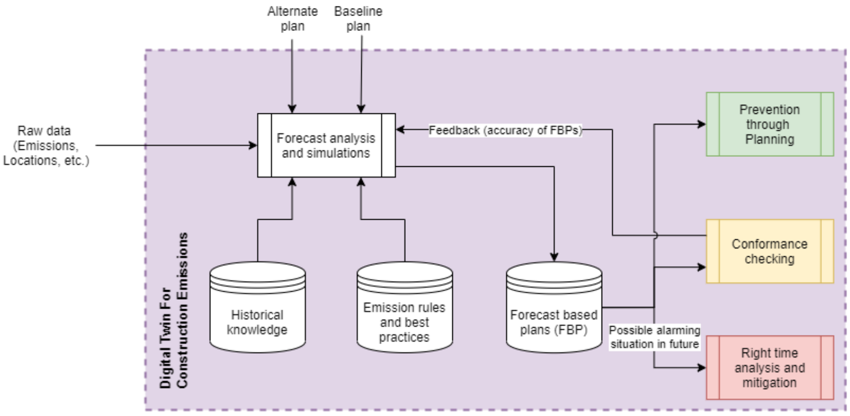

Fig. 5: Internal operation of the forecast analysis and simulations component.

3.5.5 Dynamic Training

The dynamic training module (Figure 6) includes periodic training of workers using the latest information from the DTCE. By feeding the model with the emissions and noise incidents and the area, the DTCE can produce relevant scenarios for each incident fed into the system. This will be done based on the location and type of alerts. Both the workforce and the digital twin benefit from this. The worker receives training, and the digital twin receives knowledge that can be utilized when other prevention approaches are used. Besides, this knowledge can be utilized when the Key Performance Indicators (KPI) are assessed for a plan.

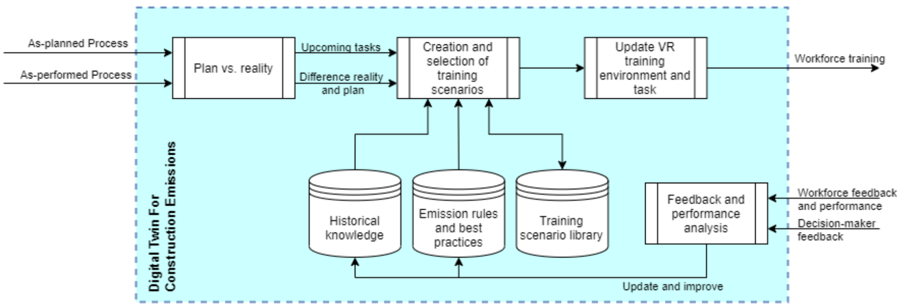

Fig. 6: Internal operation of the dynamic training component.

4. PRELIMINARY IMPLEMENTATION AND RESULTS

The proposed DTCE concept can be implemented with several technologies, including sensor networks, digital building twin tools, building information model (BIM), data analytics, and user interfaces (visualizations). The possible features and responsibilities of these technologies are briefly discussed below:

4.1 Technologies

4.1.1 Sensor Networks

Raw data is one of the essential requirements for DTCE to be functional and can be collected through a sensor network. At the selected construction site, a dense network of sensors will be set up in the construction sites and construction vehicles to monitor emissions, air quality, noise, vibrations, positions, patterns for the use of construction machinery, and real-time energy consumption. The sensor network will be arranged modularly, and its most relevant elements can thus later be transferred to other construction sites. Sensor output will be collected and stored on an ongoing basis, both before and after implementing technical and organizational measures. The systematic collection of data will be a prerequisite for carefully quantifying the effect of the individual measures. In addition, this data can serve several other purposes, such as visualization of environmental effects, assessment, modeling, and improvement of logistics. Besides, communication and data assimilation are the important aspects associated with the sensor networks. Communication protocols such as GSM can be employed for the collection of sensor data.

4.1.2 Digital Building Twin (DBT)

Digital Building Twin will be one of the challenging technologies in this case study. The actual construction site will be replicated digitally with the concept of Digital Twin technology. This digital twin will be based on building information modeling (BIM), site layout plan, schedule, and construction cost. Collectively, it can be represented by a 5D structure. Also, this twin will be integrated with the real-time sensor networks installed in the construction site. The task of this digital twin will be to evaluate and reduce the energy consumption and emissions related to the construction sites, their equipment, and transport vehicles. However, it will be crucial to identify the parameters to be considered while designing the digital tool for the construction site and to decide the nature of the digital twin (simulation-based or data-driven).

4.1.3 Building Information Model (BIM)

A Digital Building Twin developed in this project will be based on the BIM information such as construction site layout plan, construction schedule, costs, and other parameters such as equipment list. The higher resolutions and precise formation of BIM information can lead to developing an accurate Digital Building Twin for the targeted construction site.

4.1.4 Data analytics

The major task in data analytics will include developing and implementing new predictive algorithms to estimate reduced energy consumption and emission of exhaust gases based on improved construction site logistics. Further, the data analytics will help compare real-time construction sites with the digital model. Finally, the analysis and optimization of workflows can be enhanced with the data analysis strategies and the digital twin model.

4.1.5 User Interface

Visualization supports the dissemination of the digital building twin's activities and results, and that data visualization will be an important management instrument in the short-term planning of the construction site's processes. Internally, visualization is a key element in involving employees on the construction site. By showing current results on an ongoing basis, the project will inform the residents in the local area in a new way and thereby provide public knowledge about the emissions at the construction site of the future. An interactive dashboard can be used as the front-end user interface. Numerous plots and visuals can be provided through the dashboard, which will be based on the actual sensors data, data through digital twin models, and conclusions derived through the data analytics.

4.2 Case study

4.2.1 Conformance Checking

A field test was conducted with two pieces of heavy construction equipment. The laydown yard, located in an industrial area of Aarhus, Denmark, provided a safe test environment where typical machine operations can occur. The details of machine 1 and 2 are shown in Table 1. Both machines were wheel loaders and manufactured by Volvo Construction Equipment AB. The first machine was a wheel loader L90G, built in 2013 with a Stage III B (incl. particle filter) engine and a net power of 173 hp (129 kW), whereas the second machine 2 was the wheel loader L350F, manufactured in 2015 with a 528 hp (394 kW) powered Stage III A engine. Both machines had a cold start (defined as low temperature relative to its operating temperature) at an ambient temperature of approximately 23 °C). According to the European Union (EU) standards, the permitted NO_X limit values for Machine 1 and Machine 2 are 2.00 and 3.81 g/kWh, respectively (DieselNet 2021). In our case study, we followed the same standards for conformance control.

A Smart Emissions Measurement Systems (SEMS) module was mounted on the machines before they operated in the laydown yard. The SEMS module (Teizer and Wandahl 2022) is an Internet of Things (IoT) based sensory device which measures several emission parameters (e.g., NO_X, CO_2, O_2, particulate matters (PM)) that are emitted by the equipment engine. The particular SEMS also measures its (and the machine's) position details using Global Navigation Satellite System (GNSS) information, resulting in latitude, longitude, and vehicle speed data. The emissions data are further communicated from both machines to a cloud server platform where data is prepared to supply it to the DBT, finally processed and visualized in near run-time. The gathered data relates to several observed activities such as driving behavior and constriction operations as noted in Table 1 in more detail. Figure 7 shows the trajectories of Machines 1 and 2 along with their NO_X emissions generated while different activities were observed. The color coding of these trajectories represents the NO_X emissions from the respective machines. A benchmark was set with respect to the applicable EU standard. A performance comparison between both machines is possible, since the same color coding is used for representing the NO_X emissions.

The forthcoming text explains some of the main functionalities of the proposed DBT based on the concept of the proposed DTCE.

Table 1: Details of equipment used in the case study.

Machine	1	2
Model image		
Manufacturer	Volvo Construction Equipment AB	Volvo Construction Equipment AB
Equipment model	WHEEL LOADER L90G	WHEEL LOADER L350F
Year built	2013	2015
Engine net power	173 hp (129 kW)	528 hp (394 kW)
Engine type	Stage III B	Stage III A
Particle filter	Yes	No
Cold start	Yes	Yes
Observed activities (numbers refer to locations as seen in Figure 7)	Start of engine (1), Changing tool, excavation/loading on ground surface (2), idling (2), and driving at slow (3) and fast (4) vehicle speeds in laydown yard	Driving one slow round and one fast round in laydown yard

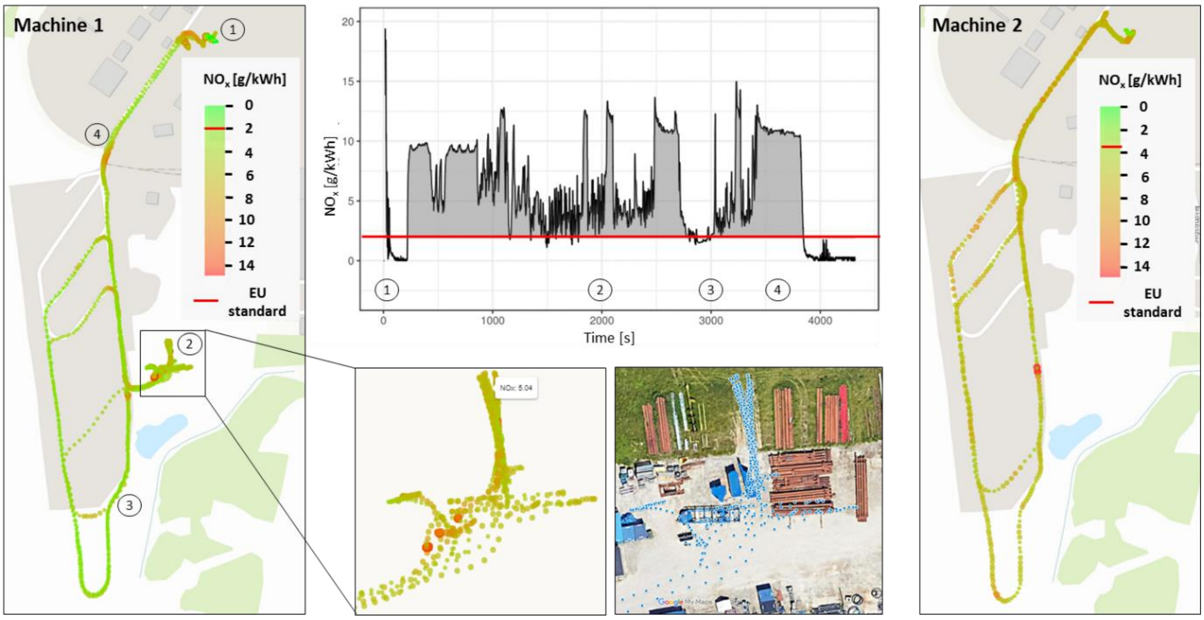

Fig. 7: Trajectories of equipment with NO_X emission levels.

4.2.2 Right-time Analysis and Mitigation

The purpose of DTCE is to track and monitor construction equipment emissions. The intent of the DTCE is to continuously perform right-time analysis on the collected data (Teizer 2016). In the performed case study, the DTCE had continuously monitored the emissions from the individual machines only. Additional data may come from the overall collective emissions at the construction site. For test purposes, a hypothetical alarm threshold is set according to the ED standard or the user's best practice. Latter might be, depending on the project owner's and/or contractor's own ambitions, tighter than governed by regulations. Figure 8 (left image) displays a heat map where emissions from Machine 2 cross a user-defined threshold (i.e., 14 g/kWh). Upon the occurrence of such events, the DTCE attempts to mitigate it by sending such information to the respective personnel, e.g., equipment operator, construction site manager, or HSE responsible staff. Given the early type of our DTCE work and as shown, right-time data analysis was implemented and successfully tested, however, the impact of corrective means neither deployed nor measured. This is believed to be part of future work, e.g. longer-term test that withstand rigorous scientific testing.

4.2.3 Forecast Analysis and Simulations (FAS)

The FAS component is not implemented in the present version of DTCE; however, the conceptual stage of its main functionalities are documented in this sub-section. While the DTCE is continuously in operation, it collects large amounts of time series data. These include several events information, containing underlying root causes being used in historic evaluations. Besides, the DTCE is equipped with information to alternative construction site layout planning (dynamically generated as BIM updates) that can be selected as an alternative future. The FAS component will use all available data resources to attempt the most likely event predicting with least possible impact of emissions. For example, time series data related to specific work activities or generated alarm events can accordingly calibrate the accuracy of the FAS component.

4.2.4 Dynamic Training

The proposed DTCE allows feeding the model with other important emission values that typically are present in construction sites, for example excessive noise, dust, and vibration incidents. The DTCE is capable of storing such data while making it available in personalized training scenarios as shown in Figure 8 (right image). According to research in HSE (Teizer 2016), it is believed that human operator training has one of the most significant impacts in reducing equipment-related emissions. The DTCE therefore serves as an ideal to develop several preventive approaches not related to technology but to human skills.

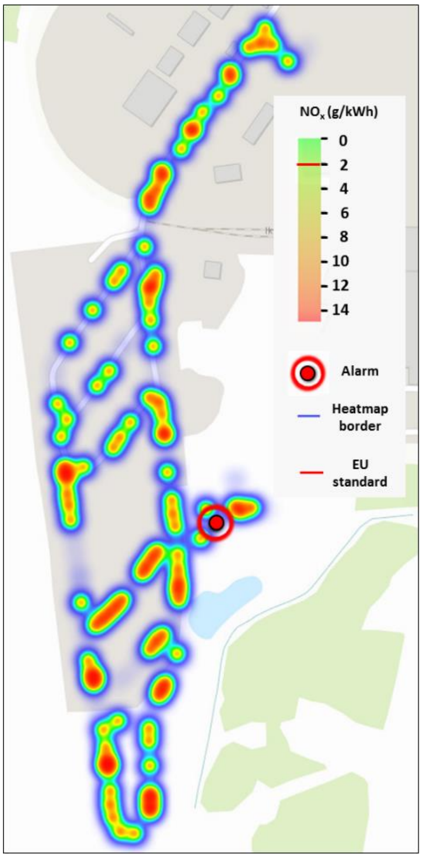

Fig. 8: Image to the left: DTCE dashboard showing an emissions heat map and an alarm pointing to levels that may surpass standard or user defined limits. Image to the right: Self-guided learning of earthmoving operations using an equipment simulator at a vocational school. Note: training operator behavior to reduce emissions is not part of the current learning objectives of equipment simulators, except that excessive use of fossil fuel consumption is part of the personalized feedback at the end of a training session. However, this provides user little to no answers which parts of the operations can be improved to lower the emissions or impact thereof.

5. CONCLUSION

This paper demonstrated the initial concept of a Digital Twin for Construction Emissions (DTCE), including the core information and control elements. Following the more general definition of a Digital Twin, the proposed concept of a DTCE represent models for information-driven management and control of physical systems including equipment operators and construction staff, operational processes, and sensor as well as data processing and communication technology and user interfaces. The DTCE targeted equipment emissions tracking, monitoring, and reduction from site operations by four vital steps: (1) emission prevention through detailed planning and scheduling; (2) proactive forecasting, focusing on excessive emission warnings; (3) continuous performance evaluations and improvements with personalized as well as project-based feedbacks; and (4) mitigation of situation with alarms and too high emissions. Based on these core elements, we advocated and demonstrated a DTCE information system workflow, including information models and rule sets, monitoring technologies, and performance feedback, in a preliminary implementation of digital twins for construction emissions. Since not all of the proposed elements were implemented, further research and evaluation thereof are needed.

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A MULTI-LEVEL KNOWLEDGE MASTERY ASSESSMENT SYSTEM FOR CONSTRUCTION SAFETY EDUCATION IN VIRTUAL REALITY

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ABSTRACT: *Hazardous nature of the construction site is a direct threat to human life and its properties. Not only the hazards at the worksite but also the negligent behaviour of construction workers can cause harm to others. Thus, workers' knowledge of construction safety, as well as the behaviour of themselves and others in hazardous situations, need to be assessed prior to permitting them to enter the site. This research is focused on developing a comprehensive construction safety knowledge assessment for students of construction-related disciplines. A scenario-based Virtual Reality approach was adopted for this study which is proven effective compared to other methods. The framework was developed based on the taxonomy of significant learning as it assists in assessing the learner's cognitive and behavioural aspects in learning. The developed multi-level knowledge mastery assessment system was tested with 21 construction engineering students. Task load, application performance, and participant performance were analysed, and results suggested that the intended objectives of the application have been successfully achieved and the application has the potential to assess students' construction safety knowledge comprehensively.*

KEYWORDS: *Construction Safety, Knowledge Assessment, Safety Education, Fink's Taxonomy, Virtual Reality (VR), Scenario-based*

1. INTRODUCTION

Accidents in a construction site have become a critical issue for the performance of the construction industry as a whole. The USA reported 5,250 fatal injuries in 2018, a 2% increase compared to the prior year (U.S. Bureau of Labour Statistics, 2019). Several reasons could be found for such accidents, namely, lack of knowledge and training, lack of means to conduct the work safely, carelessness, error of judgment, or recklessness (Sawacha, Naoum, & Fong, 1999). Thus, construction companies and research institutions take efforts in introducing various Construction Safety Management (CSM) practices and concepts such as safety training (Leder, Horlitz, Puschmann, Wittstock, & Schütz, 2019), hazard identification (Hadikusumo & Rowlinson, 2002), zero accident concept (Sherratt, 2014) to construction site. Among them, construction safety training and education play a pivotal role in CSM since it produces skilful and knowledgeable construction personnel to mitigate the risks in the working environment (Pedro, Pham, Kim, & Park, 2019). Even though companies take all the precautions to confront risks, such as site preparation, enforcing disciplinary measures, and providing protective equipment, still the workers can harm themselves through the decisions they make while on duty (Sacks, Perlman, & Barak, 2013) and sufficient safety training can reduce the effect.

However, education institutes do not allocate sufficient resources to provide stand-alone safety courses to the students. Some institutes included safety topics in their curricula, and some did not (Le, Pedro, & Park, 2015). Furthermore, there is no tailor-made assessment system to assess the students' safety knowledge in the particular institutes as the conventional paper-based assessment systems are not aligned with the application of safety knowledge in reality (Pedro et al., 2019). Safety training and assessment can be done both onsite and distant. Past studies found that high-engagement training (involve behavioural modifications, first-hand practice) is significantly effective than low-engagement training (videos and written materials) (Sacks et al., 2013). Similarly, text-based assessment systems do not have the potential to address complex and dynamic safety scenarios (Li, Chan, & Skitmore, 2012). In brief, the traditional paper-based assessment system fails to assess whether the students actually possess the true knowledge and whether they are able to apply the absorbed knowledge in practical scenarios (Pedro et al., 2019). Successful teaching and production of knowledge-rich students in the industry can only be achieved through an effective assessment system (Di Lauro & Johinke, 2017). Thus, this study attempts to develop a scenario-based knowledge mastery assessment system incorporating VR. A scenario-based assessments system is an alternative approach that consists of innovative methods such as simulations to provide an immersive experience to the learners to apply their safety knowledge in a realistic scenario before entering the industry as a professional (Williams, 2008).

The reduction of accidents is directly affected by the effectiveness of safety training. Considering the mindset of construction personnel, they highly prefer learning by experience rather than memorizing safety facts. Thus, learning by experience is found to be highly effective. Experiential learning also considers both content and context, in line with the total learning environmental philosophy (Hawtrey, 2007). A scenario-based approach can address both context and content than the conventional methods. Therefore, assessment with scenario-based questions is more appropriate in the context of construction safety education. Similarly, the cognitive process of learning has six major categories: 1) Knowledge, 2) Comprehension, 3) Application, 4) Analysis, 5) Synthesis, and 6) Evaluation (Bloom, Engelhart, Furst, Hill & Krathwohl, 1956). In order to gain a better learning outcome, these six aspects of an individual should be stimulated. Still, limiting these three aspects won't optimise the aim of safety training. Working on a construction site is not an individual task. It is more collaborative, and site personnel needs to work together with others. Caring for others and pushing themselves to self-directed learning will enhance construction safety drastically. Thus, while stimulating the cognitive process of learning, safety training should also address the collaborative safety behaviours and continuous learning aspects of the trainees. The developed conceptual framework for safety assessment addresses all the above-identified three aspects of learning (Cognitive, behavioural, and continuous learning). Thus, a scenario-based safety assessment system developed adopting this framework will directly impact all the learning aspects of construction safety and will ultimately aid in reducing safety-related accidents. On the other hand, this framework contributes to research on safety training as it broadens the horizons of safety assessment.

2. CONSTRUCTION SAFETY TRAINING AND ASSESSMENT

After conducting a thorough literature analysis for construction safety training and assessment, it is found out that the higher focus is given to safety training compared to safety knowledge assessment. This section briefly summarises the key literature findings for both safety training and assessment.

2.1 Construction Safety Training

"Safety training within the construction industry is often quite mundane and generic, which is a problem for an industry combatting with high fatality rates on job sites for decades" (Bhandari, Hallowell, & Correll, 2019). According to Park & Kim (2013), with the proper establishment of the safety management process, safety planning, inspection, training, and education, most construction safety-related accidents could have been reduced. Therefore, research on safety education has become quite popular in the past few decades. Researchers focus on various aspects to develop more effective and efficient safety training programs. Earlier, students gained their safety education with the use of resources such as chalkboards, handouts, and computer presentations that are many words and few visual elements (Li, Yi, Chi, Wang, & Chan, 2018). Still, static images or presentations to represent active operations in a construction site restricts to one capture even though a picture is worth a thousand words (Lin, Son, & Rojas, 2011). Therefore, many argued that on-the-job training is highly effective since it gives a first-hand experience to the learner (Goulding, Nadim, Petridis, & Alshawi, 2012). However, there are severe drawbacks to on-the-job training as it is expensive, hazardous, time-consuming, and needs expertise involvement (Goulding et al., 2012; Li et al., 2018). Therefore, Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR) technologies have been introduced to construction safety education and training (Li et al., 2018)

From the start, researchers put their effort into finding out which method is more effective between the traditional paper-based method and the Virtual Reality prototyping method. The earliest could be found from the research done by Lucas & Thabet (2008), in which they have developed a VR-based program to train the conveyor belt operators. A similar but advanced VR training model was developed by Sacks et al. (2013) for stone cladding, cast-in-situ work, and general site safety. In addition, Teizer, Cheng, & Fang (2013) conducted research on ironworkers' safety training and education using location tracker and data visualisation technology. Likewise, the majority of the safety education research carried out on developing VR models to aid trainees to learn and identify potential hazards and act upon the situation (Hafsia, Monacelli, & Martin, 2018; Li et al., 2012). A different approach was taken by Goulding et al. (2012), which is to develop and VR environment that enables unforeseen problems often caused by professionals' decisions, faulty work, and health and safety issues to occur; where the implications of which can be evaluated in respect of time, cost and resources.

2.2 Safety Assessment

Research on safety knowledge assessment is given a lesser priority compared to safety training. Among the few research available, Le et al. (2015) researched on developing a mobile-based VR and AR incorporated safety education system. This framework consists of three modules, namely, Safety Knowledge Dissemination (SKD), Safety Knowledge Reflection (SKR), and Safety Knowledge Assessment (SKA). Another research conducted by Li et al. (2012) introduced a new safety assessment method, 4D Interactive Safety Assessment, focused on risk identification. This method involves different safety scenarios related to the construction project for workers to identify and select safety actions from the given pool. Even though there are different levels in the assessment system, all levels stimulate the same cognitive functions, identification, and analysis. In terms of developing a systematic and comprehensive assessment system, Pedro et al. (2019) research on developing a context-based knowledge assessment system is remarkable. The assessment system was developed based on Bloom's taxonomy and is well structured. With a careful analysis, it is found that Bloom's taxonomy is commonly used in designing teaching curricula to address the students' knowledge and cognitive processes (Krathwohl, 2002), which is focused on individual knowledge development.

However, the Hong Kong Occupational Safety and Health Regulation describes another aspect of safety education: the employees at work to take care of others and to co-operate with the employer (Labour Department, 2012a). "Caring" is an interpersonal skill, rather than a personal skill, not covered in Bloom's taxonomy and can be developed with collaborative training. Le et al. (2015) also support the idea that collaborative training increases the efficiency of the learning experience. The majority of the activities in a construction site require more than one person, and workers usually act collectively. Due to this collective behaviour, there is a high probability of recognizing more potential hazards in the working environment rather than when acting individually. On the contrary, workers get distracted more often when they work as a group, and as a result, they can miss a deadly hazard which can be extremely harmful. To eliminate this drawback, collaborative training and assessment should be incorporated into safety training curricula. By adding this, workers can get experience on how to behave in a site where more people work together, how to analyse others' behaviour in hazardous situations and how to communicate effectively to avoid other workers from getting injured by hazards.

Even though assessing collaborative behaviour is critical, no research could be found addressing this issue. Similarly, construction safety scenarios need to be carefully selected to avoid repetitions and the same cognitive demand. Ultimately, the developed system needs to be comprehensively assessed to see whether the final product address all the learning objectives. Thus, this research aims at developing a multi-level knowledge mastery assessment system (MKMAS) to provide a collaborative safety knowledge assessment. In order to achieve this aim and answer the above research questions, three objectives have been formulated: 1. To develop a conceptual framework based on a learning taxonomy that can assist in obtaining the mastery level of the proposed assessment tool, 2. To identify, design, and integrate appropriate construction safety scenarios according to the developed conceptual framework and 3. To implement and evaluate the developed MKMAS to check whether the final product provides intended learning objectives.

3. RESEARCH METHODOLOGY

The research methodology of this study can be categorised into four parts. As the first part, the most appropriate learning taxonomy has been recognised through a literature survey and developed a conceptual framework based on the recognised taxonomy. Second, construction safety scenarios have been identified and designed virtually. Then a complete VR application was developed incorporating application navigation and assessment scoring functions. Thirdly, an experiment is conducted with voluntary participants to evaluate the system and participants' ability to conduct a virtual construction safety assessment. Finally, the results of the experiment are assessed, discussed, and concluded comprehensively. Research methodology is explained in detail in the following sections.

3.1 Conceptual Framework Development

A conceptual framework assists the researcher in identifying and constructs the phenomenon that is being researched in the study (Adom et al., 2016). After reviewing few learning taxonomies such as Bloom's taxonomy (Bloom et al., 1956; Krathwohl, 2002), the SOLO (Structure of the observed learning outcome) (Biggs & Collis, 1982) and Fink's taxonomy (Fink, 2003) from literature, Fink's taxonomy, also known as the taxonomy of significant learning, has been utilised to develop the conceptual framework of the study. The taxonomy of significant learning goes beyond the cognitive domain to address a new set of skills such as learning how to earn, leadership, communication, and ethics (Fink, 2003). Fink's taxonomy addresses both cognitive and behavioural aspects of the learner. Thus, this is a perfect solution to address the research gap identified in the previous section. There are six key components in Fink's taxonomy that affect the students in different ways (Levine et al., 2008): foundational knowledge, application, integration, human dimension, caring, and learning how to learn.

Based on that, the conceptual framework for this study is designed, including five levels. The framework consists of six levels of learning (Fig. 1), and each level is linked to an assessment module and assessment target. Two levels, Caring and Human dimension, are combined into one assessment module since both of them are designed to learn about oneself and others as well as to develop feelings, interests, and values towards others. In this study, the combined effect of these traits of the participants will be assessed. Thus, the assessment system consists of five main levels. The whole system is comprised of real construction scenarios obtained from construction safety education curricula, safety manuals, and related journal articles. Scenarios are carefully selected to match the intended learning outcomes of each level.

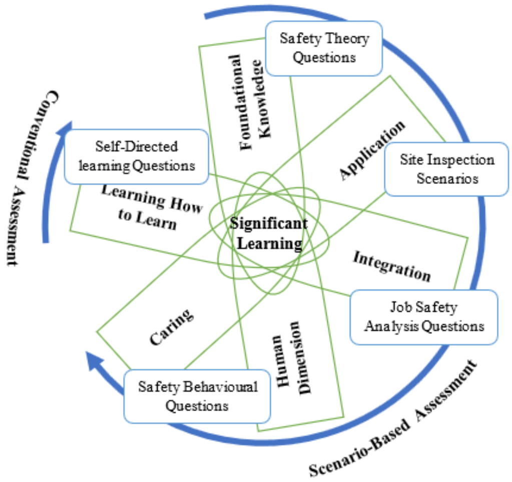

Fig 1. Theoretical framework

3.2 Implementation of Framework

This section demonstrates how the developed conceptual framework is being implemented as a scenario-based assessment system for construction safety education. Level one (Foundational knowledge) comprises Safety Theory Questions (STQ) which test the basic theoretical knowledge through different scenarios. To assess the knowledge application (level two), a Site Inspection Scenario (SIS) is introduced. Students are required to apply their safety knowledge to identify hazards in the construction site and suggest appropriate safety measures for such hazards. Level three comprises Job Safety Analysis (JSA). To a given construction scenario (i.e., a room in a building where the structure is completed and ceiling work and painting are pending), students are required to analyse the job-site and to identify the actions that will be taken place in the site (i.e., material hoisting, plastering, installing ceiling panels), identify the potential hazards (i.e., collapsing of scaffoldings, falling of objects, tripping) and provide relevant hazard controls (i.e., proper installation of scaffoldings, wear safety helmets, keep the floor clean). To perform this task, students need knowledge of construction technology, project management, and safety management. A collaborative site inspection task is included in level 4 (Safety behaviour) to test how students behave in hazardous situations as well as how they communicate with each other to protect others from harm's way. The last component is 'Learning how to learn', which encourages continuous learning of new safety measures and preventive and proactive actions to mitigate the risks. This part is completed through a standard questionnaire which consists of questions and recommendations to the students to learn more about construction safety (Level 5 is not assessed in this study).

3.3 Scenario Identification and Development

Once all the levels were outlined in accordance with the conceptual framework, scenario identification was conducted for each level. Hazard scenarios are decided after studying the content of "Approval Conditions for Operating Mandatory Safety Training Courses Part II – Module 1(a)" published by the Hong Kong Occupational Health and Safety Branch (Labour Department, 2012b) and an article (Perlman, Sacks, & Barak 2014). The selected scenarios are most common but not limited to a building construction site. The selection varies among general site work, concrete work, masonry, preliminary work, finishing, etc. Identified scenarios are summarised in Table 1. The scenario selection was based on some of the common hazards in a construction site that cover different hazard types (i.e., fall hazards, electrical hazards, fire hazards, hazards by heavy machinery) and which are visually recognizable to the participants in the virtual environment.

Table 1: Identified scenarios at each level

Assessment Level	Scenario
Level 1	1. Concrete drilling work with a hand-held drilling machine. The electrical cord is damaged and laid on the ground near some reinforcement bars. 2. Concrete pouring work using the pouring machine. Workers on the concrete mixture do not wear a hard hat and gloves. 3. Oil spill near a stack of bricks. Workers are working nearby with all the PPE gears. 4. Wall painting work. Workers stand on an improvised platform (Planks laid on two ladders). Workers are equipped with all the safety gear. However, the platform is unsafe. 5. Workers are standing very close to an unstable stack of blocks
Level 2	1. Moving excavator without an assistant to the operator. Blind spots are not barricaded. 2. A stack of unprotected R/F bars laid on the floor, not in an orderly fashion. 3. A set of scaffoldings fixed below the Head Hight. No warning sign is placed. 4. A gas tank is kept near to a welding work. The welder and the supporter are not wearing gloves and masks. However, they are equipped with goggles.
Level 3	Potential hazards need to be identified by the participant.
Level 4	1. A moving crane carries a weight overhead. No barricades or warning signs in the area. 2. A large open pit. 3. Wood planks are laid on the ground, and some nails on planks can be visible. 4. An open scaffolding and the opened side faces a large pit.

Once the scenarios have been finalised as listed in table 1, prototype development has been initiated. Unity 3D is mainly incorporated for application development. Additionally, Autodesk Maya is utilised in developing 3D assets for the game. The main construction environment and two sample scenarios are illustrated in figure 2.

Fig. 2: Scenes in the VR application: (a) Main construction site, (b) Level 1 – scenario 1, (c) Level 4 – scenario 4

Five scenarios in level 1 are designed as static scenes which only focus on emphasizing the hazard scenario. Each scenario comprises only the essential assets to avoid confusion. Multiple choices (5 choices) related to the hazard were displayed near each scenario. Participants can inspect the scenario and select the most appropriate answer from the given list. Level 1 is considered to be the easiest of all levels. Level 2, which targets the application of safety knowledge, is comparatively difficult against level 1. Level 2 is designed utilising the complete construction site with all kinds of props and assets spread all over the scene. Furthermore, designed safety scenarios are also not highlighted. In order to find the hazards, participants need to walk around the construction site and click on the hazardous locations. Once the participant clicks on the correct location, a list of related answers appears, and the most appropriate answer should be selected. Level 3 is designed to test the knowledge integration skill of the participant. In order to achieve this, a job site analysis activity is designed. A Voice recording facility is incorporated in this level so that the participants can speak out the answers. With the voice recording facility, participants can save much time typing answers and worry about spelling and grammar. Level 4, which is the final level of the application, is focused on multiplayer site investigation. This level is designed to target the human dimension and caring aspects of Fink's taxonomy. Same as in Level 2, participants have to walk around the same construction site but with totally different hazards placed in different locations. At this level, a group of a maximum of 4 participants can visit the site together, and each player can see the other participants and their current positions. Once a participant recognises and clicks on a hazard, a warning sign will appear on top of the hazard, and this sign will only be visible to that participant. Thus, he/she needs to communicate this finding with other participants and instruct them about the location and nature of the hazard.

3.4 Application Features

The developed VR application is comprised of few distinct features that primarily contribute to ease of use. Among these features, a hierarchical menu system, Animations, Automatic scoring, and voice recording are significant.

Menu system: In order to navigate easily between levels and different scenarios, a hierarchical menu system was integrated into the application. The application starts with the main menu, and it directs to a sub-menu that consists of links to all the levels and scenarios of the application. Each scene (scenarios in level 1 or other levels) has two-way access (from sub-menu as well as from the preceding scene) anywhere in the application. In this way, students can easily navigate between levels and scenarios without losing much time.

Animations: To replicate the dynamic nature of the construction site, few animated objects are also placed in both level 2 and level 4. In level 2, an excavator, and in level 4, a mobile crane was animated, assigning some hazard situations in relation to those activities as well. Following figure 3.9 demonstrate both animations.

Automatic Scoring: Scoring of the assessment at level 1 and level 2 was automated, and a text file was generated with the participant ID number as the file name. This file contains all the answers given and the related mark to the given answer. Hence, manual scoring of level 1 and level 2 was eliminated. Still, the investigator has to score for level 3 and level 4 since automatic scoring for qualitative answers can be difficult and tricky. A sample scoring sheet is provided in figure 3.10

Voice recording: Previous studies such as Pedro et al. (2019) conducted a virtual job site analysis by instructing the participants to type their answers, such as potential hazards and hazard control techniques in a given scenario. Typing an answer in a virtual environment can be tedious and frustrating. In addition, participants can get caught with grammatical and spelling errors, which will hinder the time utilization for this task. As a solution, a voice recording function is integrated at level 3 so that the participants can convey their answers by voice, and those answers will be recorded for the assessor to listen and give marks at the time of scoring.

3.5 Experiment Process and Data Collection

A total of 21 construction engineering students from the City University of Hong Kong were invited for testing. The experiment was conducted at the ACE BIM lab (See figure 3).

Fig. 3: Experiment process

Before starting the assessment, participants were asked to watch an instructional video on construction site safety. The video runtime is approximately 11 minutes, and only the key safety concerns were highlighted during the video duration. To increase the understanding of its content and to keep the participants' interest throughout the video, key points were annotated in bold letters. The safety instructional video cover use of personal protective equipment, proper use of machinery, electrical, fire, and fall hazards, site cleaning, and so on. This video is intended to refresh the participant's knowledge of construction safety and onsite hazards.

Next, a brief instruction was given about the assessment, its structure, and what was expected from the participants. Then, HTC Vive was introduced to the participants to get them familiar with the VR operation. Once the participants were satisfied with the preliminary instructions, they were invited to conduct the experiment pairwise, and the investigator recorded how they delivered answers and behaved in the last two levels. Once the assessment was completed, the participants were asked to fill two questionnaires- the NASA-TLX survey and the Application assessment survey. The time spent on filling both the questionnaires was around 7-10 minutes.

In the NASA-TLX survey, participants are asked to rate their experience from low to high on five subscales: Effort (E), Frustration Level (FL), Mental Demand (MD), Performance (P), Physical Demand (PD), and Temporal Demand (TD). Next, the participants were asked to conduct a pairwise comparison on which criteria contributed more against the other. The application assessment survey is also a two-part questionnaire survey that is designed to obtain participants' level of agreement towards the content of the VR application. Once all the participants completed the task, results were compiled and brought for analysis. The experiment was concluded with a feedback session.

4. DATA ANALYSIS

This section describes the analysis of collected data from the VR experiment. Data analysis is divided into four main categories – 1. Demographic analysis, 2. Workload analysis, 3. Application performance analysis, and 4. Participant performance analysis.

4.1 Demographic Analysis

In this section, participant demography is analysed based on their gender, age, and years of experience in the construction industry. Then, this information is used in assessing the respective workload and participant performance at later stages.

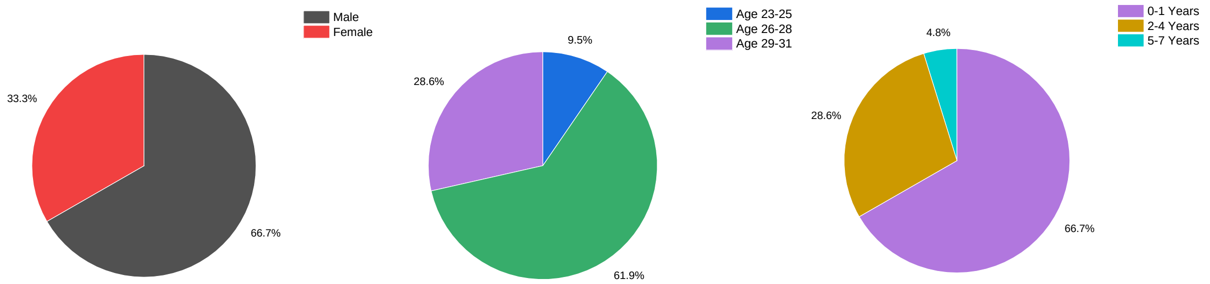

Fig.4: Participants' demographic information- gender, age, and years of experience

As shown in figure 4, a majority (2/3) of the participants are male, and 62% of the participant falls into the age 26-28 category. The reason is all the participants are Ph.D. students who have already completed their bachelor's degree, and most of them are currently in the second year or final year of their study. Years of experience depending on the path that the participant chose to do the Ph.D. Thus, the majority of the participants do not have or have less than one year of experience as they may have pursued their Ph.D. just after graduating with their first degree.

Still, this sample is a mixture of experienced and inexperienced participants in the construction industry and its environment. All the participants are directly come from construction or closely related background. Thus, it can be concluded that the results generated from this experiment are valid from an industry perspective as well as from a student perspective.

4.2 Workload Analysis

Results of the NASA-TLX survey were compiled and generated the mean weighted workload as illustrated in figure 5. Analysing the below graph, it is visible that out of six workload subsets, MD carries the highest average value, which is 227.62, indicating that the developed assessment system is mentally demanding comparatively to the other subscales. Compared to MD, E and TD carry the medium workload, and according to the participants, PD is the lowest that gives an average value of 21.43. The lowest value in PD indicates that the assessment was not physically demanding. Analysing the performance criteria indicates that participants feel like they have an average performance in identifying, analysing, and integrating safety hazards within the assessment. Average FL is also at the lowers side, indicating that participants feel comfortable conducting the assessment. Similarly, the distribution of interquartile range (IQR) can be seen in the same pattern as the highest IQR from MD and the lowest from PD. E and TD contain approximately similar IQR where FL and P fall between PL and PD in terms of IQR. Few outliers are also identified FL, P, and PD.

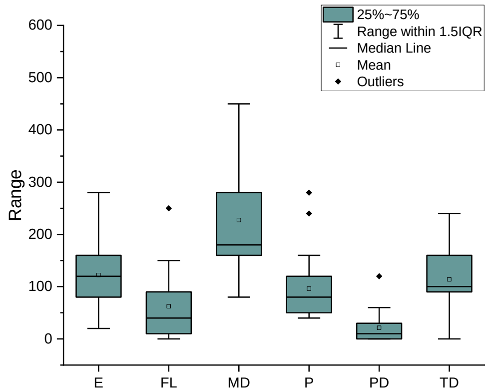

Fig. 5: Mean weighted workload

4.3 MKMAS Performance Analysis

The performance of the developed MKMAS is analysed from the responses generated from the questionnaire survey. Prior to analysing the statistical data, Cronbach's alpha coefficient (Taherdoost, 2016) was calculated to test the reliability of the questionnaire. The above Cronbach's alpha equation is applied to the two sections of the questionnaire survey 'Satisfaction of Fink's Taxonomy' and 'Transparency evaluation'. Results show that Cronbach's alpha coefficient for 'Satisfaction of Fink's Taxonomy' and 'Transparency evaluation' are *0.84* and *0.88,* respectively, which are over the minimum value of 0.7 (Whitley, 2002).

4.3.1 Satisfaction of Fink's Taxonomy

Satisfaction of Fink's taxonomy by the assessment system was investigated through four key components of the taxonomy, namely foundational knowledge, Application, Integration, and Human dimension and caring. In this section of the questionnaire, 14 questions were asked to increase the accuracy of the responses. Participants' level of satisfaction was recorded through a 5-point Likert scale ranging from strongly disagree to strongly agree. Mean and standard deviation (SD) were then calculated. Results show that all four categories of 'satisfaction of Finks taxonomy' received an almost similar level of mean values, which were *4.4, 4.6, 4.3* and *4.24,* and SD were *0.407, 0.509, 0.350* and *0.546,* respectively. All the values belong to the 'Strongly agree' category, where participants agree that the VR application is highly in line with the objective of Fink's taxonomy. By analysing the standard deviation (SD) of the average values, it is visible that they are small, suggesting higher consistency of responses from the participants. Next, a pairwise comparison was conducted to investigate the prominent component of Fink's taxonomy in the assessment system. Following Table 2 demonstrate the results from pairwise comparison.

Table 2: Pairwise comparison- components of Fink's taxonomy

	FK	A	I	HDC	Score	Rank
FK	-	1/2	2/3	13/21	1.79	**1**
A	1/2	-	5/7	11/21	1.74	**2**
I	1/3	2/7	-	16/21	1.38	**3**
HDC	8/21	10/21		-	0.86	**4**

According to the above table, Foundational knowledge appears to be the prominent feature of the assessment system. Application, Integration and human dimension, and caring have been ranked from second to fourth, respectively. Furthermore, it is evident that foundational knowledge and application got *1.79* and *1.74,* respectively, indicating that those two components are closely prominent in the assessment system.

4.4 Transparency Evaluation

Transparency of the assessment system was evaluated under three criteria fairness, clarity, and practicality. Fourteen questions were formulated under these three criteria for the participants to respond accurately. Results show that all three criteria received almost similar levels of mean values, which were *4.15, 4.10,* and *4.00,* and SD were *0.527, 0.631,* and *0.400,* respectively, which ascertain that participants agree that the assessment system is fairly transparent. A pairwise comparison was also conducted for the above three criteria, and the comparison results are as follows.

Table 3: Pairwise comparison- transparency criteria

	F	C	P	Score	Rank
F	-	11/21	10/21	1.00	**2**
C	10/21	-	3/7	0.90	**3**
P	11/21	4/7	-	1.10	**1**

Considering the prominent criteria of the assessment system, practicality was ranked as number one with a score of *1.1* and fairness was given second place with the score of *1.00,* and *0.9* was given to the clarity ranking it as the third. Still, the value difference is fairly low, which suggests that even practicality is numerically prominent, all three criteria are recognised as equally significant by the participants.

4.5 Feedback Session

To obtain further insights into the assessment system, a discussion was carried out with the participants, where they were asked to freely express their opinions about the assessment system, its functions and features. An abundance of positive feedback was received, such as the assessment is enjoyable to conduct, the assessment is comprehensive, it gets harder when moving up, and the system architecture was user-friendly, which enabled easy navigation. Few noteworthy comments were also received for further improvement. The need to address dizziness during the assessment, allocate time limitations for each task, allow for incorporating multi-languages to the platform, and increasing the number of hazards are a few of the improvements that are suggested by the participants.

4.6 Participant Performance Analysis

During the assessment, participants were scored according to the answers given at each scenario at each level. Since the scenarios at levels 1 and 2 have one correct answer, those answers were scored automatically by the application. At level 3, participants verbally answered the questions, and those answers were manually scored by the assessor. At level 4, participant behaviour in a collaborative environment is assessed manually. Following figure 6 summarises the marks obtained by each participant.

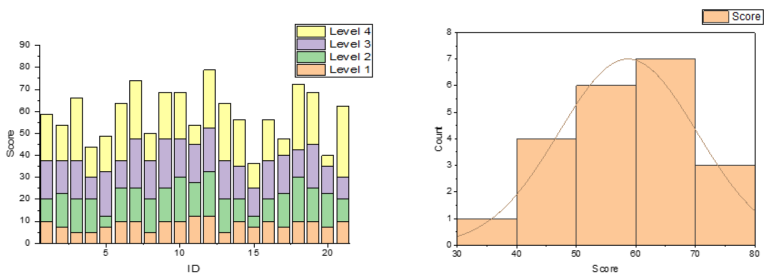

Fig. 6: Marks obtained by each participant and marks distribution

According to the above figure 6, participants have obtained marks ranging from *36.25* to *78.75* out of *100*. Score allocation for each level is *12.5, 20, 30* and *37.5,* respectively. Analysing the figure, it is visible that there are no drastic variations in level 1 and level 3 scores compared to the other two. The participant who had the lowest marks got low marks at every level, and the highest scorer was vice versa. It is also visible that participants who scored higher marks have done well in level 4. Similarly, the distribution of the total marks among the participants is normal. The correlation coefficient was calculated for total marks obtained by each participant and their performance value given at the NASA-TLX survey to derive the relationship of these two parameters. The correlation coefficient of these two variables was *-0.287,* indicating that there is no significant correlation

5. DISCUSSION

This section discusses the analysed findings from section 4 in detail. The performance of MKMAS was evaluated through a cognitive and mental workload assessment, satisfaction of the theoretical framework and the transparency of the system.

The cognitive and mental workload was assessed employing the standard NASA-TLX survey, and a complete statistical analysis was conducted in the previous section. The design and operation of the MKMAS highly correlate with the results generated. Due to the complex and dynamic nature of the activities and scenarios, MD is significantly higher than other criteria. Similarly, the assessment is easy to conduct physically, just in one sitting. Necessary instructions for all the aspects such as assessment criteria, purpose and navigation are clearly expressed verbally and visualized in the assessment screens when necessary. Thus, PD and FL values became lower. Moreover, assessment gets harder in upper levels, and participants have to work hard on completing each task successfully. Thus, it requires some effort which denotes by the moderate E value. Marks obtained are not displayed, and hazards in upper levels are not distinctive. This results in uncertainty in how participants perceive their performance which is indicated by the moderate value of P. Still, the relationship between the participant's actual performance and his/her perception of the performance is not significant, which indicates that they tend to over or underestimate their performance. Even though the time spent on each level was not critically assessed in this experiment, the application seemed to have a moderate temporal demand. Considering one of the common feedback received from the participants, dizziness might be the reason that they rushed to complete the assessment. This issue needs to be considered when further improving the application.

Next, the performance of the MKMAS was analysed through a two-part questionnaire survey on how the application satisfies the conceptual framework and its transparency. Results suggest that all the four components of Fink's taxonomy are highly satisfied by the application. Participants strongly agree that MKMAS consists of foundational knowledge at level 1, application at level 2, integration at level 3, and human dimension and caring at level 4. Thus, it can be concluded that MKMAS satisfactorily fulfilled the learning objectives of Fink's taxonomy. Furthermore, the pairwise comparison suggests that out of four components, Foundational knowledge is prominent compared to others. This is due to the fact that to complete all four levels, and foundational knowledge is essential even though it is only tested at level 1. The second part of the questionnaire is intended to evaluate the transparency of the developed MKMAS. Results generated from the responses indicate that they 'agree' that the application is transparent. Ample time was provided for all participants to conduct the assessment, and everybody got a fair chance to complete it. Similarly, all the participants were required to watch the instructional video irrespective of their gender, age, or experience. In terms of clarity, clear instructions were given at the start of the experiment about MKMAS, what is expected from the participants and how to properly use VR gear. Besides, the same instructions were provided at the start of each level, and the participant had the ability to read them at any point of the time. Furthermore, the instructor assisted each participant during the entire assessment period. In terms of practicality, all the scenarios are carefully selected from training manuals and previous research to demonstrate the actual hazards at the construction site. This also agrees with the response on practicality criteria. The pairwise comparison suggests that the assessment is more practical compared to fairness and clarity. Still, the level of significance is nearly equal, suggesting that MKMAS is balanced.

The feedback session generated some noteworthy comments from the participants for improvements to the MKMAS. Overall, participants are excited to conduct the assessment, especially those who are new to VR. They suggested that the application is properly organised and versatile in terms of navigation between scenarios and levels. A major concern of the application was dizziness, which was persistent with the majority of the participants. Motion sickness is an inherent feature of VR headsets and can be controlled by using the latest versions of the VR gear (Munafo, Diedrick, & Stoffregen, 2017). The application itself used some methods to reduce motion sickness, such as slowing down the walking and falling speed and removing unwanted objects on site.

As for the suggestions for improvement, displaying scores were suggested. Authors argue contrary to that since it can assist the participant in changing the answer and keeping on selecting answers. That can undermine the aim of the assessment. Furthermore, suggestions were given to integrate multi-lingual features to the MKMAS and to reduce the size of the site at levels 2 and 4. These suggestions will be considered in further developments.

Finally, participant performance was analysed. Every participant scored sufficiently, and it is visible that there is some correlation to the level of experience and the mark obtained, suggesting that participants with higher safety knowledge scores well compared to the ones with low safety knowledge. This proves that the intended outcomes of a safety assessment are fulfilled by the developed MKMAS.

6. CONCLUSION

Despite the continuous evolution for centuries, the construction industry is still considered one of the hazardous industries in the world. Even though mandatory construction safety training and assessment have been introduced, statistical data suggest no significant improvement of the outcome. Several key drawbacks have been identified of current safety training and assessment programs, such as ineffectiveness of traditional training methods and expensiveness and hazardous nature of onsite training. As a solution to both major drawbacks, the applicability of VR is extensively researched. Activities at a construction site are generally performed by a group of workers, and one person's behaviour affects the other. This phenomenon of collaborative behaviour in construction safety training has not been discussed before. Thus, this research aimed at developing a multi-level knowledge mastery assessment system (MKMAS) that encourages collaborative behaviour in construction safety assessment.

Fink's taxonomy, also known as the taxonomy of significant learning, was adopted to develop the theoretical framework of the MKMAS. Based on the developed theoretical framework, a four-level scenario-based VR assessment system was developed containing 14 construction safety scenarios. The developed MKMAS was then evaluated via experiment followed by a questionnaire survey for mental and cognitive workload assessment, application performance assessment, and participant performance assessment. Results suggest that the developed MKMAS is robust and has the potential to apply to university education curricula by incorporating more relevant and appropriate tasks to meet the requirements. This assessment system is an improvement to the previously researched VR-based assessment systems, and this also has the potential to improve and explore the construction safety domain.

The developed MKMAS system opens few research directions on adopting VR for construction safety. Introduced multiplayer approach for collaborative site inspection needs to be explored extensively on replicating the true dynamic nature of a real construction site. Also, this study can be explored with other construction types such as infrastructure construction (roads, bridges) by customizing the content. Current and previously developed VR applications for safety training have only used digitally constructed sites, and this hinders the true nature of the environment. Thus, it is suggested to explore integrating real construction environments to the VR environment and test the effectiveness.

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The Application of Eye-tracking Technology in Architecture Engineering and Construction Industry: A Systematic Review

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ABSTRACT: *Despite the scholarly attention on eye-tracking technology in the AEC industry, no studies thus far have attempted to aggregate the findings or knowledge. To bridge this gap and to better understand the state-of-the-art of eye-tracking technology's application in the AEC industry, this study reviews and synthesises the existing research evidence through a systematic review. Such a review is highly critical in this area, given the vast number of published work albeit a lack of aggregation of the findings and knowledge. A full range of journal articles between 2010 and 2020 (inclusive), that address the application of eye-tracking technology in the AEC industry was systematically assessed after a thorough search of key academic databases. Based on rigorous inclusion and exclusion criteria, 18 eligible articles were selected for final review. This study develops a generic taxonomy built upon a wide range of Scholarly journals. Further, the eligible literature was classified based on this taxonomy and presented.*

KEYWORDS: *Eye-Tracking, Construction, Human-Behaviour, Visual Search*

1 INTRODUCTION

Despite being one of the largest industries in the world economy, Architecture Engineering and (AEC) industry has persistently displayed a poor productivity index(Barbosa, et al. 2017). Modernisation and resulting in poor human performance were once the biggest challenge faced by the AEC industry (Rakib, et al. 2020). However, in recent years the AEC industry has been constantly exposed to the advancements in digital information and technology leading to the development of innovative tools and processes. Eye-tracking technology is one of such technological advancements embraced by the AEC industry recently. The use of eye-tracking technology equips the industry with the ability to measure various gaze metrics and visual behaviour that can provide unique insights into human behaviours, which are otherwise impossible to measure using subjective tools (Yousefi, et al., 2015). This exciting opportunity offered by eye-tracking technology has attracted the attention of a growing number of researchers from the AEC domain.

Apart from the application of eye-tracking in aviation, driving, marketing, neuroscience, psychology etc, various studies (e.g., Dzeng, et al. 2016; Gestson, at al. 2019; Liao, et al. 2021) have reported that eye-tracking technology can be highly beneficial in building design, construction, and operation activities such as safety assessment, site inspection, space planning design evaluation, assessment of visual acceptability of design and ergonomics. Thus, eye-tracking technology's application in the AEC industry belongs cannot be over-emphasised. However, some studies (e.g., Yousefi, et al. 2015) have pointed out that, the wider utilisation of eye-tracking technology in the AEC still faces challenges due to lack of knowledge about opportunities and complexity of the technology as well as associated methodologies for its effective use. To bridge this gap and to better understand the state of the art of eye-tracking technology's application in the AEC industry, this study reviews and synthesises the existing research evidence through a systematic review. Such a review is highly critical in this area, given the vast number of published work albeit a lack of aggregation of the findings to understand the knowledge domains.

2 EYE-TRACKING TECHNOLOGY

The human retina is bombarded with a vast amount of visual information as they move through a rich and complex environment in everyday life. In this complex environment, the human brain uses a mechanism called *selective attention* by which the brain selects and focuses on a few important areas for cognitive and visual processing **Error! Reference source not found.**. Thus, tracking eye movement offers a direct way to measure overt spatial attention, cognitive process and arousal, providing a direct window into the brain **Error! Reference source not found.**. Eye-tracking is a sensory technology that makes it possible for a computer or other device (screen-based, glasses or virtual reality-based) to understand where a person is looking based on optical tracking of corneal reflection, thereby making the analysis of eye movements and gaze positions in both 2D and 3D environments **Error! Reference source not found.**. Through the utilisation of eye tracking, it is now possible to acquire unique insights into human attention and what information is processed, which could provide a deeper understanding of what affects human behaviours, decisions making and emotions. This provides both qualitative and quantitative analysis of the gaze, which is highly valuable in understanding human choice behaviour and perceptual decision making (Blair, et al. 2009). Initially used by psychology researchers in human behaviour research followed by marketing research, eye tracking gradually caught the attention of researchers from a wider domain like engineering, neuroscience, medicine and so on. For example, (Alruwaythi & Goodrum, 2019) used eye-tracking to understand how the gaze pattern of craft workers are influenced by the information format (2D and 3D) and spatial cognition which building complex spatial tasks. **Error! Reference source not found.** utilised eye-tracking to evaluate the spatial orientation of attention, performance in visual tasks, the user's reaction to information presented on websites, and the emotional and cognitive impact of various spurs of the brain. Similarly, in the medicine domain also studies (e.g., **Error! Reference source not found.** have utilised eye tracking to understand the decision making and the mechanism underlying misinterpretation of a misdiagnosis. Beyond studies based on basic visual search, eye-tracking technology has also been of interest to the broader research community with applications ranging from saliency models of visual content analysis **Error! Reference source not found.**, design evaluation (Bylinskii et al., 2017) usability studies (Nielsen & Pernice, 2010), as well as by gaming industry (Heimler, et al. 2014).

3 EYE-TRACKING TECHNOLOGY IN AEC INDUSTRY

Even though eye-tracking has been widely used for decades in vision research, language and usability studies, in recent years a greater interest has been witnessed by the researchers from the AEC industry. This could be because of the lagging productivity in the AEC industry which is mainly attributed to the issues related to human factors, where eye tracking can provide greater insights into human behaviours and cognitive processes, which is impossible to elicit using subjective measures. For instance, studies (Liao et al., 2021) suggest that human error is one of the main factors contributing to 80% of construction site accidents due to the lack of situational awareness. Apart from the pain, suffering and distress, these accidents and fatalities pose a considerable amount of economic burden on this sector. Estimates suggest that in the UK alone, the annual cost of the injuries exceeds 1.2 billion which accounts for 8% of the total cost across all industries as well as 2 million working days (Itti & Koch, 2001). With the use of eye-tracking, it is now possible for the researchers to objectively study the role of cognitive failures (i.e., inattentiveness) in accidents and improve construction safety training based on these data. Similarly, eye tracking can assist architects and designers to design and develop complex buildings and potentially reduce the cost by understanding human behaviours and creating human-centric designs (Pring, 2018). The application of eye-tracking in the AEC industry is not only limited to areas related to visual search patterns. For instance, **Error! Reference source not found.** used a similar approach to understand end-user satisfaction in a building design. Further, studies (e.g., Gestson, et al. 2019) have also used eye-tracking to understand the problem-solving persons of civil engineering practitioners. Cumulative evidence shows that eye tracking has huge potential in the AEC industry. However, when compared to the application of other emerging technologies like virtual reality and augmented reality, a dearth in research can be seen in relation to eye tracking in the AEC industry. Yousefi et al., (2015) point out wider utilisation of eye-tracking technology in the AEC still faces challenges due to a lack of knowledge about the complex eye-tracking metrics and potential of this technology. Thus, this study aims to reviews and synthesises the existing research evidence and aggregate those findings and knowledge for future studies.

4 METHODOLOGY

To comprehensively explore the role of eye-tracking in the AEC industry, a systematic review was conducted supported by both descriptive statistics and qualitative analysis of content. The additional qualitative data analysis was carried out to identify thematic areas of the application of eye-tracking in the AEC industry. A qualitative methodology is best suited for this study as it will aid in identifying findings from various studies on the subject area that will aid in achieving greater understanding and accruing a higher level of conceptual or theoretical knowledge of how eye-tracking technologies are evolving in AEC research (Campbell et al., 2003). The research stages in this study consist of *a)* identification of journals *b)* review of journals *c)* definition of classification framework *d)* classification of journals based on the framework.

To identify suitable literature an inclusion and exclusion criteria were developed for this study which aims in answering two key questions: *a)"* Is the study relevant for the review purpose?" *b)* "Is the study acceptable for review?” as proposed by (Meline, 2006) (p.22). This laid fountain for the development of reliable inclusion and exclusion criteria. Even though a reliable inclusion and exclusion criteria might reject a large proportion of the literature, it promises a quality systematic review (Chambers, 2004).

4.1.Inclusion and Exclusion Criteria

- Articles published between 2000 and 2020 (inclusive) were only considered to maintain currency.
- Articles that utilise eye tracking in the AEC industry was only considered
- Only peer-reviewed journals were considered for this study to maintain a predetermined threshold of quality. Conference papers, book chapters or non-international journals were excluded, thus satisfying the best evidence principle proposed by (Slavin, 1986).
- Literature that discusses theory, concepts or proposals without any experimental testing were also excluded.

This study utilised a four-stage approach (Figure-1) based on the preferred reporting items for systematic literature review and meta-analysis (PRISMA) framework (Moher, et al. 2009) and the inclusion-exclusion criteria were applied to identify relevant literature. Two prominent databases (Scopus and Science Direct) within the construction engineering and management domain were chosen to identify the eligible literature. Figure 1 explains the four stages of the literature selection process. The search criteria used to identify the literature within the scope of this study were: *(“Eye-tracking”) AND (“AEC” OR “Construction” OR “Engineering” OR “Architecture”).* A total of 18 articles were identified as eligible for the final qualitative synthesis of this study.

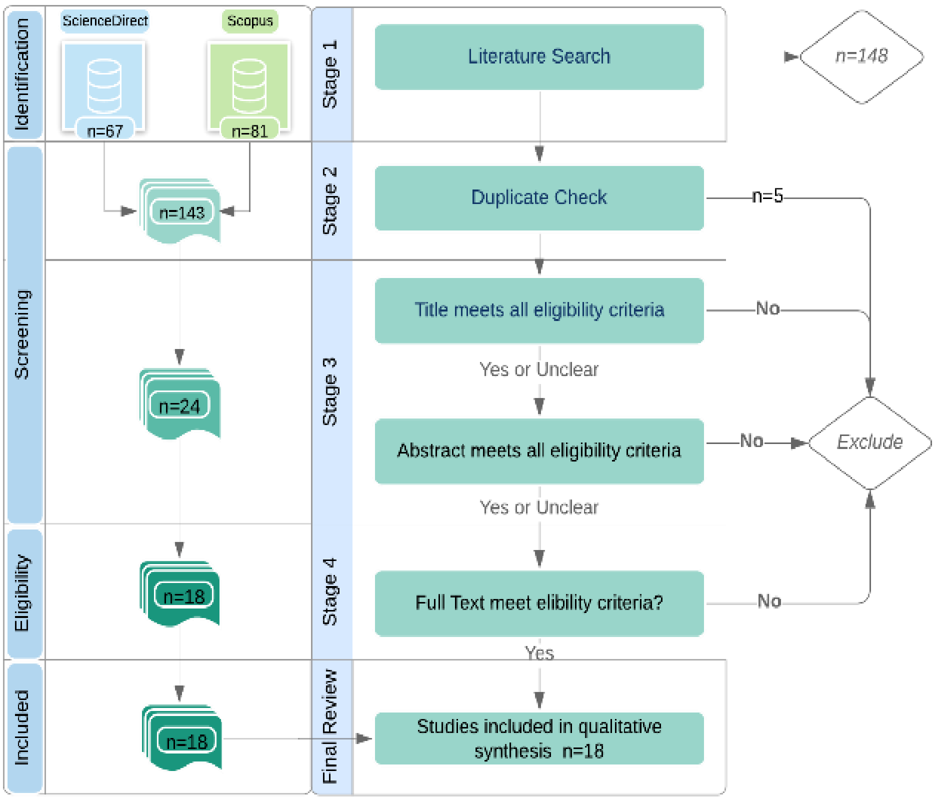


Figure 1- Literature Selection Process

5 FINDINGS AND DISCUSSION

5.1.Framework for classification of literature

A grounded theory method (Gestson, et al. 2019) which is an emerging methodology popular in the categorisation of literature in ICT (Urquhart, et al. 2009) was used in developing the classification framework (Table-1) that aided in the effective comprehension and segregation of the eligible literature as indicated in Figure 2. For definitions of all the eye-tracking metrics mentioned in Table 1, refer to (Holmqvist, 2011). Figure 3 further presents the yearly publication of literature based on the eye-tracking application between 2000 and 2021 (inclusive). Figure 2, reveals that the majority of the studies have explored eye tracking in construction safety (CS) (66.67%), followed by architecture (Arc) (16.6%), building services (MEP) (11.11%) and engineering education (EE) (5.5%). A higher number of literatures in CS is because, as human error is the reason for 80% of the accidents in the construction industry, studies have shown that eye tracking can provide greater insights for the researchers to understand the factors that lead to human errors using reliable objective measure (Liao et al., 2021). This also supports the findings from the task classification of the literature which revealed that the majority of the literature used eye-tracking to understand humans' ability to recognise hazards i.e., even more, important in construction where 57 % of site hazards remain unrecognized due to human error (Albert, et al.2014; Perlman, et al. 2014). It also revealed that the majority of the studies (66.6 %) were conducted in a laboratory setup. This could be due to the fact that in a real-site condition, the dynamic nature of the construction site poses a number of limitations for safety management and experimental stimuli that are difficult to overcome. However, experiment setups in laboratory conditions also pose limitations when the stimuli used are planar. Subtle environment factors like noise, lighting conditions, task and equipment movements are impossible to replicate in the laboratory and real site (Albert, et al.2014).

Table 1: Categorisation Framework

Dimensions	Categories
Utilisation Area	Construction Safety (CS); Engineering Education (EE); Architecture (Arc); Building Systems (MEP)
Task	Hazard Identification (HzD); Decision Making (DM); Situational Awareness (SA); Design Review (DR); Building Inspection (BI); Building Maintenance (BM); User Experience (UX);
Condition	Laboratory; Field
Sampling Rate	60 to 500
Eye tracker Technology	Screen Mounted (SM); Wearable Glass (WG); Virtual Reality Eye Tracking (VRe)
Stimuli Type	On-Site, 2D Based, Immersive Virtual Environment
Eye Tracking Metrics	Fixation Count (FC); Dwell Time (DT); Saccade (SC); Scan Path (SP); Pupillary Response (PR); Fixation Duration (FD); Fixation Time (FT); Blink Duration (BD); Blink Rate (BR); Attention Map (AM)

Further, this study also reveals that the majority of the studies (55.5.%) used two-dimensional stimuli. However, using planar stimuli reduces the dimensionality that could lead to the simplification of the stimuli representation, resulting in distorted visual search patterns yielding misleading eye movement data as opposed by (Liao et al., 2021). Thus, utilisation of an immersive virtual reality environment would be an ideal solution as the development of high-fidelity virtual environments that can evoke experiences in users that are similar to real-world are now possible using various game development engines. Further, this study revealed that a wearable glass-based eye tracker was mostly used for the experiments. Even though these eye trackers are costly than screen-based ones, the data reliability is higher as well as it is easy to control noise creating factors like lights for wearable eye trackers (Narayan, 2019). Further, this study also identified the majority (27.7%) of the literature used an eye tracker with a sampling frequency of 60 Hz & 90Hz. Even though sampling frequency is very rarely highlighted in methodical discussions it is critical when precise measures (e.g., small saccades) are required for the study(Andersson, et al. 2010). Further, fixation count (FC) (72.2%) is the most commonly used eye-tracking metric followed by fixation duration (FD) (27.7%).

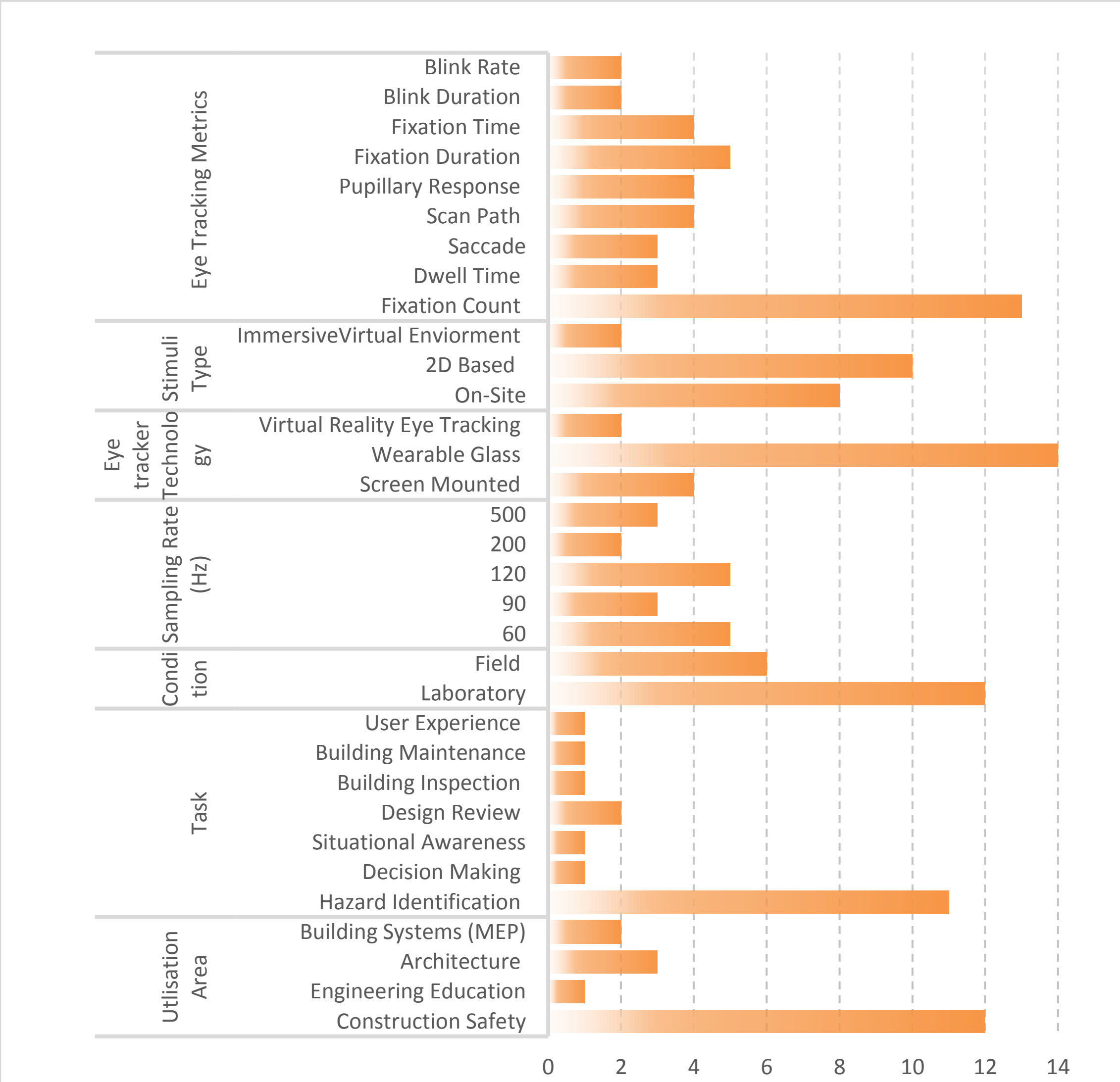


Figure 2 Literature Classification

As the majority of the literature identified by this study focuses on CS in regard to hazard perception, this higher number of FC and FD are common, as cross-comparison of FC with FD can give insights into the areas that generate interest (i.e., potentially hazardous area) and those that caused confusions (i.e., bottom-up processing during identification of a hazard) for the users (Hasanzadeh, et al. 2017b). Further, the yearly publication (Figure 3) shows a steady increase in the number of publications utilising eye tracking in the AEC industry (articles published in 2020 was up to the end of October 2020) which indicates that research interest in this area is gaining momentum, even though one of the factors that could slow down the utilisation of this technology is the exorbitant cost of the eye-tracking peripherals and the software (Kumar, 2006). Figure 4 depicts the utilisation area of eye-tracking in the AEC industry in relation to the eye-tracking metrics.

Most of the CS studies have utilised various eye-tracking metrics to understand the human behaviour leading to failure in hazard identification. stimuli. Out of all the eye-tracking metrics identified FC is the most used eye-tracking metrics in all utilisation areas, as FC could provide information about a person's interest in specific. However, there are other least explored metrics like a pupillary response (PR) which can provide much detailed information about cognitive load while engaged in multiple tasks that can have an adverse effect on the hazard identification capabilities. Further research could explore these metrics by recreating subtle environment factors like noise, lighting and multiple tasks to understand how these could affect human performance in hazard identification.

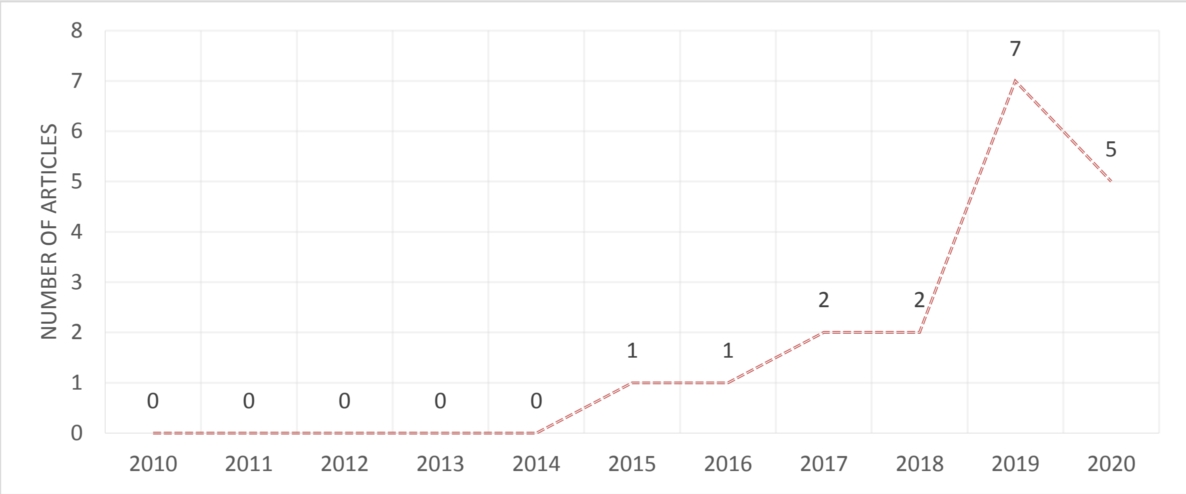
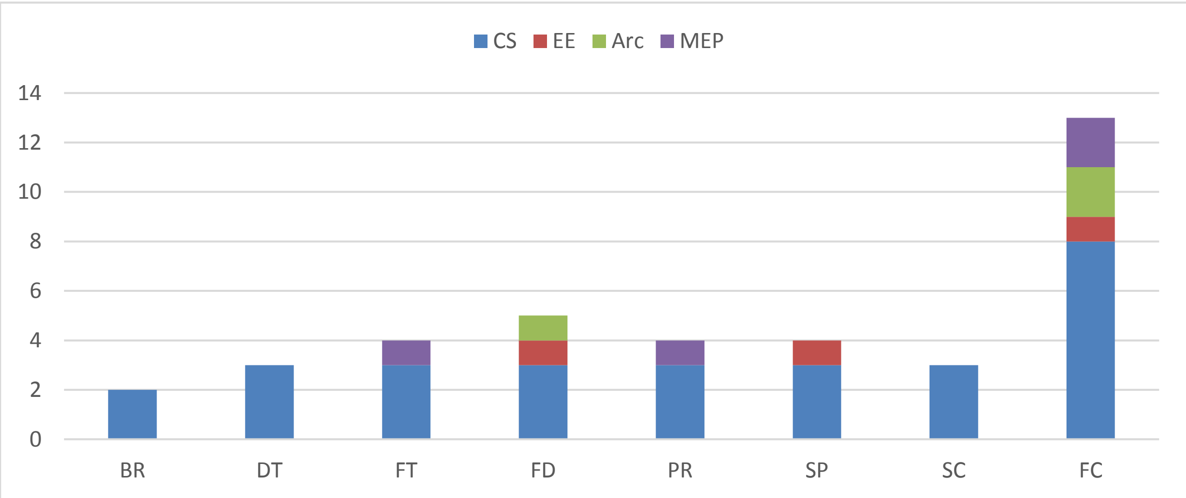


Figure 3 Yearly Publication 2010-2020



Note: BR = Blink Rate, DT = Dwell Time, FT = Fixation Time, FD = Fixation Duration, PR = Pupillary Response, SP = Scan Path, SC= Saccade, FC = Fixation Count

Figure 4 Utilisation Area Vs Eye Tracking Metrics

It is interesting to note that some of the highest cited literature (table 2) which utilised eye tracking in the AEC industry (e.g., Dzeng et al., 2016; Hasanzadeh, et al. 2017a; Hasanzadeh et al., 2017b) to understand human visual search patterns have used planar stimuli to evoke participant responses. Even though these studies are the most notable once that focuses on the use of eye-tracking in construction safety analysis, the results of these study might yield contradictory findings if the experimental set up was in a real or immersive environment due to the aforementioned fact that subtle environment factors like noise, lighting conditions, task and equipment movements are impossible to replicate in such stimuli (Albert, et al.2014) as well as they reduce the dimensionality that could lead to the simplification of the stimuli representation, resulting in distorted visual search patterns yielding misleading eye movement data as opposed by (Liao et al., 2021). This points out that future research must focus on the utilisation of immersive virtual reality-based stimuli which can overcome these challenges. However, one of the factors that might restrict the utilisation of such technologies is the cost of hardware and software associated with conducting such experiments.

Table 2 Eye Tracking Metrics used in AEC Studies Literatures

Literature	Utilisation Area	Sample Size	FC	DT	SC	SP	PR	FD	FT	BD	BR	Citation
(Dzeng et al., 2016)	CS	25	√		√	√		√				41
(Liao et al., 2021)	CS	48					√					0
(Han, et al. 2020)	CS	55	√		√							0
(Gestson, et al. 2019)	CS	16	√			√		√				1
(Xu, et al. 2019)	CS	47				√						2
(Hasanzadeh, et al. 2019)	CS	11	√			√						16
(Jeelani, et al. 2019)	CS	23			√			√	√			14
(Hasanzadeh et al., 2017a)	CS	31	√	√								20
(Hasanzadeh, et al. 2018)	CS	28	√									2
(Alruwaythi & Goodrum, 2019)	MEP	60	√						√			2
(Li et al., 2019)	CS	12	√				√	√		√	√	7
(Li et al., 2020)	CS	6					√			√	√	3
(Shi, et al. 2020a)	Arc	63	√									2
(Shi, et al. 2020b)	MEP	90	√				√					0
(de la Fuente Suarez, 2020)	Arc	14	√				√					0
(Jeelani, et al. 2018)	CS	6	√	√					√			21
(Hasanzadeh et al., 2017b)	CS	27	√	√					√			29
(Mohammadpour et al., 2015)	Arc	8	√				√					6

Note: CS = Construction Safety, Arc = Architecture, MEP = Building Systems

6 Conclusion

This study aimed to identify the areas of application of eye-tracking technology in the A &C industry. A full range of construction journal articles between 2010 and 2020 (inclusive), that utilised eye-tracking technology in the AEC industry was systematically assessed. Based on rigorous inclusion and exclusion criteria,18 eligible journal articles were selected for final review. A generic taxonomy based on grounded theory was developed based on a wide range of scholarly journals. The eligible articles were classified based on this taxonomy and are presented. The review revealed that eye-tracking studies in the AEC industry are mostly focused on improving construction safety through an understanding of human behaviours in hazard identification. This study also identified a paucity of studies in the areas like user experience in a facility, building inspection and maintenance, decision making and design reviews. Further, laboratory-based experiments are found to be the most performed methods in understanding human behaviour using eye-tracking in the AEC industry. A higher number of studies have used wearable glass-based eye trackers and only studied have tried to use immersive technology to recreate stimuli. Further, most of the studies have used 2D based stimuli regardless of their drawbacks (i.e., reduces the dimensionality that could lead to the simplification of the stimuli representation, resulting in distorted visual search patterns yielding misleading eye movement data). Also, real site stimuli were the second most preferred stimuli used in the experiments. Further, fixation count followed by fixation duration is the most commonly used eye-tracking metric used by most studies. This systematic review revealed that that eye-tracking technology is growing in popularity with safety being one of the most critical areas that require further development and recent advancements in ICT is naturing this trend.

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EXPERIMENTAL STUDY ON CONSTRUCTION PLANNING THROUGH 4D BIM-BASED VIRTUAL REALITY FOR LIGHT STEEL FRAMING PROJECT

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ABSTRACT: *The construction industry has actively attempted to tackle the low-productivity issues arising from inefficient construction planning. With new emerging technologies, there is a need to comprehend how construction practitioners perceive the functionality of technology integration in construction planning. This study intended to uncover unique experimental findings by integrating 4D-Building Information Modelling to Virtual Reality (VR) technology during construction planning among construction professionals at Light Steel Framing (LSF) projects in Malaysia. The building industry participants were invited to provide inputs on two different construction planning methods: the conventional and innovative methods. The conventional method involved the participants using traditional platforms such as 2D computer-aided design (CAD) and physical visualisation to complete construction planning-related tasks. Comparatively, the participants need to finish the same tasks but using more innovative platforms such as 4D BIM and a virtual reality (VR) environment. A Charrette Test Method was used to validate the findings, highlighting an improvement in usability (+10.3%), accuracy (+89.1%), and speed (+30%) using 4D BIM with VR compared to the conventional paper-based method. The findings are also validated by a paired t-test, which is supported by the rationality of the same findings. This new blend of technologies—combining 4D BIM and VR in industrialised construction projects—potentially directs future initiatives to drive the efficiency of construction planning in the building lifecycle.*

KEYWORDS: *Building Information Modelling; Virtual Reality; Industrialised Construction; Light Steel Framing; Construction Planning; Immersive Technology*

1. INTRODUCTION

The construction industry is regarded as an important source of national economic growth. However, it is regularly criticised for problematic issues such as project delays, cost overruns, and low quality levels, primarily driven by the complexity of construction projects (Ahmad *et al.*, 2018). The fragmented nature of the construction industry amplifies these issues as in traditional construction planning, where individual team members of projects focus on achieving individual goals (Vrijhoef and Koskela, 2005). The study by Crotty (2013) claimed that the conventional method of producing building information is the main culprit of poor-quality projects. In past decades, the construction industry has gathered momentum to adopt innovative approaches to project information coordination, such as Building Information Modelling (BIM). BIM allows for the creation of intelligent multidimensional modelled elements consisting of graphical and non-graphical information related to object-based properties such as time, cost, materials space constraint, design and manufacturing information, and finishes in a shared digital space (Lester, 2017). This integrative working environment encourages better communication in the project team. The widely acknowledged benefits of BIM include better coordination between stakeholders, enhanced visualisation, improved safety management, removing of building element clashes in the early design stages, and improved overall efficiency of construction management (Golparvar-Fard *et al.*, 2011; Grilo and Jardim-Goncalves, 2010).

However, with 3D BIM, time-related issues persist as the construction schedule is not adequately refined from the conventional planning method (Hardin and McCool, 2015). The authors claim that traditional project management schedules and planning are prone to erroneous assumptions based on guesswork and past experience. Hardin and McCool (2015) stated that 70% of conventional planning and schedules for construction projects are impractical in practice. ‘4D’ BIM has emerged as a potential solution to such problems, as it complements the existing 3D BIM model by adding the dimension of time for scheduling data to be included in the description of components, allowing planners to have a well-defined visualisation of project development within its lifecycle. This provides a virtual environment to identify potential conflicts and errors before construction, giving a far greater immersive perspective of a project program. Developed countries are currently actively involved in BIM while developing countries such as Malaysia still reluctantly move forward (Ismail *et al.*, 2017). The Construction Industry Development Board (CIDB) of Malaysia has been recorded the BIM adoption rate at barely 10% in 2015 in compare to Singapore which has achieved 65% adoption rate as a neighbour country in the same year (CIDB, 2015). This low BIM adoption rate in developing countries might lie in the lack of practical experimentation and low awareness of modernisation and innovation in the building industry. Therefore, there is a need to understand how construction practitioners perceive the practical functionality of 4D BIM with immersive technologies, such as Virtual Reality (VR), during the construction planning phase. The virtual training environment could bring trainees into a close to real operational context to equip them about on-site operation with minimum exposure to risk and hazard during building construction training (Ibrahim *et al.*, 2014). This study uncovers unique experimental findings of integrating 4D-BIM to Virtual Reality (VR) technology during construction planning among Malaysian construction professionals at Light Steel Framing (LSF) projects. This study's main research question stated: How does 4D BIM in a VR environment influence construction planning in a Light Steel Framing (LSF) project among Malaysian construction players? In line with that, the study intends to recommend what the construction workforce expect from 3D/4D BIM in a VR environment, particularly during construction planning in LSF projects.

2. 4D-BIM AND INDUSTRIALISED CONSTRUCTION

This section reviews the relevant literature systematically for integrating BIM-based VR technology for effective planning of industrialised construction.

2.1 Light steel framing system

Industrialised Construction is a holistic approach to building that is focused systematisation, control, a standardisation of processes and production as a framework for continual improvement and refinement, distinct from traditional construction’s project-focus (Lessing, 2015). Traditional construction is typified by unique one-off design solutions, the variable nature of the site, and by temporary teams that execute projects (Gann & Salter, 2000). By contrast, industrialised construction focuses efforts with a long-term view, separate to project delivery, across eight areas: process control, systems development, off-site manufacture, long-term supply chain relationships, construction logistics, customer-focus, use of ICT, and performance measurement (Lessing, 2006). In support of that, the study by Rashidi and Ibrahim (2017) defines Industrialised Construction as “a computer-integrated design, manufacturing and construction system using the concept of off-site or on-site prefabricated mass-production technique within a controlled environment while utilizing proper coordination and planning to transport, position and install building components with minimal in-situ works.”

Moreover, Saikah *et al.*, (2017) conducted a study on implementing the light steel building system in Malaysia. They discovered that the current utilisation rate of LSF systems in the country is low. Light steel framing (LSF) is a practical structural technique consisting of a lightweight skeleton to support floors, roof and walls of a building attached to the frame (Martinez *et al.*, 2019). However, they mentioned that the adoption of the LSF systems contributes to the three main pillars of construction: time, labour, and cost. Due to the fast and straightforward assembly process, time and labour can be reduced, resulting in a lower cost for the building contractors. The authors posit that using this technology is beneficial to increase the supply of affordable housing, which is a significant contribution to the nation as the housing cost persistently being severely unaffordable in Malaysia. In Malaysia, the LSF system falls under one of the five prefabrication categories in Industrialised Building System (IBS) (Rashidi and Ibrahim, 2017). Nawi *et al.*, (2014) claimed that the most hindering barrier of widely applying IBS in Malaysia could be explained by the fragmented delivery method, which is currently approached by the nation. Therefore, it is recommended to integrate the 4D BIM technology in the IBS project lifecycle process.

2.2 4D-building information modelling in virtual reality

The fragmented working environment in building construction is susceptible to interdisciplinary collisions, where coordination meetings with unguaranteed success are frequently held to resolve the conflicts (Czmoch and Pękala, 2014). BIM technology has emerged as an effective alternative to substitute the traditional delivery method. The study by Poirier *et al.*, (2017) emphasises the impact of BIM on reshaping an individual's cognitive determinants to influence collaboration throughout project delivery. In this innovation, project delivery is shifted from segregation to integration, which catalyses a project's success by enabling a project team's professionals to work collaboratively. It helps encapsulate the values of chasing common goals rather than individual targets. BIM requires early project documentation and allows earlier clash detections (Umar *et al.*, 2015). In Malaysia, despite slow uptake of BIM, research on 3D BIM is progressing and mainly covered the challenges, benefits and its impact on labour productivity (Latiffi *et al.*, 2016; Memon *et al.*, 2014; Mohd Noor *et al.*, 2018; Wong *et al.*, 2020; Zakaria *et al.*, 2013a, 2013b).These BIM-related studies conducted in Malaysia highlight a shortage of recent studies on construction planning as well as the post-construction phase for industrialised construction. This study will be conducted in a way that it branches out from this convention to emphasise the functionality of BIM on construction planning.

The insertion of scheduling data supplements the richness of 3D BIM. The integration of 3D BIM and time is theoretically termed '4D' BIM. The additional temporal information allows dynamic simulation of a project timeline, giving an overview of the actual occurrence of activities at the site in the temporal dimension. This ability is helpful to provide visualisation of the chronological events in the construction, especially for stakeholders such as a client who might not be specialised in reading building blueprints. Traditionally, construction planners rely on the Gantt chart or Critical Path Method (CPM) for construction scheduling. However, these primitive measures consistently create difficulty in detecting errors in construction plans and interpret project schedule. This happens as they are deficient in exhibiting spatial context for planners to make decisions in an almost temporal environment (Koo *et al.*, 2006). In 4D BIM, project simulation can be imitated as closely as possible with the input of logical sequencing, precise durations of activities and characteristics of high-risk events. The comparison between planned progress and actual progress is facilitated, prompting timelier project delivery (Crowther and Ajayi, 2019). Boton (2018) stated that spatial management in the construction industry is challenging due to the complexity of site conditions, spawning numerable spatial-temporal conflicts in a project. 4D BIM appears to be a suitable alternative, where it aids to envisage the flow of vehicles and participants on-site, reducing the occurrence of overlapping elements, and different activities happening concurrently at the same place in the construction site. With this trait, 4D BIM technology helps the construction team to visualise and predict logistical events, thereby allowing just-in-time (JIT) purchasing and delivery of material. 4D BIM was also found to focus on communication improvement, comparative analysis on planned and actual construction activities, dynamic collision detection, spatial-temporal conflict analysis (Akinci *et al.*, 2002; Kiviniemi *et al.*, 2011). Although it remains theoretically proficient for its associated benefits, it is required to be justified with more research efforts to be employed widely in the construction industry. This research provides more insights into this research gap, particularly in the field of construction planning by 4D BIM visualisation.

Moreover, the recent studies on VR technology have proven positive changes for the Architecture, Engineering, and Construction (AEC) industry such as digital design and hazard identification in construction safety management (Zhou *et al.*, 2012). Moreover, Paes *et al.*, (2017) conducted a quantitative study on VR technology in facilitating the spatial context of digital models and obtained positive results that signified a better spatial understanding of virtual building mock-ups. An essential product of this technology is a collaborative environment. Sherman and Craig, (2018) defined the collaborative environment as a virtual world that allows the interactions of multiple team professionals in a common environment.

In the global context, there have even been a number of efforts to connect VR with 4D simulation in the AEC industry (Boton, 2018). Waly and Thabet, (2002) introduced a virtual construction environment (VCE) in relation to a predefined 3D model for construction planning purposes in order to identify the spatial conflicts. Fernando *et al.*, (2013) proposed a collaborative environment that supported collaboration among multi-disciplinary team members in building design meetings to resolve design issues professionally and efficiently. In Malaysia, the research on this blended technology is limited, leaving a considerable research gap unfilled in the local building construction context. This research attempts to cover part of the gap by comprehending the perceptions and performances of the local construction practitioners on this new mixed-use of technology.

3. RESEARCH METHOD

An experimental study on the performance and perceptions of practitioners using the traditional and innovative method was performed. The following discussion describes participants, variables, instrumentation, experimental procedures and validation methods. The quantitative experimental research design flowchart is shown in Figure 1.

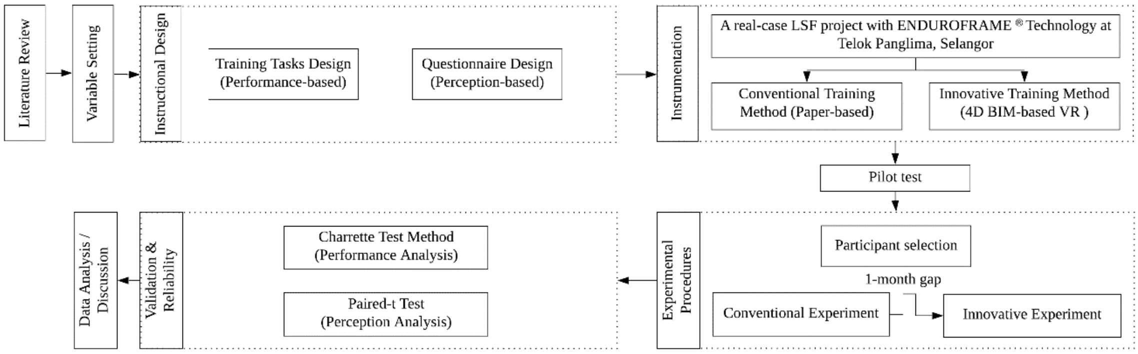

Fig. 1: Research design flowchart

This experimental study selected 15 participants in line with the selected validation method called the Charrette Test Method (Clayton *et al.*, 1998). The target audience was people with AEC background and basic knowledge of drawing interpretation and construction planning. In addition, independent variables were chosen, which were systematically generated after the process of literature review. A framework of the identified independent variables is shown in Table 1.

Table 1. Identified variables of 4D BIM regarding the impact upon construction planning

No	Independent Variables	References
1	Spatial Understanding	(Paes *et al.*, 2017)
2	Spatio-temporal Conflicts	(Hardin and McCool, 2015), (Zhang *et al.*, 2018)
3	Project Collaboration between Stakeholders	(Boton, 2018)
4	Training & Education	(Li *et al.*, 2018)
5	Project Schedule & Sequencing	(Hardin and McCool, 2015), (Crowther and Ajayi, 2019)
6	Safety Management	(Li *et al.*, 2018)

This set of variables would be utilised in the instrumentation of the research. The first two variables would be tested based on performance and perception analysis, while the remaining four would be tested based on perception analysis. The dependent variable in this study is construction planning. This experimental study is limited to just one dependent variable to emphasise the particular performance changes in building construction lifecycle.

3.1 Virtual building model development

This section describes the development of a 4D BIM-based LSF model in VR environment from a scratched 2D CAD model accompanied by a Gantt chart.

The reference project is a LSF project in Telok Panglima Garang, Selangor state in Malaysia. The 2D drawings were provided and transformed into 4D models that are compatible with VR headset technology developed by HTC and Valve that is called HTC Vive in this research project. The HTC Vive uses room scale tracking technology along with motion-tracked handheld controllers to interact with virtual building model in the fully immersive 3D environment. The LSF building model developed in the 3D environment and it is integrated with project scheduling extracted from conventional Gantt chart and make the 4D BIM-based LSF model. The 4D BIM-based model visualised in the VR platform by utilising the Autodesk Revit®, Autodesk Navisworks® and Enscape® software as shown in Figure 2.

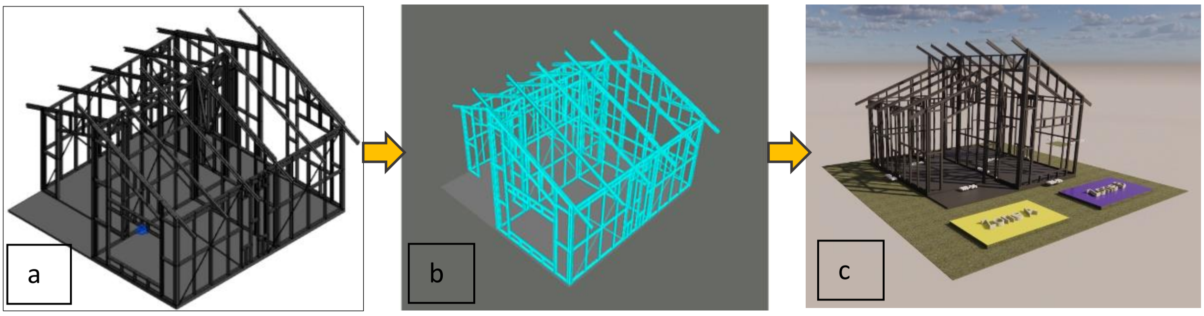

Fig. 2: Virtual building model development for the LSF project; a) 3D BIM model in Autodesk Revit®, b) 4D BIM model in Navisworks® software, c) 4D BIM Model in VR Environment using Enscape®

3.2 Experimental procedures

The experimental design procedure is a one-group pre-test-post-test design. This type of within-subject experiment is designed to determine the effect of a treatment on the same selected sample group of participants tested first under the control condition and then under treatment condition. The rationale for choosing a "within-subjects" experiment was to reduce the variability among skill level and knowledge of the participants (Clayton *et al.*, 1998). The 15 participants targeted for this experimental study and first underwent the conventional experimental study. They were asked to answer the task testing and questionnaire using the paper-based method that the practitioners conventionally use for construction planning. After a gap period, the participants were exposed to a more innovative method, which was 4D-BIM-based in VR environment. They were again asked to perform the same task testing and questionnaire form. A pilot test was also conducted to ensure that such a disadvantage did not stand. The experimental procedures can be visually observed in Figure 3.

Fig. 3: Participants are completing task testing and questionnaire at the construction company; a) the conventional (Paper-based) method, and b) the innovative (4D BIM in VR) method.

Within-subject experiment design establishes a danger to the final results as the participants are to perform the same questions before and after treatment. Effects of learning favour the results in the second trial. To confront this issue, a 1-month interval between the two experiments was applied to reduce learning effects, following the Ebbinghaus' forgetting curve that shows how the memory of new learning information decays in the brain with the drastic drop in knowledge retention occurring after 31 days (Ebbinghaus, 1885; Murre and Dros, 2015). The participants of this experiment were asked to complete a series of tasks, followed by a questionnaire survey that was identical in conventional and innovative approaches, as shown in Figure 1. A task test was conducted to evaluate the performance of the participants, while a questionnaire was used to assess how the users perceived the training system.

The first experiment was conducted using the conventional paper-based method. The participants were seated and provided a set of construction drawings and a Gantt chart for the selected LSF project. Each participant was given ten minutes to understand and visualize the project using the provided documentation. They were then asked to complete five question-based tasks. In the first task, each participant was asked to calculate the number of wall panels in the project. The participants had to flip through the layout plans and the assembly drawings to gather the correct answer. As part of the second task, participants were asked to highlight a discrepancy between the layout plans and the photo of the completed works. The participants had to apply their imagination to turn paper-based drawings into their mental representation of the actual building. In the third task, participants were asked to estimate the number of glass windows and doors. The answer can be found in the floor plan and elevation drawings. On the fourth task, it was assumed that two designated zones existed for the LSF wall assembly on the day of site installation. The participants were asked to suggest how the prefabricated wall panels should be staged, considering the sequence of work. The participants are challenged to plan spatially and temporally for the assembly of the LSF structures. In the fifth task, a specific site boundary was defined to restrain the available space. It was asked which is the most efficient assembly sequence for all the wall panels, so as to require the least amount of workers. Participants were required to examine the project drawings, Gantt chart, and site conditions, and then formulate a plan that best meets the needs of the project.

A month after the first experiment, a second experiment was conducted using the innovative model-based method. They were asked to use the HTC Vive headset to view the 3D and 4D models in the virtual reality environment of the same LSF project. In the same way, they were given 10 minutes to walk around and become acquainted with the project. In the same manner, five question-based tasks were asked. The participants had to walk around the model to calculate the number of panels for the first task. To answer the second task, a photo of completed work was shown. They were required to point out the discrepancy between the model and the as-built. A third task involves calculating the number of doors and windows by walking through a modelled house. For the fourth task, participants were allowed to wander the modelled-to-actual-scale environment in order to strategize the staging of materials at the two designated zones prior to the site works. A fifth task asked the group to prioritize using the least amount of manpower with optimal assembly sequencing, based on the site condition.

Besides testing the tasks, a questionnaire form was also carefully designed to collect participants' feedback on different construction planning approaches after the experiments. The 12 closed-ended questions which are tabulated in Table 1 were formulated based on six independent variables and used a five-point Likert scale, ranging from strongly disagree to strongly agree. In addition to these questions, demographic related questions and an open-ended question are included at the end of the questionnaire to solicit participants' thoughts on the advantages and disadvantages of the different approaches.

3.3 Validation and reliability

This study applies two validation methods, the Charrette Test Method and paired t-test, to evaluate the results of this experimental study. The Charrette Test Method (CTM) is developed as the validation method to be used for a study that compares simulated data directly and is tested by practitioners under a controlled environment (Yee *et al.*, 2013). Clayton *et al.*, (1998) stated that the method is to evaluate "whether a process performed using one set of tools is superior to a process performed using another set of tools". The Charrette Test Method is intended to compare an innovative approach to a traditional approach to the same tasks. To make an inference on the superiority of the innovative process over the traditional process, 'effectiveness' of the new proposed approach must outweigh the existing approach. (Clayton *et al.*, 1998) framed effectiveness in three dimensions: usability, accuracy and speed. Usability measures the number of participants who can accomplish the tasks; accuracy measures the number of participants who provide the same responses with the prematurely set answers; speed measures the average duration they spend on the tasks. The three hypotheses tested in this Charrette Test Method are:

- Usability: The AEC industry practitioners can use 4D BIM in VR to perform construction planning tasks.
- Accuracy: 4D BIM in VR can benefit from increased accuracy in performing tasks related to construction planning.
- Speed: 4D BIM in VR can benefit from increased speed in performing tasks related to construction planning.

The Charrette Test Method was used to validate the results from task testing, e.g., performance analysis, amongst the traditional and innovative approaches in construction planning.

3.4 Paired t-test

The study conducted based on one-group pre-test-post-test experimental design procedure and paired t-test used to compare two sample size population means in which observations in one sample before the treatment can be paired with observations in the other sample after the treatment. This study is used to assess whether there is any statistical evidence that the mean difference between the traditional and innovative approaches to construction planning is significantly different for the perception analysis.

The purpose of the paired t-test in this research is to improve the internal validity by manipulating the effects of the independent variables on construction planning instead of observing a corroborated association without conducting any intervention. In addition, with this method, it could be revealed which independent variables are perceived by the practitioners to potentially alleviate construction planning processes by using 4D-BIM in a VR environment. In this study, the paired t-test was conducted to analyse the results from the designed questionnaire in both construction planning methods, e.g., perception analysis from targeted practitioners in this experimental study.

4. RESULTS AND ANALYSIS

This section is divided into four sub-sections to elaborate the demographic profile, performance analysis, perception analysis, and overall deliberation of the test subjects. The demographic profile of the 15 participants is shown in Table 2.

Table 2. Demographic information in this experimental study related to construction planning

Demographic Profile	Frequency	Percentage (%)
Age		
20-24	6	40
25-29	3	20
30-34	1	6.67
35-39	4	26.67
40-44	0	0
45-49	0	0
50-54	1	6.67
Organisation		
Consultant	3	20
Contractor	7	46.67
Supplier	5	33.33
Awareness of 3D BIM		
YES	8	53.33
NO	7	46.67
Awareness of 4D BIM		
YES	2	13.33
NO	13	86.67

Responses to age showed that the highest proportion (40%, n=6) held the age of 20-24. The oldest participant had the age range of 50-54. For organisation classification, the most frequent response (46.67%, n=7) was ‘contractor’. There were 3 (20%) and 5 (33.33%) participants from consultant and supplier firms, respectively. Slightly more than half of the participants (53.33%, n=8) were aware of 3D BIM, but only two of them (13.33%) knew 4D BIM.

4.1 Performance analysis in construction planning

The conventional approach utilised the paper-based method. There were two tasks that some participants failed to generate a response. Compared to the innovative approach that employed 4D BIM in VR, the response rates for all tasks were universally collected. The overall usability rate was 90.67% for the traditional approach and 100% for the innovative approach. The traditional approach, on average, performed worse in terms of accuracy, with 42.3% of accuracy compared to 80% of accuracy procured using the innovative approach.

For the comparison of speed, the pre-test experiment resulted in an average of 114.4 seconds for the five tasks, while the post-test experiment yielded an average of 80.1 seconds. This again proved that the innovative approach outscored the traditional approach by being the faster method. An interesting point lies in Task 2, which was to find a mistake between the model and the building site. The innovative approach's speed averaged 8.4 seconds, but for the traditional approach, the participants took an average of 84.2 seconds. The accuracy also rose from

33.33% to 100%, from the latter to the former approach. The usability also showed some improvement in moving to the innovative approach. This shows that for a simple task that challenges visualisation, 4D BIM in VR can be very beneficial for construction planning. The results are represented in Table 3.

Table 3. Comparative performance analysis for the conventional approach and innovative approach with the Charrette Test Method

Description	Conventional			Innovative			Performance Change		
	Usability (%)	Accuracy (%) – Mean (SD)	Speed (seconds) – Mean (SD)	Usability (%)	Accuracy (%) –Mean (SD)	Speed (seconds) – Mean (SD)	Usability	Accuracy*	Speed*
Task 1	100	86.67 (8.88)	43.8 (25.0)	100	86.67 (6.23)	69.7 (39.8)	0	0	-59.1%
Task 2	80	33.33 (22.50)	84.2 (30.3)	100	100 (0)	8.4 (4.8)	+25%	+200%	+90%
Task 3	100	53.33 (13.56)	132.8 (79.9)	100	93.33 (2.58)	82.4 (34.5)	0	+75%	+38%
Task 4	73.33	18.18 (23.60)	173.6 (68.8)	100	40 (27.87)	136.5 (50.3)	+36.7%	+120%	+21.4%
Task 5	100	20 (40.67)	147.5 (57.4)	100	60 (33.00)	104.1 (73.8)	0	+200%	+29.4%
Total	90.67	42.3 (30.53)	114.4 (72.0)	100	80 (21.87)	80.1 (60.8)	+10.3%	+89.1%	+30%

In summary, for the three aspects that the Charrette Test Method uses to measure effectiveness, 4D-BIM-based model in VR is experimentally evidenced to perform better than the conventional paper-based method. Statistically speaking, there was a performance change of +10.3%, +89.1%, +30% for: usability, accuracy, and speed. The overall comparative performance between the two methods is shown in Figure 4.

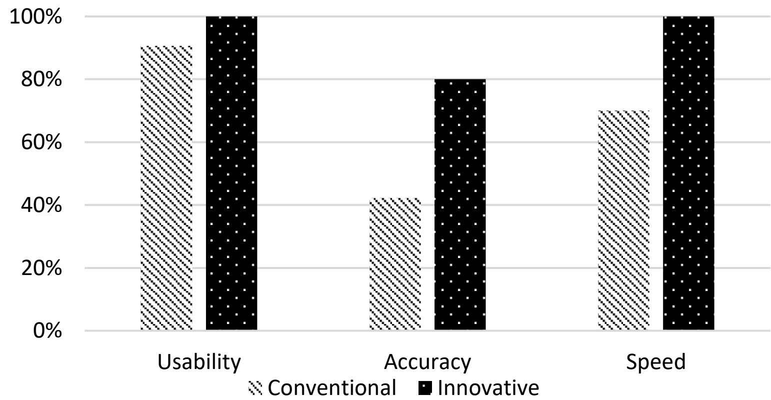

Fig. 4: Comparative performance based on usability, accuracy and speed

However, there was one task that went against the general conclusion, which was Task 1. The task is designed to find the total number of wall panels in the project. After the statistical analysis, there was no improvement in the accuracy and a downgrade of 59.1% to the speed by using the innovative approach. Therefore, for the construction tasks that required the counting of the structural elements, from this study, it was deemed to be more ineffective using 4D BIM in a VR environment. Typically, the number of the wall panels was clearly displayed on the papers in the conventional method. However, despite better visualisation in the innovative method, the participants couldn't take notes and had to calculate the panels manually in a fully immersive environment. In some cases, it turned out that they tended to count incorrectly after walking around the 3D model one time. Hence, the dizziness of VR made counting difficult particularly in a real-scale building model in a virtual environment.

Nevertheless, for the construction tasks that deal with the counting of the structural elements that are not obvious in the drawing plans, the innovative approach could still prove to be beneficial, as shown in the results from Task 3. The task was to calculate the number of doors and windows, which were not clearly demonstrated in the given floor plans. For Task 4 and Task 5 that is tested the spatial and temporal understanding of the project, the improvement of the effectiveness was staggering in all dimensions. Using the paired t-test (two-tailed test) with 15 samples on the collective performance of all tasks, it was statistically proven that the post-test accuracy and speed had a significantly better improvement from the pre-test, with p-value less than 0.001 for both cases.

4.2 Perception analysis in construction planning

The results from the questionnaire reflected the same findings which were obtained from the task testing. There was an increased number of participants who agreed that the innovative approach is satisfactory compared to the traditional approach in all 13 questions listed in the post-experiment questionnaire.

All the questions were classified into the 6 independent variables previously determined from the literature review. The impact of each independent variable on the construction planning after the treatment was examined, as shown in Table 4. The general variable directly queried the perceptions of the practitioners on the adopted approach.

Table 4. Paired t-test on the questionnaire study based on the independent variables

Variable	Test Type	Mean	S.D.	t-value	p-value
1	Pre-test	3.73	0.691	6.117	<0.001
	Post-test	4.60	0.498		
2	Pre-test	3.23	0.728	5.574	<0.001
	Post-test	4.23	0.679		
3	Pre-test	3.67	1.155	3.657	0.001
	Post-test	4.57	0.568		
4	Pre-test	3.00	1.363	3.953	0.001
	Post-test	4.67	0.617		
5	Pre-test	3.90	0.885	1.608	0.119
	Post-test	4.20	0.484		
6	Pre-test	3.32	1.189	4.475	<0.001
	Post-test	4.20	0.484		
General	Pre-test	3.47	1.246	2.323	0.036
	Post-test	4.20	0.561		

Variable: (1) Spatial Understanding, (2) Spatio-temporal Conflicts, (3) Project Collaboration between Stakeholders, (4) Training & Education, (5) Project Schedule & Sequencing, (6) Safety Management

Selecting the significance level as 5%, paired t-test revealed that the null hypothesis could be rejected for all variables except project schedule & sequencing. In other words, there was high statistical significance in the mean value before and after the test. The lower p-value, the more substantial support for the alternative hypotheses. The compilation of the questionnaire results is in Table 5.

Table 5. The breakdown of the practitioners' perceptions on the construction planning of LSF building based on the independent variables

Questions	Test Type	Strongly Disagree/ Disagree	Uncertain	Agree/ Strongly Agree
Variable 1: Spatial Understanding				
1a. I had a good understanding of the spatial information of the 1-storey Light-Steel Framing house	Pre-test	6.67	33.33	60
	Post-test	0	0	100
1b. I could easily visualise the location of the structural elements	Pre-test	0	26.67	73.33
	Post-test	0	0	100
Variable 2: Spatio-temporal Conflicts				
2a. I had a clear vision of the construction progress spatially and temporally	Pre-test	6.67	53.33	40
	Post-test	0	13.33	86.67
2b. I could easily identify if there were any potential spatio-temporal conflicts	Pre-test	20	53.33	26.67
	Post-test	0	13.33	86.67
Variable 3: Project Collaboration between Stakeholders				
3a. Communication between stakeholders would be accessible with this method	Pre-test	6.67	6.67	86.67
	Post-test	0	6.67	93.33
3b. The integration of drawings from different professionals could be easily	Pre-test	26.67	26.67	46.67

visualised	Post-test	0	0	100
Variable 4: Training & Education				
4a. For beginners, they would gain a comprehensive knowledge of onsite construction tasks as well as the dynamics and complexities involved in the project with this method	Pre-test	46.67	6.67	46.67
	Post-test	0	6.67	93.33
Variable 5: Project Schedule & Sequencing				
5a. With this method, I would tend to provide a schedule for construction tasks with reduced errors and uncertainty	Pre-test	13.33	20	66.67
	Post-test	0	6.67	93.33
5b. Planned progress of the construction activities could be easily monitored with the actual progress on site to facilitate on-time project delivery	Pre-test	6.67	6.67	86.67
	Post-test	0	0	100
Variable 6: Safety Management				
6a. This method was useful for early-risk and high-risk identification in the conceptual stage of the project	Pre-test	26.67	26.67	46.67
	Post-test	0	6.67	93.33
6b. In a larger project, safety management could be potentially enhanced with this method	Pre-test	26.67	33.33	40
	Post-test	0	0	100
General				
Overall, construction planning could be enhanced using this approach	Pre-test	20	33.33	46.67
	Post-test	6.67	0	93.33

Spatial understanding, spatiotemporal conflicts, project collaboration between stakeholders, training & education and safety management are the independent variables that statistically showed a highly significant difference between the pre and post-test results. More specifically, there was a proven improvement for these aspects using 4D BIM in VR compared to the conventional paper-based method.

For the general variable, the computed p-value was found to be 0.036. Pursuant to the selected significance level, it can also be concluded that there was a significant difference as in the previous cases. In real terms, there is a 3.6% chance that the alternative hypothesis will be mistakenly rejected. However, the p-value is comparatively close to the cut-off value of 0.05 and considered to be marginal that could go either way. For instance, if the significance level was changed to 0.01, the null hypothesis would be otherwise retained. The fifth variable, project schedule & sequencing, albeit having generated a higher mean in post-test, failed to prove a significant difference in the mean difference after the treatment. The p-value was calculated to be 0.119, which was higher than the threshold value of 0.05. The variable is related to the time management and scheduling of the project.

5. DISCUSSION

The task testing experiment was conducted to examine the spatial understanding (3D) and temporal understanding (4D) of the construction practitioners on the selected LSF building project. After the experiment, it was discovered that construction planning could be ameliorated by introducing 4D BIM in a VR environment. The findings, which universally exhibited a substantial enhancement in terms of usability, accuracy, and speed, were validated by the Charrette Test Method. The validation method provided a systematic external validity in virtual design and construction applied in this study. In addition to the external validity, this research study also improved internal validity from the structured questionnaire design, which was embedded in both methods. Based on the analysis of the questionnaire's results, it was found that the innovative approach outperformed the conventional approach. Participants jointly came to the statistical conclusion that construction planning could be enhanced with the utilisation of 4D BIM in a VR environment. Moreover, they indicated that spatial understanding, Spatio-temporal conflicts, project collaboration between stakeholders, training & education, and safety management are aspects of construction planning that could significantly improve from the adoption of innovative technologies such as 4D BIM in VR environment.

Apart from the propositions, the Charrette Test Method also necessitates the observations and feedback from the participants. Hence, informal discussions and an open-ended question in the questionnaire were designed to collect such information. The participants' input was gathered and collated. As a collective compilation, the use of 4D BIM in VR was found to be beneficial to construction planning in the following ways:

- A comprehensive spatial and temporal understanding of the model from many views is provided. In the paper-based method, the spatial understanding relies on the imagination and experience of the

practitioners to fathom the drawings and scheduling data. With 4D BIM in VR, the immersive visualisation not only simplifies the complexities to understand the blueprints, but also the simulated animation of construction progress visualising the chronology of planned events.
- A virtually visualised structure can be displayed in precise near, to real, scale facilitating early construction planning and error detection that can ultimately minimise the cost of modification before starting the construction programme.
- The visualisation is literally down to the scale of nuts and bolts. This provides a detailed understanding, including the connection of the various structural elements, and diminishes the confusion over the design.
- For clients who do not have background knowledge in construction design and engineering and may struggle to read layout drawings, this platform facilitates accessible visualisation of the building process and elaborates on the necessary details related to the project they will pay at each milestone throughout the construction lifecycle. A new strategy to win jobs might lie in 4D BIM in VR.

On the other hand, the negative challenges posed by this novel innovation include:
- The discomfort of current VR equipment. The headset was too heavy and bulky for some participants after 30-minutes of usage. Moreover, some participants felt dizziness in the immersive virtual environment after wearing the VR equipment. Nausea occurs as there are conflicting signals conveyed to the brain from the sensory receptors of the humans.
- The lack of familiarity with the technologies, such as 4D BIM and VR, causes some confusion in novice participants.
- Current development of the 4D software, Navisworks®, does not allow the participants to navigate through the virtual model temporally.
- The virtual model is only accessible to one person at a time meaning that communication among a group of practitioners is not feasible. If multiple VR equipment is required in the future the cost may be prohibitive.
- Difficulty to get the agreement of local construction practitioners to embrace the idea. Firstly, the cost of adoption is high due to the required equipment and the lack of skilled talent. Secondly, the current delivery method in Malaysia is still in fragmented nature, which is leading to slow adoption and integration of this innovative method in construction planning.

This study posits positive results on construction planning from the utilisation of modern practices and technologies. It may provide some potentially realisable directions for the construction industry to improve efficiency as intended by CITP 2016-2020 (CIDB, 2015).

6. CONCLUSION

This paper has discovered how construction practitioners perceive the usage of 4D BIM in a VR environment for construction planning purposes. The conducted experimental study was found that construction planning could be enhanced by moving away from the paper-based approach to 4D BIM in the VR approach. The findings were evidenced by both external and internal validity methods. The Charrette Test Method proved that there were improvements on the three hypotheses—articulated as usability, accuracy, and speed in the experimental study. The paired t-test on the predetermined independent variables revealed that, out of the six variables, five of them showed a significantly positive difference between pre-and post-test study. The only variable that has not shown a positive sign, project schedule & sequencing, might be due to the experimental flaw to support proper Navisworks navigation on VR temporally. However, in general the questionnaire supported the findings of improved construction planning by using 4D BIM in a VR environment. These findings are significant for the current local construction industry that is facing low productivity issues due to poor construction planning.

Further studies can be done to design and develop more user-friendly VR technologies to reduce the current negative impacts of using VR tools such as motion sickness and dizziness, particularly for senior professionals. Furthermore, this experimental study is based on a small-scale LSF project. Future studies on this topic may enlarge the project scale and refer to a more complex multi-storey building. In this way, the spatial and temporal understanding of the project is challenged extensively and might offer different results. It is also foreseeable that visualisation technologies will continue to improve and their uptake increase in the coming years. The Mixed Reality (MR) environment, unlike virtual reality, provides the merging of real and virtual objects which is currently undergoing various experimental development tests to provide a potentially more practical and interactive training environment in the virtuality-reality continuum. Future recommendations for the relevant studies could focus on this emerging technology in design and construction planning.

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AN ANALYSIS OF BIM IMPLEMENTATION IN THE DESIGN PHASE FOR COMMERCIAL BUILDINGS

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ABSTRACT: *Innovations due to the increase of the technological developments have exposed Architectural, Engineering and Construction (AEC) industries into a cultural change. Even if there has been some hesitancy in accepting innovations due to ongoing traditional approaches, Building Information Modeling (BIM) made its way in the frequently-used AEC tools due to its positive impact on collaboration among parties as well as other project performance outcomes. An increase in the use of BIM is apparent in the industry, however, keeping up with this technology requires new steps for a successful implementation rather than the well-known traditional approaches. This paper aims to investigate the critical success factors (CSFs) for BIM implementations in the design phase by using a project-based framework. An extensive literature review was conducted and BIM adaptation at the company and project levels were evaluated via case studies. All aspects of BIM implementations were included in the framework composed of drivers, inputs, barriers, enabler, benefits, and impacts. The results showed the ranking of factors for a successful BIM implementation in a variety of project types. The leading driver for commercial buildings was the need of "Design Improvement", followed by "Improving Collaboration" and "Project Performance", as expected. The primary barrier was "Fragmented Nature of the Industry". Surprisingly, "Lack of Government Support" and "High Costs" were ranked as the least effective barriers for BIM Implementation in commercial building projects.*

Key words: *Building Information Modeling (BIM), BIM Implementation, Architectural, Engineering and Construction (AEC), Industry Applications*

1. INTRODUCTION AND BACKGROUND

Over the past century, Architectural, Engineering, Construction (AEC) industries have had traditional and somewhat rigid approaches due to the nature of the industry being different than others when it comes to adopt new technology. Recent improvements in technological developments have caused the industry members to proceed and communicate through object-based designs easily. Object based data modeling has gained popularity in the last decades of the 20th century and its standardization began with the publishing of the Industry Foundation Classes (IFC) by International Alliance for Interoperability (IAI) formed in 1995. After a decade of the integration due to new developments in the technology, the adoption of innovations in AEC industries has started to gain popularity. With the inclusion of these innovative approaches that contribute to the construction sector, our traditional project management perception has also changed.

In 2004, the National Institute of Standards and Technology (NIST) published a report stating that lack interoperability and poor data management costs approximately 16 billion U.S. dollars to AEC industries (Gallaher et al., 2004). Considering this situation, in the upcoming years, National Building Information Model Standard (NBIMS) defined the Building Information Modeling (BIM) as "a digital representation of physical and functional characteristics of a facility" (NBIMS, 2007). In the meantime, design tools and other software in the AEC industries have been improved to deliver more accurate models aligned with the BIM implementation process which allows the shift to (i) increase; productivity, efficiency, infrastructure value, quality, and sustainability, (ii) reduce; life-cycle costs, lead times and duplications.

Among various studies in the field to understand the benefits and barriers of BIM implementation, several of them have focused on the adoption of BIM processes in AEC industries (Sun et al., 2017). Studies mentioned the importance of integration of knowledge management systems in BIM processes and how BIM's potential can be enabled in the construction industry (Ghaffarianhoseini, et al., 2017). Case studies were used to show how BIM can be applied to address project challenges with 3D/4D modeling (Mostafa & Leite, 2018). Furthermore, perceptions regarding the benefits of 5D BIM was studied and the perceived barriers to 5D BIM implementation within the construction industry were summarized as: a lack of software compatibility; prohibitive setup costs; a lack of protocols for coding objects within building information models; lack of an electronic standard for coding BIM software, and the lack of integrated models (Stanley & Thurnell, 2014). Even overall framework and organizational transformation strategies for contractors to adopt BIM within their entities were proposed (Ahn et al, 2015).

There have been specific studies on the application of CSFs in construction industry. Shang et al. (2014) developed a framework of BIM implementation to improve project collaboration, while emphasizing the lack of systematic analysis on CSFs for BIM implementation in construction projects (Shang & Shen, 2014). There are various studies of CSFs in construction industry, such as exploring CSFs of enterprise resource planning (ERP) implementation in the construction industry in developing countries (Ozorhon & Cinar, 2015). Studies were also performed to analyze CSFs of BIM implementation in developing countries, which indicated 16 CSFs that were human-related, industry-related, project-related, policy-related, and resource-related factors (Ozorhon & Karahan, 2016). Although, there are many studies to explain the importance of BIM processes in various industries, there is a limited number of studies that has investigated the analysis of critical success factors (CSFs) for BIM implementation including the drivers, enablers, inputs, barriers, and benefits of such a technology to construction companies especially separately in the design and construction phases. This study aims to fulfill this gap by investigating the CSFs for BIM implementations specifically in the design phase. As a secondary purpose, the ranking of CSFs that will be presented as an outcome of this study will be used to support the members of AEC industry, especially in the developing countries where companies do not possess background information regarding BIM, to help them understand and utilize successful implementations of BIM during the design phase.

2. METHODOLOGY

The methodology of this study includes adopting a CSF framework from literature, collecting literature review data on BIM-related studies, performing interviews for selected case study projects, and finally compiling and analyzing data to see BIM implementation trends, as briefly shown in Figure 1.

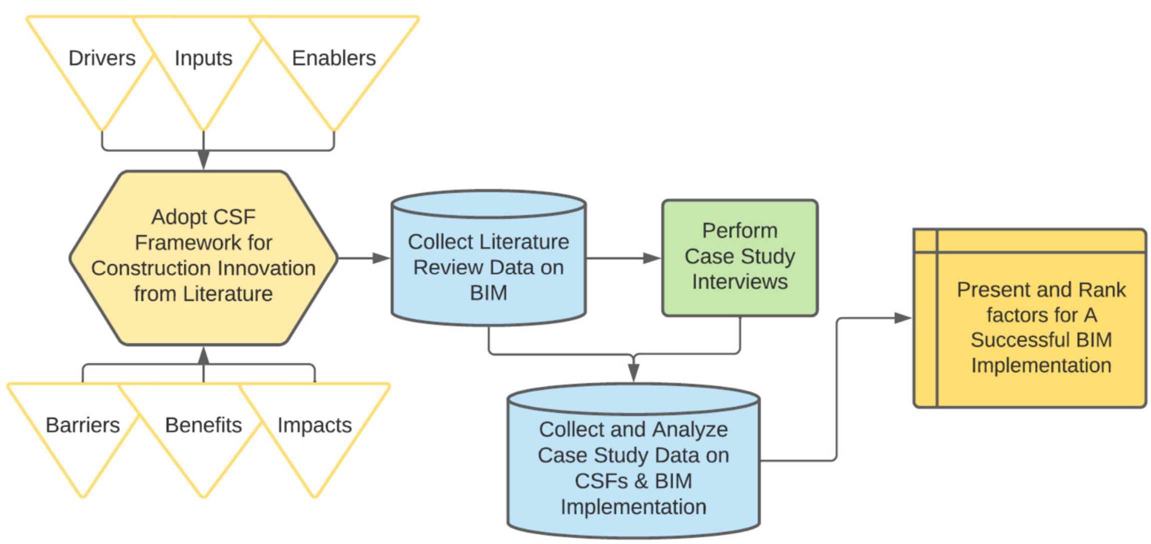

Fig. 1. The Step-by-step Diagram to Find BIM Implementation Factors

2.1 Adopting a CSF Framework

In order to find the CSFs, first, a framework highlighting the six (6) components of BIM implementation as drivers, inputs, enablers, barriers, benefits and impacts was adopted from a previous study, as shown in Figure 2. This framework provides the CSFs in all dimensions and emphasizes that each component is linked to each other for a successful BIM implementation. Drivers are defined as the motivations behind the willingness to shift from the traditional approach to more digitalized environment of BIM. Enablers are defined as the facilitators or the accelerators for the adoption of BIM. Barriers represents the hindering factors and challenges that have a negative impact on the adoption of BIM applications. These components play a crucial role on the decision to follow the BIM flow, as they are the first components to be considered. Inputs cover the tools and requirements to implement a successful BIM application. Benefits represents the project level gains that are also defined as the short-term gains to be observed through the BIM implementation. Impacts refer to the benefits in the company level, which can be the medium- or long-term gains that a firm can benefit in the long run by adopting BIM.

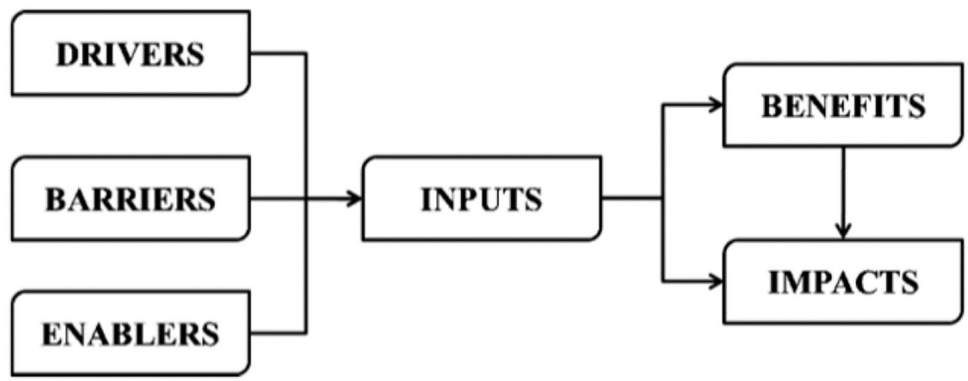

Fig. 2. Framework Model for BIM Implementations (Ozorhon, 2013)

2.2 CSFs for BIM Implementation

An extensive literature review about related studies' experience, methods, and findings were compiled to find the related factors for each component of the framework. Previous studies tried to find answers to the questions such as "how beneficial is implementing BIM?", "what are the enablers for BIM implementations?", "what are the driving factors to use BIM?", "what are the risks to shift BIM?" or "what are the possible challenges and barriers for the adoption of BIM?" are taken as relevant studies to validate the framework's components as well as the CSFs. Regarding to the aim, forty-five (45) research papers were examined to highlight the up-to-date studied literature CSFs in this topic.

The data collected from literature case studies were analyzed to reveal CSFs. To identify the key factors under each component as mentioned above, total of 181 factors were found in the literature review. A related study investigated *the benefits and the barriers of BIM* in UK's AEC industry by applying a questionnaire survey that compares the traditional CAD implementations vs BIM with around 70 individuals. Their method started with reviewing the literature and finding why some companies were eager to utilize this technology, while others did not (Yan & Damian, 2008). Sun, et al. (2017) also studied barriers which were categorized in five (5) groups as technology, cost, management, personnel, and legal. Lack of understanding, education, and training, start-up cost, and changing the way of how the construction has been done were the top ranked barriers hindering the BIM adoption. Some of the top benefits were stated as decreasing the rework, while consequently improving scheduling, sequencing coordination, visualization, communication, productivity, and safety. Decreasing the number of change orders and improving scheduling were summarized as the two top benefits in a recent study (Barlish & Sullivan, 2012). On the other hand, *critical BIM enablers* were listed as the ability to reduce risk and cost of the project, while improving quality, time constraints, and accuracy of the final product (Newton & Chileshe, 2012). Studies have also mentioned the potential *drivers* related to barriers of BIM implementation such as improving design, collaboration, and the project performance.

2.3 CSF Case Studies

There are two main information collected from case studies in this research. The primary information consists of any documents about CSFs in BIM like reports, forms, and letters. Archives such as project drawings and name lists are examples of primary information. Secondary information consists of interviews made with project personnel or clients for each case. A case study interview from was designed in 3 parts. Part 1 included questions about the respondents' career in the industry, such as the respondents' professions, positions, and their total experience years in the industry. In Part 2, company level data such as the establishment year, fields of the operation, expertise areas, number of employees, the adoption year of BIM, number of finalized projects utilizing BIM, and the specific BIM functions used in the company were gathered. Part 3 focused on the investigation of the cases and the evaluation of the CSFs. Identification of the project type and duration, total gross construction area, number of the BIM team members, and software involved in the cases were collected. Questions supporting the benefits such as a cost or time saving occurred due to implementing BIM were also asked to the respondents. The last part also reviewed the factors for the 6 components of the framework to find the critical factors for each. It was requested for respondents to rate each factor of the components on a 1 to 5 scale, 1 being insignificant and 5 being very significant.

Case studies were collected from twenty-five (25) respondents currently working to implement BIM in fifteen (15) well-known companies in the local construction industry. 52% of the respondents identified themselves as architects, 40% as civil engineers, and 8% as both. 44% of respondents have had more than 10 years of experience in the industry. The BIM functions utilized in companies showed that each company provided 4D level of BIM implementation, while 87% of them used 5D level. 6D and 7D levels were rarely used with 33% and 27%, respectively. Among interviewed cases, sample commercial building project information is presented in Table 1.

Table 1: Sample Interviewed Case Studies

Company	Project Type	Interviewed Party	Duration (months)	Size of the BIM Team	BIM Application
C1	Commercial	Designer	14	30	7D
C5	Commercial	Designer	36	7	5D
C6	Commercial	Designer	24	15	5D
C7	Commercial	Designer	24	7	6D
C9	Commercial	Project Manager	6	8	7D
C12	Commercial	Designer	18	3	6D

Since companies' familiarity with the BIM technology is one of the key parts of this study, the adoption within the organization and the respondents' knowledge of BIM functions were also investigated. Regarding to respondents' answers, BIM adoptions among the companies is shown in Figure 3 chronologically. This figure shows that only one company have had experience above ten (10) years and most of the companies' familiarity with BIM process has ranged around seven (7) years. The functions that were utilized with the BIM technology, such as 4D, 5D, 6D, and 7D BIM, are shown in Figure 4. Results showed that every company provided 4D level of BIM implementation at minimum in their organization. 87% of the companies interviewed also implemented 5D level of BIM implementations. 6D and 7D level of BIM implementations were rare in the analyzed data set, as they were ranked by 33% and 27% of the companies, respectively.

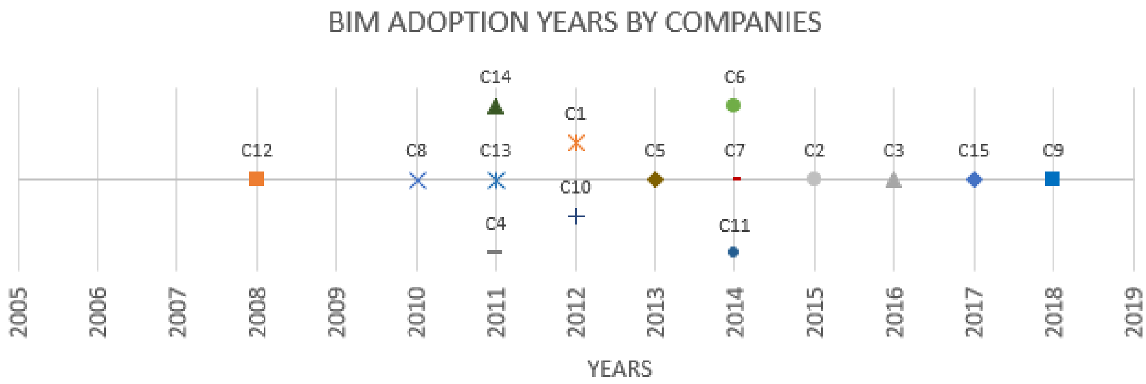

Fig. 3. BIM Adoption Timeline of Companies

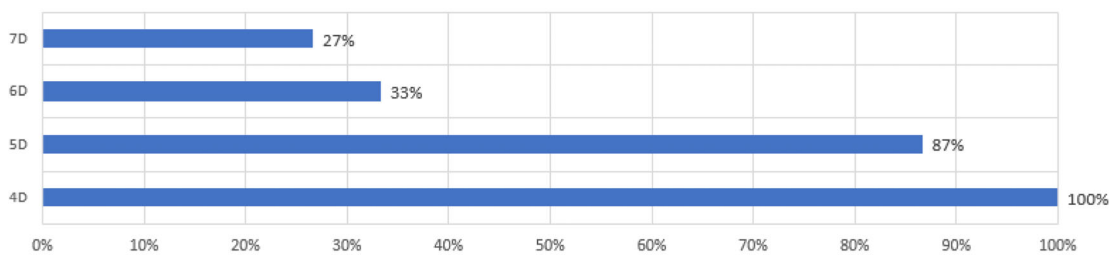

Fig. 4. Distribution of BIM Functions among Companies

When the establishment years of the companies and the BIM adoption years were compared (Figure 3), it was noticed that company C1 was founded as a BIM based design company and company C2 was the quick adopter. The rest of the companies could be classified as "late-comers" except C12. Since the establishment year of the company C12 was in late 1960s, it was the first adopter among the 15 companies. Late-comers might have failed to adopt BIM early possibly because of the transition problems.

3. FINDINGS AND DISCUSSIONS

Case study results presented a list of a list of ranked factors for the six (6) components of BIM implementation as drivers, inputs, enablers, barriers, benefits, and impacts. Case study results are further compared with the results gathered from the literature studies. Table 2a shows a comparison of *drivers* for a successful BIM implementation in case studies vs literature. According to the comparison "Improve Coordination and Collaboration", " Improving Project Performance" and "Design Improvement" factors were found as *significant factors* in both studies. "Reducing Life Cycle Cost of the Building" factor had the same significance level in both studies. "Improving Health, Safety, and Environmental (HSE) Activities" was ranked to be *insignificant* in both results. No differences in the rankings were realized in "Improving Corporate Performance" and "Client Requirement" factors, however "Improving Building's Energy Performance" and "Governmental Push" factors were ranked higher in literature. A similar comparison was performed for *barriers* for a successful BIM implementation. "Lack of Government Support", "Project Specific Problems", "Change Process Problems", "Legal Protocol Problems", and "Lack of Best Practices" showed consistency in both lists. However, the remaining factors; "Fragmented Nature of the Industry", "Interoperability Problems of Different Parties", "Unclear Benefits", "Technology Related Problems", and "High Costs" were ranked differently in the case studies.

Table 2: Comparison of the Drivers in Case Study Results vs Literature Results

General Case Study Results	Ranking	Literature Review Results
Improving Collaboration and Coordination	1	Design Improvement
Improving Corporate Performance	2	Improving Project Performance
Improving Project Performance	3	Improving Collaboration and Coordination
Design Improvement	4	Improving Construction Productivity
Client Requirement	5	Improving Building's Energy Performance
Improving Construction Productivity	6	Reducing Life Cycle Cost of The Building
Reducing Life Cycle Cost Productivity	7	Improving Corporate Performance
Improving Building's Energy Performance	8	Governmental Push
Improving HSE Activities	9	Client Requirement
Governmental Push	10	Improving HSE Activities

A further look into the ranking of each factor for the six components of the BIM implementation was performed to see the most important vs the least significant items in each list. The rankings in commercial projects for *drivers and barriers* are shown in Table 3 and Table 4.

Table 3: Rankings for Drivers of BIM Implementation from Case Studies

	DRIVERS	Significance Ranking on a 1-5 Scale
DR1	Improving collaboration and coordination	4.60
DR2	Improving corporate performance	4.20
DR3	Improving project performance	4.60
DR4	Design improvement	4.80
DR5	Client requirement	3.60

DR6	Improving construction productivity	3.67
DR7	Reducing life cycle cost of the building	3.40
DR8	Improving building's energy performance	3.40
DR9	Improving HSE activities	1.00
DR10	Governmental push	1.00

Table 4: Rankings for Barriers of BIM Implementation from Case Studies

BARRIERS		**Significance Ranking on a 1-5 Scale**
BA1	Fragmented nature of the industry	4.33
BA2	Interoperability problems of different parties	2.67
BA3	Unavailability of knowledge based on experience	3.40
BA4	Change process problems	3.40
BA5	Project specific problems	2.00
BA6	Unclear benefits	2.60
BA7	Legal and protocol problems	2.20
BA8	Lack of best practices	2.40
BA9	Technology related problems	2.60
BA10	High costs	1.80
BA11	Lack of government support	1.40

General case study results of drivers' factors showed similarity with the results of specifically investigated commercial project cases except "Design Improvement". This factor was the leading motivation for the BIM applications in commercial projects. In terms of inputs, "Internal Knowledge", "Project Information", and "Company's BIM Policy" were all ranked higher than 4.40. On the other hand, the higher ranked barrier was the "Fragmented Nature of the Industry" with 4.33 and the "Unavailability of the Knowledge Based on Experience" was ranked second with 3.40. That is why, one of the inputs, "Planning of BIM Execution Process" factor's importance was evaluated to be at 4.60 in the commercial projects. It was noticed that through implementing BIM in commercial projects, the significance level of "Project Financial Benefits", "Right and Accurate Construction Activities", "Right and Accurate Technical Office Works", "Knowledge Management Benefits" and "Project Management Benefits" factors were all highly ranked in the commercial building projects compared to other project types in the general case study results.

4. CONCLUSIONS

Throughout this study the aim was investigating the successful BIM implementations through a CSF-based framework in the design phase of commercial building projects. The case study method was used with respondents from different companies in the local industry to evaluate which factors were crucial in their projects. Regarding the collected information and analysis, major drivers were observed as "Improving Collaboration and Coordination", "Improving Corporate Performance", "Improving Project Performance", and "Design Improvement" factors, all being ranked close to the *very significant* level. The least significant drivers were “Improving HSE activities” and “Governmental push’, which showed that countries’ approach and support on BIM is important for governments to become a driver in BIM implementation in construction. The major barriers were observed as "Fragmented Nature of the Industry", “Unavailability of knowledge based on experience”, "Change Process Problems", and "Interoperability Problems of Different Parties" factors. Surprisingly, “Lack of Government Support” and “High Costs” were ranked as the least effective barriers for commercial buildings.

Considering the results of this study ensuring the development of successful BIM applications at the industry level, industry members need to be encouraged to overcome their resistance to change by getting inform about BIM. Strategic national BIM implementation guidelines or standards are needed to support the update to BIM and to see the long-term effects in the industry. The guidelines or standards prepared in this way has a potential to prevent damages caused by the fragmented nature of the industry by addressing how improvements can be made among project parties, who have difficulties in handling the project together. Future work can include collecting further data on various project types other than commercial, and comparing the ranking of the factors in the six (6) CSF areas with the commercial projects.

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A SYSTEMATIC REVIEW OF AUGMENTED REALITY APPLICATIONS IN CONSTRUCTION - A FOCUS ON PRODUCTIVITY GROWTH

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ABSTRACT: *Prevalent low productivity remains one of the primary causes of cost overruns in construction projects globally. Although, a significant number of research have been conducted to ameliorate the devastating impact of low productivity in construction, the situation is still worrisome to the industry practitioners and academics. The construction industry has begun to transit from its conventional practices to adopting technologies that is able to promote performance. One of such technologies is Augmented Reality, which is being embraced in different aspects of construction projects. The purpose of this paper is to review areas that Augmented Reality technologies (ARt) could contribute to productivity growth in construction projects. The research took into account ARt studies conducted from 2010-2021 in journal of automation in construction. The study found that ARt applications are significant to construction productivity growth and could be leveraged to promote operation efficiency in construction projects. The study created awareness of ARt significance to construction productivity improvement.*

KEYWORDS: *Augmented reality, Construction, Design, Literature, Productivity, Technology*

INTRODUCTION

Productivity in construction indicates a general pattern of decline compared to other industries. Productivity is commonly expressed at the activity, project, and industry levels (Yi and Chan 2014). These are respectively concerned with productivity on construction tasks, construction projects, and the industry long-term productivity trends (Shan et al., 2016). Due to the growing knowledge that the construction industry significantly contributes to economies, productivity growth is becoming more vital to the industry's stakeholders and policymakers than ever (Fadejeva and Melihovs, 2010). The concept is relevant to every sector; thereby contributes to diverse knowledge and perceptions to its meaning. In construction, productivity is understood as the units of work placed or produced per man-hour, while considering some predetermined measurements (Attar et al., 2012). It represents an essential parameter for measuring the performance of any construction organisation. Several research projects have been conducted to address the pervasive low productivity in construction (Olomolaiye et al., 1987; Kaming *et al.*, 1997; Alinaitwe et al., 2007; Alaghbari et al., 2019; Toan et al., 2020). Notwithstanding these studies, the construction industry has continued to be confronted with slow productivity growth and even decline in some regions. In the last two decades, the construction industry has begun to adopt advanced technologies to improve its performance. This has led to the adoption of Building Information Modelling (BIM), Internet of Thing (IoT), Virtual Reality (VR), Augmented Reality (AR) and other innovative technologies. Applications of Augmented Reality technology (ARt) have the potential to help radically improve construction productivity, reduce rework and improve communication of design intent (Kwiatek et al., 2019). Defect-related-rework is considered as a non-value adding activity which considerably affect the performance and productivity in construction projects. The occurrence of rework gives rise to expending unnecessary costs, time, materials, and manpower (Park et al., 2013).

Augmented reality is a field of research that combines the real world and computer generated data. It is an environment where data generated by a computer is inserted into the user's view of a real world scene (Milgram and Colquhoun, 1999). ARt is a technology that is generally used to ease the associating of digital information with the real world objects and spaces. It allows a user to work in a real world environment while visually receiving additional computer-generated or modelled information to support the task at hand. AR environments have been typically applied primarily in scientific visualization and gaming entertainment (Wang et al., 2012). However, practical applications of the technologies have extended to manufacturing, education, and construction to deliver a better quality of life (Fazel and Izadi, 2018). It makes sense to begin to explore ARt and other advanced technologies to promote productivity growth in construction (Irizarry et al., 2013; Yi and Chan, 2014). Consequently, ARt represents one of the technologies that the construction industry is exploring to drive performance. ARt are generally composed of three elements: data, computing, and presentation. Data phase is intended to create and prepare data, which is later used as a source to augment the reality. Computing or merging of virtual and real environments during work intensive phase, viewed from the hardware standpoint. It can take place on the mobile device or on a remote server. Two general approaches are usually used to present/display ARt (1) mobile hand-held devices such as smartphones and tablet computers and (2) head mounted devices such as Google Glass (Meza et al., 2014). ARt supplements reality with added digital elements, where computer-generated content is overlaid onto the real world and the actual reality becomes 'augmented'. According to Massachusetts Institute of Technology Review (2021), one of the ways for the construction industry to improve productivity fast and ensure long-term results is by using innovations in the field of augmented reality. The application of ARt in the construction industry have been applied to different areas of construction operations that are largely classified into design, construction, and post construction phases (Fazel and Izadi, 2018). Because this study focuses on ARt as they apply to productivity growth in construction, this paper will be considering the technologies' applications specific to the design and construction phases. The study examines applications of ARt that can contribute to productivity growth in the construction industry. Following this section in order of presentation are literature review, methodology, discussion, and conclusion.

LITERATURE REVIEW

Although the application of ARt in construction projects has tremendously increased in recent years, these technologies are still in the research stage and their full potential is not fully achieved. As technologies developed in recent years, the majority of these technologies have been used in construction operations. Virtual reality, which creates an immersive environment and augmented reality, which is an enhancement of the existing surroundings created by overlaying digital information are the two main areas of enhanced digital reality (Hou et al., 2015). Architecture is one of the application domains for ARt, especially in design and planning (Fazel and Izadi, 2018). Kwiatek et al. (2019) investigated how the use of an ARt tailored for pipe fitting and spool inspection might increase productivity and reduce rework through the clearer communication of design information coupled with visual feedback on the assembly as it is completed in real-time. Experiments were conducted with 21 professional pipe fitters and 40 engineering students, and they concluded that ARt can help save substantial time in pipe spool assembly over the conventional methods for both untrained engineers and for well trained professional pipe fitters. Design changes, errors and omissions, which often result in rework, are the primary factors contributing to schedule overruns (Love et al., 2018). Most changes made from the initial design should be recognized in the BIM. Unfortunately, at present, there is no process in place for updating the designed BIM model to incorporate the changes made during construction (Gu and London, 2010). As a consequence, Wang et al (2013) suggested that ARt can be used to map the as-built and as-planned data in a single digital environment with each component allocated with a status: ordered, procured, delivered, checked, installed, completed, commissioned, and fixed. Being able to visualize the difference between 'as-planned and as-built' progress enables 'current and future' progress to be monitored and therefore facilitates appropriate decision-making. In the construction stage, progress monitoring, assembly instruction, and quality management were dominant ARt applications (Chen and Sue, 2020). Studies have suggested that the application of ARt is more effective for the novice assemblers who undergo considerable cognitive workload (Kwiatek et al., 2019; Chen and Sue, 2020). Hou et al. (2015) investigated the impact of gender factor on assemblers' effectiveness. They found that ARt helps both male and female trainees learn the assembly routine faster and the technology is more effective for both male and female assemblers than the 3D manual.

Leveraging BIM to automatically orchestrate the necessary tasks to be allocated to a human operator and a welding robot, Tavares et al. (2019) propose a collaborative welding system using BIM for robotic reprogramming and spatial augmented reality. The spatial augmented reality system projects alignment information into the environment for helping the operator to tack weld the beam attachments that will be seam welded later by the industrial robot. This way we ensure maximum flexibility during the beam assembly stage while also improving the overall productivity and product quality since the operator no longer needs to rely on error prone measurement procedures and he receives his tasks through an immersive interface, relieving him from the burden of analyzing complex manufacturing design specifications. Wang et al (2012) investigated how BIM can be integrated into real-time communication on-site, and proposed a conceptual framework that integrates BIM with ARt so as to enable the physical context of each construction activity or task to be visualized in real-time. To achieve effectiveness, they recommended that ARt should be ubiquitous (including context awareness) and thus operate in conjunction with tracking and sensing technologies such as radio frequency identification, laser pointing, sensors and motion tracking. Multidisciplinary collaboration would be one of the trends for AR applications in construction and is suitable for information communication and exchange in construction (Wang et al., 2020). Engineers can make annotations about existing cables and pipes overlaid with AR visualizations, and the technicians can know the locations and other information of these cables and pipes before they determine whether extra pipes and cables are required (Olbrich et al., 2013).

Arising from the repeated and inevitable occurrence of defects which contribute to schedule and cost overruns in construction. Kwon et al. (2014) identified the challenges confronting a handful of site managers to perform quality management efficiently for an entire site based on inspected progress of construction works. Quality management through their visual senses has given rise to faulty construction which sometimes necessitates rework and elongation of project schedule. Kwon et al. (2014) utilised BIM, image matching, and ARt to develop two types of defect management systems, which include an image-matching system to enable quality inspection without visiting the real work site and a mobile AR application which enables workers and managers to automatically detect dimension errors and omissions on the jobsite. The application focuses on making design information easier to interpret and provides frequent feedback on completed or partially completed assemblies. This facilitates the process of completing assemblies' right the first time; increasing productivity and reducing rework. At the design stage, ARt has been popularly used for assessing the designed drawings or models in the physical environment and communicating design ideas to different stakeholders (Jiao et al., 2013). A successful application could be modified for fabrication of other types of construction project assemblies or become part of the knowledge base for developing new applications.

A study by Park et al. (2013) investigates the issues and needs of current defect management practices in the construction industry, and further proposes a conceptual system framework for construction defect management that integrates ontology and ARt with BIM. They proposed three main technical solutions, which include defect data collection template to assure data quality and accuracy, defect domain ontology to search and retrieve project or work-specific defect information, and AR-based defect inspection system to support field defect management. The system framework could enable proactive reduction of the defect occurrence during the construction process and that could greatly improve current defect management practices in the construction industry. Because safety trainings has not guarantee safety in construction, Kim et al. (2017) proposes a vision-based hazard avoidance system that proactively informs workers of potentially dangerous situations. The system enables workers to recognize and consequently avoid dangers before accidents occur by displaying augmented hazard information on a wearable device. The system comprises a vision-based site monitoring module that utilizes image capture device and wearable devices to identify site hazards, a safety assessment module that uses captured image data and fuzzy-based reasoning to evaluate the safety level of each object, and a visualization module that provides actionable information such as hazard orientation, distance, and safety level. ARt have been probed and tentatively implemented in various safety enhancement areas, such as risks identification, workforce training, skill transfer, ergonomics (Li et al., 2018). ARt is a safer option for hazardous construction sites compared to virtual reality as it retains the user's awareness of their physical environment and allows them to maintain pride in their work (Irizarry et al., 2013). Fazel and Izadi (2018) presents a new affordable interactive multi-marker augmented reality tool for constructing free-form modular surfaces implemented by integrating common accessible devices. The proposed tool consists of two digital cameras, a head-mounted display, a processor, and two markers that enable the user to virtually see the accurate location of any proposed object in the real world. The results showed that the majority of errors (91%) were less than 6 mm, and 2° for lateral placements and orientation errors. Because prefabrication and construction processes run together, coordination between the two activities is essential. Major delays can occur if a production plant does not provide enough material timeously or may cause storage issues if delivered to site early. According to Babic et al. (2010), a balance can be maintained by monitoring on-site status using ARt and project documentation integrated with a prefabrication plant. They emphasised that this may address possible construction delays and a lower demand for material buffering, improves efficiency of logistics, on-site material handling and overall project progress tracking.

METHODOLOGY

The methodology used for this study included a systematic review of augmented reality research. A literature search was conducted using the systematic approach of the Preferred Reporting Items for Systematic Review and Meta-Analysis (PRISMA) protocol guidelines. PRISMA offers evidence-based results while improving the quality of review reports through a transparent literature selection process (Alaloul et al., 2021). The search for research projects in the augmented reality area was carried out in the database of journal of automation in construction. The database was preferred in this study due to its relevant to the subject under investigation. The online search was carried out with the search string: "Augmented Reality". The search took into account research projects conducted from 2010-2021. Within this period, journal of automation in construction database yielded 289 research articles, which were subsequently subjected to further filtering processes to obtain the most relevant research articles. The study considered articles that have 'Augmented Reality' in their titles. The 34 articles, which were found to meet this criterion, were selected for reviews, while other articles were excluded from the study. This study is intended to expand its scope to other databases to obtain more relevant areas of ARt applications that have the potential to contribute to productivity growth in the construction industry.

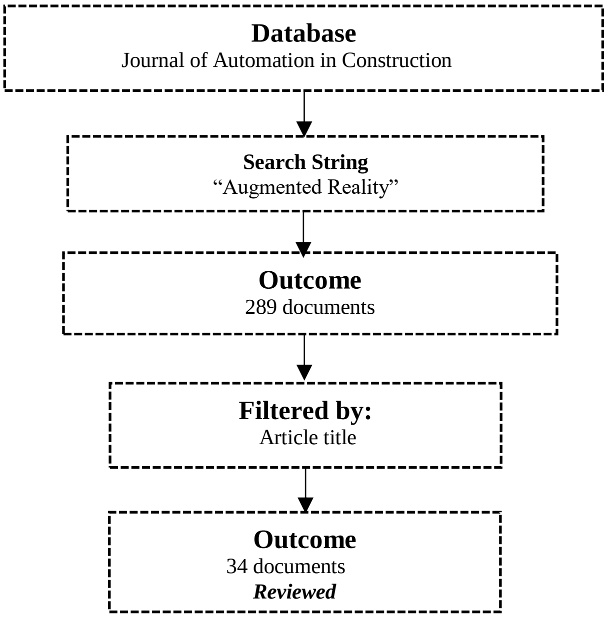

Figure 1: Research process

DISCUSSION

As the construction industry embraces technology innovation to address its myriad of challenges, augmented reality has the potential to contribute to jobsite productivity growth. Existing studies have spotlighted different areas that ARt can contribute to promoting productivity in construction. Design related problems such as errors and omissions in design and drawings remains of the challenges that constitute barrier to productivity growth in construction (Jarkas et al., 2015). Craftsmen are usually concerned about engineering drawing information (Dai and Goodrum, 2011). In the design phase, AR applications are used for visualization, which allows architects to interact with virtual spatial data and features of a proposed design in its final context. Conventionally, most of the jobsite operations such as inspection of design documentations are done manually, which requires more than one person and takes a long time to document and circulate the information to other construction team members. However, ARt can help to accurately determine potential errors in design documentations as it enables workers and managers to automatically detect dimension errors and omissions on the jobsite. A site manager regularly reports on the accomplished work. In model-based working, the site manager reports on the performed work by selecting the constructed parts of the building in the 3D model. With ARt, a project manager, who is responsible for several projects, can obtain information about activities in different locations. After the input of the actual as built progress, variances between the as built and as planned progresses can be stated and displayed using different colours, providing site managers with intuitive representation of deviation in progress. Colour schemes can indicate ‘behind schedule/delayed’, ‘on schedule’, and ‘ahead of schedule’. The project manager can compare as-planned and as-built situations and also identify existing or forthcoming difficulties related to material production and delivery. With ARt, more problems can be uncovered and solve them faster without paper blueprint hassle and communication delays. However, the ubiquitousness and context awareness of ARt in conjunction with tracking and sensing technologies will enhance its effectiveness during construction projects delivery.

A building inspector is able to discover errors early by comparing what is being built to the building information model with the aid of an AR application. With ARt, information sharing becomes more effective. ARt enables site inspector to share any error uncovered with multiple team members, while problem areas becomes easier to recognised and corrected. Besides, field workers can share their video feed from the AR glasses and receive advice or instructions from a remote expert in real time. In this way, it permits for an individual to interact with real-world projects and deal with defects, risks, and accidents before they occur. Literature has provided evidence that ARt in conjunction with BIM can be used to proactively reduce the occurrence of defects during the construction process and significantly improve current defect management practices in construction. Miscommunication causes change orders and rework. Change orders can slow down production process with attendant cost implications. With ARt, a client can see the results before even the commencement of the project. This will considerably mitigate change orders which are usually issued by clients during production.

Collaboration quality across all stages of construction can influence the time and cost of construction. ARt allow real-time 3D visualization, collaboration, and field-to-office communication across all stages of construction. Interdisciplinary collaboration is one of the trends in AR applications in construction and is well suited for communication and exchange in construction (Wang et al., 2020). The on-site real-time communication benefit of ARt provides the opportunity to save time in resolving issues before constituting delay in construction operations. In the construction phase, AR applications can overlay BIM data information directly on the construction site to aid constructors through the assembly procedure. With ARt, design information becomes easier to interpret, while frequent feedback are provided on completed or partially completed assemblies. ARt is being used in the world of construction engineering and management by placing a 3D model in the front of the eyes of the consumer and starting up a learning experience unlike any seen before. Skill shortage in construction is one of the factor that bedevil the productivity of the sector. To a large extent, the application of ARt can enhance workers' skill through series of learning experience. Through creating exposure to a project before it physically exists, ARt create a unique gaining knowledge of opportunity for the inexperienced and construction-savvy people alike by means of presenting the opportunity to locate and fix a project's flaws in a safe, hazard-free environment all in real time. ARt provides the benefit of a visual-based hazard prevention system that proactively notifies workers of potentially dangerous situations. This system allows workers to identify hazards before an accident occurs and, as a result, avoid it by displaying extended hazard information on their mobile devices. It shows that the AR-based visualization of information contained in a database such as BIM can provide those on-site with an improved understanding of their work and thus increase productivity. Once the way utilities are laid out are noticed, prefabrication of parts can be done in advance without being anxious of issues with misaligning or miscalculations. The spatial augmented reality system can help operators position the beam attachments before it is later welded by the industrial robot. With augmented reality applications, site managers can get into the BIM model, adjust the building schedule, and plan out the logistics weeks ahead. To improve productivity, minimizing the impact of rework is critical. During construction, workers can spot any error faster and prevent rework.

One of the main factors that hindered the mass implementation of ARt in construction is the high price of augmented reality. Hence, only large enterprises can afford large up-front investments in emerging technologies like ARt. Besides, IT department are not operational in most construction organisations, which may constitute a challenge to most organisations adopting these emerging technologies. This suggests that some construction organisations have not considered ARt as being beneficial to their effectives or due to cost constrain to host the technology. Nonetheless, the augmented reality application development cost is getting lower with the advent of open-source mobile toolkits. Its application is expanding and and small-to-medium construction organisations have started to take advantage of the benefits of ARt in construction. As AR technology improves, new opportunities for its application to construction will continue to emerge, as the benefits to be derived from its implementation outweigh the cost (Chu et al., 2018).

CONCLUSION

Some of the benefits construction organisations can derive from ARt during construction and design phases include: early discovery of design errors which mitigate non-value adding activities such as rework, effective real-time information sharing among project participants, early identification of potential hazard and accidents, and effective assembly with frequent feedbacks which provides improved learning experience. Integration of BIM and ARt has been found useful in construction operations. Augmented Reality has been proposed as a mechanism to enhance the process of information extraction from building information models to improve the efficiency and effectiveness of workers' tasks. Leveraging BIM, the application of ARt has been used in different stages of construction production to enhance task productivity through improved information handling. ARt has the potential to increase productivity and reduce rework through the clearer communication of design information coupled with visual feedback on the assembly as it is completed in real-time. ARt can help save substantial time in construction project deliveries.

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EVALUATING IN-THE-MOMENT FEEDBACK IN VIRTUAL REALITY BASED ON PHYSIOLOGICAL AND VOCAL MARKERS FOR PERSONALIZED SPEAKING TRAINING

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ABSTRACT: *Speaking anxiety is a major detriment to successful employment interviews and making professional connections. This paper investigates the effectiveness of personalized, adaptive, and bio-behaviorally aware in-the-moment feedback, administered in a virtual training environment, for mitigating speaking anxiety and achieving successful interpersonal communication. The training environment exposes participants to various virtual stimuli. User personalization and adaptation is achieved via a machine learning system, which tracks the speaker's real-time acoustic and physiological measures, outputs moment-to-moment estimates of state anxiety, and provides real-time feedback of cognitive restructuring when an increase in state anxiety is detected. Evaluating the system through a user study indicates significant differences with respect to acoustic and physiological measures before and after the provision of in-the-moment feedback prompts. This research lays the foundation for designing artificial intelligence systems that administer personalized in-the-moment interventions for mitigating negative outcomes in professional settings.*

KEYWORDS: *Personalized training; in-the-moment feedback; interpersonal communication, physiology; speech; artificial intelligence.*

1. INTRODUCTION

While strong verbal communication skills are considered a core learning objective in many academic programs, speaking anxiety remains one of the most common type of social fears (Dwyer and Davidson, 2012). People with speaking anxiety are 10% less likely to graduate college, earn 10% less than their peers, and have 15% less chance of obtaining leadership positions (Schneier, 2006). Among various interventions for this type of anxiety, habituation to public speaking through frequent encounters is known to desensitize the speaker to the stimuli (Bodie, 2010), and help restructure his/her negative thoughts (Ayers and Hopf, 1992). Several studies have explored displaying pictures of social stimuli (Dimberg et al., 1986), using an imaginary audience to simulate a real-life speaking scenario (Schwerdtfeger, 2004), or exposing the speaker to a small-sized real audience (Zuardi et al., 2013; Kirschbaum et al., 1995). Others have leveraged immersive experiences in virtual reality (VR) to approximate various public speaking settings (Slater et al., 1999; Pertaub et al., 2002; Heuett and Heuett, 2011; Diemer et al., 2014; Kampmann et al., 2016). Particularly, speech practicing in a virtual environment has been found to be more effective than methods that require participants to visualize their audience (Heuett and Heuett, 2011). VR environments further allow the simulation of large-sized audiences in scenarios that are difficult to replicate in real-life, and do not entail the risk of public embarrassment (Anderson et al., 2005; Harris et al., 2002).

In verbal communication, some individuals might concentrate on their physical symptoms (e.g., hands shaking, nauseousness, progressive anxiety, being judged by the audience). Combat veterans, for example, constitute a particular group that tends to depict such behavior (Orsillo et al., 1996), potentially due to maladaptive patterns of social functioning, which can have a significant effect on interpersonal communication skills while transitioning to the civilian world (Trahan et al., 2019; Behzadan and Chaspari, 2021). Cognitive restructuring feedback can help identify inaccurate or negative thoughts, and offer coping mechanisms to remedy speaking anxiety. Prior work has investigated cognitive restructuring via behavioral therapy administered by a psychologist (Anderson et al., 2005; Wallach et al., 2009; Price and Anderson, 2011) or a virtual agent (Pertaub et al., 2002; Kimani and Bickmore, 2019). In contrast to cognitive restructuring administered in a retrospective manner, in-the-moment interventions can leverage real-time information about the speaker's cognitive and affective state, and immediately provide necessary scaffolds and prompts to restructure negative thoughts, and encourage and motivate a healthier perception of the speaking task (Webb et al., 2010; Sano et al., 2017; Nahum-Shani et al., 2018).

In this paper, we investigate the effectiveness of in-the-moment bio-behaviorally aware feedback in mitigating speaking anxiety in a virtual training environment. The proposed system captures participants' speech and physiology (i.e., electrodermal activity or EDA, blood volume pulse or BVP), extracts bio-behavioral features from recorded data, utilizes these features to estimate state-based anxiety, and provides real-time feedback when an increase of in-the-moment state- based anxiety is detected. Personalization is achieved by capturing the speaker's bio-behavioral data, while adaptation is ensured through the real-time nature of the machine learning (ML) model. Feedback is provided in the form of a visual prompt, and focuses on cognitive restructuring. The proposed system is evaluated through a small-scale study of participants using a pre/post evaluation design. Specifically, we aim to answer the following research questions: **RQ1:** To what extent does bio-behaviorally aware in-the-moment feedback affect speaker's bio-behavioral reactions? **RQ2:** How do different audience reactions (i.e., negative, positive and neutral) affect the provision of bio-behaviorally aware in-the-moment feedback? **RQ3:** To what extent is the provision of bio-behaviorally aware in-the-moment feedback related to speaker's state- and trait-based anxiety? **RQ4:** To what extent does the bio-behaviorally aware in-the-moment feedback promote speaking skills?

2. PRIOR WORK AND KEY CONTRIBUTIONS

Stress induced during high-stake communications can elicit the reactivity of the autonomous nervous system (ANS), which is manifested in changes in various body processes such as heart rate (Behnke and Carlile, 1971) and sweat activity (Clements and Turpin, 1996). Grounded in this evidence, prior work has utilized physiological signals, such as EDA, BVP, and electrocardiogram (ECG) to measure speaking anxiety (Behnke and Carlile, 1971; Kimani and Bickmore, 2019; Yadav et al., 2019). Various studies further indicate that acoustic prosodic features extracted from speech (e.g., loudness, jitter, shimmer) are indicative of anxiety (Batrinca et al., 2013; Chen et al., 2014; Chollet et al., 2015; Schneider et al., 2015; Bos, 2017), since state anxiety can result in increased palpitation of the vocal folds, which is reflected in prosodic changes (Van Puyvelde et al., 2018). Several studies have focused on designing ML models that learn multimodal (e.g., speech, image, and physiology) speaking anxiety patterns (Batrinca et al., 2013; Chollet et al., 2015). Wo¨rtwein et al. (2015) employed ensemble trees to automatically assess speaking anxiety based on eye contact with the audience, voice variability, and pause patterns. Yadav et al. (2019; 2020) used feedforward neural networks to quantify speaking anxiety based on acoustic and physiological measures by taking into account speaker's demographic and psychological characteristics. Prior work has examined the provision of in-the-moment feedback to improve public speaking and communication skills. In the CICERO system, visual feedback was provided by modifying audience reactions based on the speaker's behavior, as well as via a visual indication (i.e., green/red bar) of the speaker's performance (Batrinca et al., 2013; Chollet et al., 2015). Body pose and facial expressions have been utilized to reconstruct an avatar of the speaker, which was employed alongside visual prompts to provide in-the-moment feedback (Dermody and Sutherland, 2015). In the Presentation Trainer system, visual feedback showing corrective actions based on a user's body posture, hand gestures, and voice modulation was displayed, together with a small vibration generated by a wristband (Schneider et al., 2015). In-the-moment interventions related to cognitive restructuring have been evaluated for augmenting well-being (e.g., illness management, alcohol use disorders, sedentary behavior) (Van Dantzig et al., 2013; Ben-Zeev et al., 2014). Such interventions can help individuals reflect in real-time upon their thoughts and emotions, thus helping them acknowledge potential factors that might have contributed to the internalization of feelings of anxiety. Although in-the-moment interventions were shown to be promising (Nahum-Shani et al., 2018), they have been evaluated in few studies, mostly because their implementation is complex and involves the integration of multiple expertise (e.g., behavioral science, computer science, human-computer interaction).

The main contributions of this paper are: (1) In contrast to prior work that estimates a speaker's overall state-based anxiety for the entire speaking encounter, we design a ML model that estimates state-based anxiety on a moment-to-moment basis. This contributes to administering in-the-moment interventions at times when the ML system detects speaker's anxiety; and (2) Given the theoretically-grounded rationale from behavioral sciences and initial indications that in-the-moment interventions have the potential to mitigate stress, this work examine the effect of in-the-moment feedback, administered through cognitive restructuring to alleviate speaking anxiety and lead to better performance.

3. METHODOLOGY

This section describes the design, development, and evaluation of the proposed in-the-moment bio-behaviorally-aware speaking anxiety intervention. First, we outline the ML system that tracks momentary state-based anxiety, as well as the data used to train the system. Next, we present a bio-behaviorally aware in-the-moment training interface. Finally, a discussion on the user study conducted to assess the proposed training is provided.

3.1 Machine learning model to track speaking anxiety in real-time

The data used to train the ML system that tracks state-based anxiety are collected from 53 participants who conducted 10 presentation sessions (i.e., 2 sessions in front of a real-life audience, 8 sessions in various VR environments). During those sessions, no feedback was provided to the user; rather data were collected to examine bio-behavioral patterns during real-life and VR speaking tasks. EDA, BVP, body temperature, and 3-axis wrist acceleration were recorded during each presentation by the Empatica E4, and speech signals were collected via a lapel microphone. This dataset will be hereafter referred to as "Wave 1". Observational coding was conducted by an experienced annotator using the Noldus Observer XT software to obtain moment-to-moment annotations of state-based anxiety from the recorded speech signals. The annotator was asked to rate the perceived state-based anxiety on a 5-point Likert scale (i.e., 1: none, 5: very high). To minimize delays due to perceptual and cognitive processing (Metallinou and Narayanan, 2013), the annotator was instructed to listen to each audio file once without annotating so that she can fully observe and understand the speaker's anxiety levels. Next, she conducted annotation by inspecting and modifying the ratings of each audio file as needed to achieve a consistent rating.

The ML system was designed to provide an estimate of state anxiety over a pre-defined analysis window of length (W). For this reason, the provided continuous annotations were converted into a single value representing the entire analysis window, and computed as the first value of the annotations over that window. A total of 32 bio-behavioral features (including SCL, SCR frequency, SCR amplitude, heart rate, interbeat interval, mean body temperature, and the l2-norm of 3-axis acceleration) were further extracted over the same analysis window. Acoustic features, extracted via the OpenSMILE toolbox, included the mean of root mean square (RMS) energy, fundamental frequency (F0), zero crossing rate, number of pauses, and voicing probability. To model temporal bio-behavioral changes that might be indicative of state-based anxiety, we further included the bio-behavioral measures from the previous analysis window as the input to the ML model, in addition to the corresponding measures from the current analysis window. Missing feature values were substituted by the average value of the corresponding feature, computed for each participant. To reduce the original feature space and ensure a computationally feasible real-time system, feature selection was performed using the Spearman's rank correlation between each bio-behavioral feature and the state-based anxiety over the corresponding analysis window. Features with correlation greater than 0.05 and less than -0.05 with the corresponding outcome were selected as input to the ML model, resulting in a total of 27 features for 7,587 samples.

We experimented with various types of problem formulation (i.e., classification to detect the presence or absence of anxiety, regression to estimate the level of anxiety), ML algorithms (i.e., linear regression, naive Bayes, bagging, boosting, random forest), and analysis window lengths (i.e., W = 10, 15) using Wave 1 data. The final model deployed in the user study was a random forest classifier which provided binary predictions indicating the presence or absence of anxiety within 10-second analysis windows. The classifier included 30 decision trees each with a maximum depth of 30, and was trained on the binarized annotations derived from the 5-point Likert scale (1,572 samples with perceived anxiety levels of 3 or higher were considered as the presence of anxiety class, while the remaining 6,015 samples were assigned to the absence of anxiety class). The aforementioned hyperparameters, threshold value, and analysis window were experimentally found to yield the best result (i.e., 68% balanced accuracy).

3.2 In-the-moment bio-behaviorally aware cognitive restructuring feedback

A subset of 19 participants from Wave 1 were asked to fill out a survey following the VR session. As part of the survey, respondents provided their preferences in terms of the type of cognitive restructuring feedback that they would like to receive in VR. Results from the survey are presented in Table 1. Both visual and audio prompts were at the top of participants' choices, but we decided to administer feedback using visual prompts since these would likely interfere less with the speaker's verbal communication (Radianti et al., 2020). We nonetheless kept all prompts, since they were deemed useful by the participants to some extent. We implemented a real-time system to continuously collect physiological and speech signals, and run the ML model. EDA and BVP data were collected via the Empatica E4 device and were streamed to the experimenter's laptop (i.e., Intel core i7, 64-bit Windows operating system, 16 GB RAM). Real-time speech acquisition was conducted via the OpenSMILE toolbox and the PortAudio library. Python scikit-learn library was then used to run the random forest classifier every 10 seconds. When the classifier detected the presence of anxiety, a prompt was randomly selected and appeared on the speaker's virtual screen (Figure 1). To avoid information overload while allowing ample time to observe change in physiological reactivity resulting from a feedback prompt, prompts were generated at least 40 seconds apart, even if the ML system detected anxiety over continuous analyses windows.

Table 1: Responses to survey conducted to determine the provision mode and prompts of the in-the-moment cognitive restructuring feedback.

What type of feedback would you have liked to receive in VR?	Votes
Displaying a visual prompt in VR	6
Audio message via headphone	6
Vibration via wristband	5
Written message shown right after the session has ended	1
None	1
Which prompt(s) would you like to receive in VR? Select all that apply.	**Votes**
You are doing great! Relax!	12
Take a deep breath!	10
Stop for 2 seconds and gather your thoughts.	7
Don't worry! No one is judging you.	6
You know better than the audience.	5
You are doing better than others	4

Fig. 1: Snapshot of a virtual prompt provided to the participant in the virtual training environment.

3.3 User study

The designed system was evaluated via a small-scale user study with 7 participants (3 female, 4 male). Obtained data is hereafter referred to as "Wave 2" data. Participants were graduate students, aged between 22-27 years. Each participant conducted 4 speaking training sessions (STS) in the VR environment (totaling 2 hours), while in-the-moment bio-behaviorally-aware feedback was provided. Each STS consisted of three parts. Prior to the presentation task, participants watched a 5-minute relaxation video. They were then given 10 minutes to prepare a presentation of an article, which was randomly assigned from topics of general interest. This was followed by presenting the article in an immersive VR environment (enabled by an Oculus Rift handset and Virtual Orator platform) for approximately 5 minutes. The virtual environment was randomly assigned each time out of a total of 12 settings from various room conditions (i.e., boardroom, classroom, small theater, seminar room), audience reactions (i.e., negative, neutral, positive), and audience sizes (i.e., 12, 25, 54, 90). To maximize the sense of immersiveness, a low-volume background noise of a classroom environment was played in the background through the Oculus headphones. Participants wore the Empatica E4 to capture EDA, BVP, body temperature, and acceleration, as well as a microphone that captured speech signals. In total, data was obtained from 28 STS from all 7 participants. The same physiological and acoustic features as in Wave 1 data were extracted for the Wave 2 data. Each participant completed a set of surveys before and after the study, as well as after each STS. Before the study, the self-assessments included the State Trait Anxiety Inventory (STAI trait) (Spielberger, 2010) and Brief Fear of Negative Evaluation (BFNE) (Tavoli et al., 2009), demographics, and daily experience (e.g., caffeine/alcohol/drug intake). After each STS (four times per participant), surveys were administered to capture state-based anxiety, perceived performance, and immersiveness in VR. These included the State-Anxiety Enthusiasm (SAE), VR Presence (VRP) (Witmer and Singer, 1998), and Presentation Preparation Performance (PPP) (Yadav et al., 2019). At the end of the study, participants also provided feedback on the extent to which the study benefited their public speaking skills on a 5-point Likert scale (i.e., 1: not at all, 5: extremely).

4. RESULTS

This section discusses the analysis performed based on the Wave 2 data. We present this analysis in association to the four research questions (RQ1 through RQ4) that were previously formulated.

4.1 Effect of in-the-moment feedback prompts on speaker's bio-behavioral measures

We investigate the short-term effect of in-the-moment feedback on participants' bio-behavioral measures by comparing those measures before or after the provision of in-the-moment feedback. Table 2 provides the number of times each cognitive restructuring prompt was triggered by the ML system and displayed in the virtual environment. We compare the bio-behavioral measures 10 seconds before and 10 seconds after the provision of each prompt, and employ the non-parametric Mann-Whitney U-test to examine significant differences with respect to these measures before and after the provision of feedback. Results indicate significant differences with respect to various bio-behavioral measures (Table 3). For instance, we notice a decrease in zero-crossing rate and an increase in RMS energy of the speech signal, indicating a decrease in participants' speech rate after feedback provision, while speech loudness is increasing. These suggest that cognitive restructuring prompts might be able to alter the speaker's real-time bio-behavioral reactions, and potentially alleviate their PSA even momentarily.

Table 2: Number of times cognitive restructuring prompts were administered by the bio-behaviorally aware in-the-moment training system during the user study.

In-the-moment feedback	# Times used
You are doing great!	15
Relax! Take a deep breath!	13
You are doing better than others	15
You know better than the audience	14
Don't worry! No one's judging you	13
Stop for 2 seconds and gather your thoughts	21

Table 3: Mann-Whitney U-test statistic and p-value when comparing bio-behavioral measures recorded before and after the provision of cognitive restructuring prompts.

Bio-behavioral measures	Mean (± std) (before)	Mean (± std) (before)	Mann-Whitney (U, *p*)
Zero crossing rate	0.06 (± 0.011)	0.055 (± 0.008)	(2662, 0.002)
Fundamental frequency	85.96 (± 33.7)	88.15 (± 30.56)	(3441, 0.3)
Voice probability	0.44 (± 0.07)	0.45 (± 0.06)	(3397, 0.25)
RMS energy	0.001 (± 0.001)	0.002 (± 0.001)	(3383, 0.24)

4.2 Association between cognitive restructuring prompts and the VR environment

We examine the association of in-the-moment feedback prompts with the VR environment. Previous studies have shown that the type of audience can influence the speaker's state-based anxiety (Pertaub et al, 2002; Yadav et al., 2020). We expect that VR environments with negative audiences will elicit higher levels of anxiety to participants, thus triggering more feedback prompts compared to VR environments with positive audiences. To verify this, we compare the number of prompts that are provided in each type of VR environment (i.e., positive, neutral, negative). Table 4 shows the number of times anxiety was detected by the ML system for each audience type, as well as the mean and standard deviation of this number computed over the number STS for each audience type. Results indicate that on average, the maximum state-based anxiety was experienced by participants in front of a negative audience while the least amount of state-based anxiety was experienced when participants were presenting of front of a positive audience, with the neutral audience giving the average value of 6.61, which is in between the average for positive (i.e., 5.55 average prompts) and negative (i.e., 7.33 average prompts) audience type. Even though the dataset is small (i.e., 6 STS with negative audience, 9 STS with negative audience, 13 STS with neutral audience), we observe approaching statistical significance between the negative and positive audience types with respect to the number of cognitive restructuring prompts.

Table 4: Number of STS per audience type. Number of times in-the-moment state-based anxiety was detected by the ML system for each type of audience, with the corresponding mean and standard deviation.

Audience type	#STP	Detected anxiety	
		# Times	Mean (± std)
Positive	9	50	5.55 (± 3.56)
Neutral	13	86	6.61 (± 4.63)
Negative	6	44	7.33 (± 2.28)

We also compare the three audience types with respect to participants' recorded bio-behavioral measures. In Table 5, the mean and standard deviation values of bio-behavioral measures are provided, while Table 6 presents the results of Mann-Whitney U-test that performs pairwise comparisons between the three types of audiences. Results indicate that participants' heart rate, RMS energy, voice probability, and fundamental frequency are larger in the presence of positive audiences, followed by the neutral and the negative audiences. High RMS energy in the presence of positive audiences suggests that participants spoke louder and potentially more confident in these settings, while that was not the case for negative audiences. This difference appears to be statistically significant.

Table 5: Mean and standard deviation for positive, negative and neutral audience type based on number of feedback prompts, heart rate, and acoustic measures.

Bio-behavioral measure	Audience type	Mean ± standard deviation
	Positive	95.74 ± 4.72
Heart rate	Neutral	94.53 ± 4.65
	Negative	91.81 ± 3.54
	Positive	0.0018 ± 0.0014
Root mean square energy	Neutral	0.0014 ± 0.0011
	Negative	0.0007 ± 0.0004
	Positive	0.46 ± 0.04
Voice probability	Neutral	0.44 ± 0.05
	Negative	0.42 ± 0.06
	Positive	94.26 ± 26.8
Fundamental frequency	Neutral	84.66 ± 23.8
	Negative	73.51 ± 37.12

Similarly, the higher voice probability in the presence of a positive audience potentially means that participants spoke faster because they may have felt more comfortable in front of that audience. However, results on the F0 and heart rate are slightly different from what we would have anticipated. These measures are estimates of physiological and vocal reactivity (Clements and Turpin, 1996; Van Puyvelde et al., 2018), therefore we would expect those to be higher under the more stressful negative environment. The large values of F0 and heart rate in the positive environment could be explained considering that participants felt more comfortable in this setting and put increased effort in performing well, therefore yielding an increased cognitive load, which was depicted by higher physiological and vocal reactivity. We also need to consider additional factors that might have contributed to these results, such as audience size, room type, topic provided for public speaking, and participant's traits.

Table 6: Mann-Whitney U test comparing between positive, negative and neutral audience types based on the number of cognitive restructuring prompts, heart rate, and acoustic measures.

Bio-behavioral measure	Audience type 1	Audience type 2	Statistic/*p*-value (U, *p*)
# Prompts	Positive	Negative	(17.0, 0.13)
	Negative	Neutral	(31.5, 0.27)
	Neutral	Positive	(62.5, 0.62)
Heart rate	Positive	Negative	(14.0, 0.07)
	Negative	Neutral	(25.0, 0.12)
	Neutral	Positive	(49.0, 0.27)
Root mean square energy	Positive	Negative	(10.0, 0.02)
	Negative	Neutral	(23.0, 0.09)
	Neutral	Positive	(49.0, 0.27)
Voice probability	Positive	Negative	(16.0, 0.11)
	Negative	Neutral	(29.0, 0.20)
	Neutral	Positive	(41.0, 0.13)
Fundamental frequency	Positive	Negative	(19.0, 0.19)
	Negative	Neutral	(30.0, 0.23)
	Neutral	positive	(47.0, 0.23)

4.3 Association between in-the-moment feedback prompts and participants' anxiety

We anticipate that participants who are inherently more anxious or depict high levels of anxiety during speaking, will receive on average more feedback prompts from the system. We will quantify anxiety both in terms of the bio-behavioral measures captured during the speaking tasks, as well as by the self-reports, thus obtaining both trait and state anxiety estimates. We first examine associations between the number of cognitive restructuring prompts administered by the system in each STS and participant's corresponding bio-behavioral measures. Table 7 presents the Pearson's correlation between the number of prompts and bio-behavioral features. Results signify moderate association between the number of prompts and the bio-behavioral measures recorded from the participants. We further examine the Pearson's correlations between the number of times anxiety was detected and participant's zero crossing rate during the STS. Zero-crossing rate represents the number of sign changes within the speech signal, thus suggesting that the system provides more prompts when observing increased rate of variation in the speech signal. F0 and RMS energy are also positively correlated with the state-based anxiety predictions. Since F0 is a measure of vocal reactivity, which is indicative of state anxiety, it is expected that the ML system provided more prompts when increased F0 was observed.

Table 7: Pearson's correlation between participants' bio-behavioral measures and the number of cognitive restructuring prompts administered by the proposed in-the-moment bio-behaviorally aware training system.

Bio-behavioral measure	Statistic/*p*-value (U, *p*)
RMS energy	$r(26) = 0.12, p = 0.53$
Zero crossing	$r(26) = 0.62, p < 0.001$
Fundamental frequency	$r(26) = 0.21, p = 0.29$

We further investigate associations between the number of in-the-moment cognitive restructuring prompts and the self-reported measures of state-based anxiety, VR immersiveness, and perceived performance provided after each STS (Table 8). We observe that the ML system provides a larger number of prompts to participants who retrospectively reported higher levels of state anxiety after the STS. Positive correlation is also observed between the degree of immersiveness and the number of prompts provided by ML system, but these results are not close to significance. There was, however, no association between self-reported performance and the number of prompts. Finally, we examine associations between participants' trait-based characteristics and the number of prompts, by computing the Pearson's correlation (Table 9). We observe positive associations between the number of prompts and participants' trait anxiety (i.e., quantified via the BFNE and STAI trait questionnaires), which suggests that participants who are inherently more anxious receive more cognitive restructuring prompts from the system.

Table 8: Pearson's correlation between state-based anxiety obtained after the end of each session and the number of cognitive restructuring prompts administered by the pro-posed in-the-moment bio-behaviorally aware training system.

Self-assessment of state anxiety	Statistic/*p*-value (U, *p*)
State Anxiety Enthusiasm (SAE)	$r(26) = 0.18, p = 0.34$
Virtual Reality Sense	$r(26) = 0.16, p = 0.42$
Post Presentation Performance	$r(26) = -0.01, p = 0.96$

Table 9: Pearson's correlation between trait-based anxiety scores and the number of cognitive restructuring prompts administered by the proposed in-the-moment bio-behaviorally aware training system.

Self-assessment of state anxiety	Statistic/*p*-value (U, *p*)
Brief Fear of Negative Evaluations (BFNE)	$r(26) = 0.24, p = 0.22$
State-Trait Anxiety Inventory (STAI) - Trait	$r(26) = 0.16, p = 0.4$

4.4 Effect of in-the-moment feedback prompts on promoting speaking skills

Five participants stated that the user study helped them improve their speaking skills to some extent, while two participants said that the study did not contribute to the same outcome. A potential reason for this might be the fact that participants only conducted a small number of four sessions. Increasing the number of sessions might have provided more opportunities to participants in receiving feedback and therefore, might have contributed to helping them alleviate their anxiety.

5. DISCUSSION

Findings of this work should be considered in the light of certain limitations. The ML model used to trigger the in-the-moment cognitive restructuring feedback depicted moderate performance (i.e., 68% balanced accuracy). A potential reason for this is that momentary state anxiety annotations were based on a single annotator. Training the model using data from multiple annotators could remove underlying bias and improve model performance. Also, this study does not consider visual behavioral cues (e.g., facial expression, body gesture), which can be included to further improve the detection accuracy of the state anxiety outcome. Results indicate that the proposed in-the-moment system provides prompts in a reasonable manner. We found that more prompts are provided in VR environments that include negative audiences, as well as for participants who depict higher levels of both trait and state anxiety. We also observed that participants' momentary bio-behavioral measures (i.e., zero-crossing rate, F0, RMS energy) were different before and after the provision of the cognitive restructuring prompts, suggesting that the proposed feedback has the potential to impact momentary behaviors. Participants also reported that the thought that the proposed system benefited their speaking skills. However, these results are obtained on a small number of 7 participants, each performing 4 STS. This might be a potential reason for the relatively high p-values observed in our analysis. Also, due to study limitations, no control condition was utilized. Finally, the time of administering the prompts was determined based on the decision of the ML system, which was trained on a separate set of participants (i.e., Wave 1) compared to the ones that were used to evaluate the study (i.e., Wave 2). We anticipate that we could have obtained improved results if we had fine-tuned the models using part of data from Wave 2 participants. This was not conducted because practically it would not be feasible to obtain third party momentary annotations in a short time interval while Wave 2 participants were in session. As part of our future work, we will include additional control conditions, such as systematic VR exposure to speaking without in-the-moment feedback, and in-the-moment feedback administered in random times during STS. We further plan to administer and evaluate in-the-moment speaking training to groups with increased social anxiety, such as combat veterans (Behzadan and Chaspari, 2021) or individuals with autism spectrum disorders.

6. CONCLUSIONS

This research examined the effect of in-the-moment cognitive restructuring feedback on the bio-behavioral measures and speaking anxiety experienced in an immersive VR environment. Statistical analysis indicates significant differences between bio-behavioral measures recorded before and after the feedback prompt is displayed in the virtual environment. Results also indicate that more prompts are administered in the presence of negative VR audiences, as well as to participants with higher anxiety levels. A brief self-assessment of the participants further suggests that a majority found the systematic exposure to VR with in-the-moment reinforcing feedback interventions beneficial for improving their speaking and verbal communication skills. The ML model with in-the-moment bio-behaviorally-aware feedback interventions developed in this research provides promising results which indicate that further exploration of in-the-moment feedback prompts can be beneficial for alleviating speaking anxiety.

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SEMI-AUTOMATIC GENERATION OF VIRTUAL REALITY PROCEDURAL SCENARIOS FOR OPERATION IN CONSTRUCTION BASED ON 4D BUILDING INFORMATION MODELS

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ABSTRACT: *In the context of digital transformations of industry, Virtual Reality based industrial training is an efficient and promising digital tool. In the construction industry, studies have been conducted on the realization of virtual reality scenarios for construction operations, but the challenges lie in procedural scenario creation based on the knowledge and digital data of the construction project. Moreover, the evolution in time of the construction site and the tools and procedures adapted to each construction project must be integrated in the VR simulations. With the 4D Building Information Modeling (BIM) methodology, the 3D model of building as well as the 3D operating procedures contain a time dimension (4D) representing the construction phases or planning. This paper introduces a system allowing the semi-automatic creation of operating procedures scenarios in virtual reality through the exploitation of 4D BIM and procedural knowledge.*

KEYWORDS: *Virtual Reality (VR), VR training, 4D Building Information Modeling (BIM), UML, Industrial scenario, Operating procedure.*

1. INTRODUCTION

Architecture, Engineering and Construction (AEC) projects are complex and challenging, involving multiple knowledge and stakeholders. For several decades now, Building Information Modeling (BIM) has revolutionized the process of handling construction project and has led to improvements in productivity, collaboration, and construction quality [1]. Technical knowledge from records, data or documents on operating procedures for construction can be teach as step-by-step methods. It is in opposition with tacit knowledges such as experience, skill and thinking that are also essential but not easily structured and transmitted through experts and operators [2][3].

VR has proved its efficiency through several literature papers in term of using it into a training process [4][5][6]. This technology has helped with teaching as an active way of learning by being immerged into situations where interactions are required to progress through a training procedure [7]. Research papers in the field of the AEC industry can be found about the use of VR in activities and training for Construction Management, Design Review, Maintenance, Quality Control and Logistics [8]. However, a very few were found for Operation on Site activities or training in VR because of the complexity of representing gestures and knowledge. To overcome the lack of content diversity [9] proposed to use gamifications elements in VR to teach and train either experienced workers or novice workers. The main drawbacks in VR trainings remain the lack of diversity of content and the outdate of the information. Indeed, the creation of content is complex and required a certain amount of development, without update it leads to stiff experiences with non-long-term reusability.

To overcome these limitations, semantic modelling and training scenario models for virtual environment are studied. These works mainly use modeling approaches based on the Unified Modeling Language (UML) formalism [10][11] or on ontologies [12][13][14] to represent procedural scenarios and knowledge needed for VR training. The approaches, offering a layer of abstraction and allowing to define virtual scenarios have been validated on targeted use configurations and therefore need to be extended to cover virtual reality scenarios for construction operations based on the knowledge and digital data of the construction project. Moreover, the evolution in time of the construction site and the tools and procedures adapted to each construction project must be integrated in the VR simulations. Each site environment is different, depending on whether the project is for rehabilitation, in an urban environment or requiring specific equipment.

Our paper introduces a solution for creating virtual reality scenarios, semi-automatically generated from the BIM model of a procedure. The freedom to add, reorganize or remove steps in the scenario is essential in these complex procedures where the tacit knowledge, that lives in practices, are not all modellable in BIM. It is based on an UML model containing the procedural training scenario model and templates of VR operations that are adapted from the approach proposed in [14]. This solution would also allow the user to easily generate a new procedure scenario without the need for redevelopment:

- Scenario edition with added steps on technical operational knowledge,
- Operating procedure is simulated in the virtual environment considering the time (4D) in the construction

of the building,
- Reuse of BIM metadata to create the scene and VR functionality.

2. Related work

Several authors have explored how to facilitate the development of VR scenario or have explored the use of BIM associated to VR trainings and some selected works are presented in Table 1.

Scenarios in operational trainings are designed to lead the operator to achieve tasks through a step-be-step process. Complex scenarios might require precise tasks, several actions, and tools in order to complete the procedure. Its representation in a Virtual Environment and the designed VR interactions associated to tasks imply a lot of development and expert support for the developer. [15] proposed to leverage the abstraction of concepts of the VR scenario by using semantic web. The experts can create or modify a scenario within an excel sheet that is exported into a scenario ontology. The semantic VR training scenario is then parsed to the 3D engine to be transformed as an interactive VR simulation. [16] studied the automatic generation of VR scenarios by extracting accident reports' data and using machine learning techniques to connect game design and accident cases. This approach helps on deciding which kind of safety scenario should be provided to construction worker as training but is not investigating how to facilitate the development of associated VR actions in the scenario.

[17] developed a VR training for quantity surveying practice and education. Students walk through the BIM model into a VR scene, but no scenario or interactions are provided. Structuring knowledge bases for VR construction training scenario using BIM has been studied in the literature. [18] proposed a risk-hunting VR simulation on a virtual worksite using the BIM metadata to trigger hazard events. Although hiding risks are random at each session, each scenario is identically scripted, and it is not possible to edit them by adding or removing some of them. [19] developed a system for analyzing workers safety's position in VR to ensure safety construction space and planning using 4D BIM. However, there is no additional scenario in the VR activity simulation beside the BIM objects that being placed phase by phase in the scene.

The presented articles studied solutions for creating scenarios but are not integrating 3D data-oriented models of the construction project for the operator to interact with in the VR training. The studies that are using BIM for VR scenarios are presenting solution that are entirely scripted with no action freedom for the operator into the training session. Therefore, we propose in this paper a system allowing the semi-automatic creation of operating procedures scenarios in virtual reality through the exploitation of 4D BIM and procedural knowledge.

Reference	Scenario technique and tools	VR actions	Use of BIM	Domain
[15]	Use of semantic web, the scenario knowledge base is modeled into a scenario ontology	Trigger buttons on a control panel	No use of BIM	All expert domains
[16]	Use of reports data and machine learning to generate scenario	Not mentioned	BIM geometry is displayed in the VR scene	Safety in construction
[17]	No scenario, only VR walkthrough the BIM model	No interaction	BIM geometry is displayed in the VR scene	Quantity surveying engineering education
[18]	Scripted scenario, hazardous situations are randomly initialized in the VR training	Not mentioned	Use of BIM metadata to determine floor surfaces for VR teleportation script	Safety in construction
[19]	No scenario, the system is for analyzing workers safety's position in VR	No interaction	Use of BIM 4D metadata to check worker safety position over time	Safety in construction

Table 1. VR scenario in operational trainings

3. PROPOSED SYSTEM

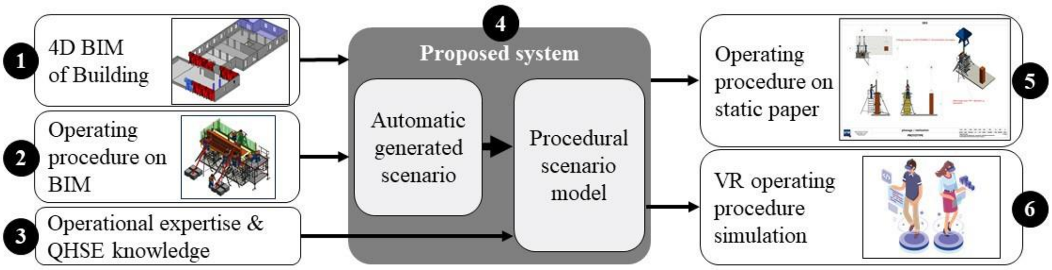

Figure 1. Global process schema

3.1 Global process

The figure 1 represents the global process of the system proposed in this paper. As an input to the system, we have the knowledge bases necessary for the creation of an operating procedure. The BIM building phased in 4D including the 3D geometry as well as the metadata which allow the representation of the constraints of the environment according to the time. The operating procedure created in BIM with a partial representation of the tools used to perform the entire construction operation. And finally, the technical and QHSE (Quality, Health, Safety and Environment) knowledge which today is not formalized but only held by experts or described in paper documents [2]. With these data, the system must be able to automatically generate a procedural scenario from the BIM models and their given metadata to define the assembly steps to follow. Inputs from the experts to modify the generated scenario, to add steps with other tools that are not necessarily available in the BIM procedure or to add verification steps related to QHSE knowledge are also considered. This will result in the generation of a scripted VR simulation and/or the automatic generation of the procedure as a 2D electronic document from the edited procedural scenario.

3.2 Data, knowledge, and model description

The proposed system is structured as an UML class diagram shown in figure 2. The labeled numbers are matching the figure 1 with figure 2 for a better understanding of the entries in the system of the different knowledge bases. On the left side of the diagram, we can find the BIM based on the IFC format inspired by the concept of entities in EXPRESS studied by [17]. This part contains the data and knowledge of the 4D BIM of the building (figure 2 – 1) as well as the operating procedure in BIM (figure 2 – 2). In the parser part of the UML that receives this knowledge, the class ScenarioGenerator is used to generate the Automatic generated scenario. The operational expertise and QHSE knowledge can be found in the Scenario side where the Experts can edit any additional steps (figure 2 – 3). Each step contains a VR action represented in the right side of the UML diagram. This will lead to the final Procedural scenario model (figure 2 – 4) and will create the VR operating

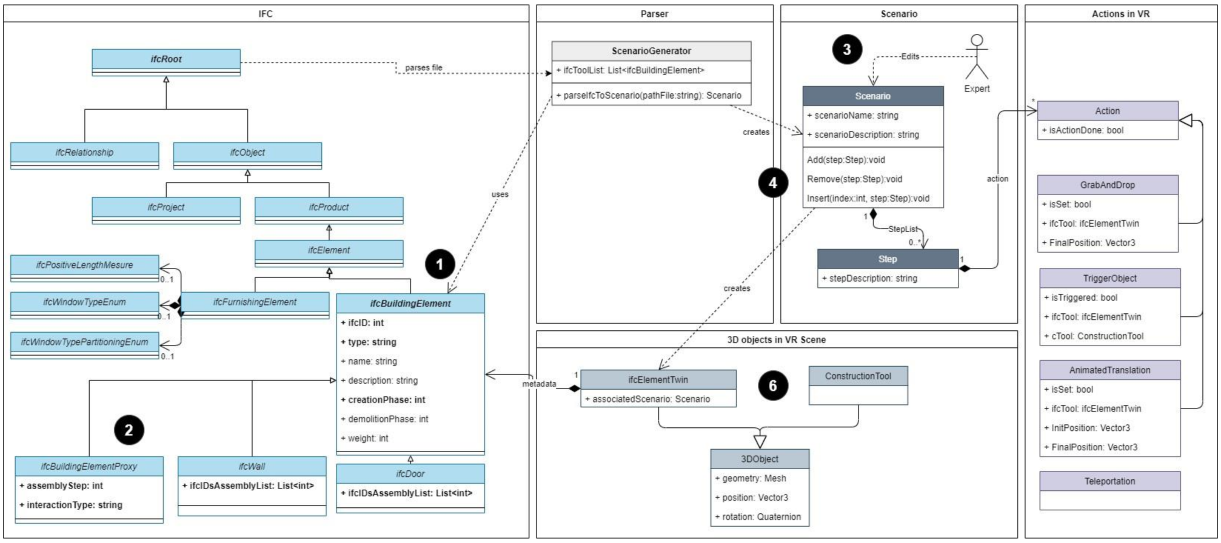

Figure 2. UML class diagram of the proposed system

procedure simulation (figure 2 – 6) with ifcElementTwin that is corresponding to BIM 3D object. Moreover, ConstructionTool that is 3D object from a library of construction tool, is used so as to define common 3D model representing object used to perform operation and that are not existing in the BIM operating procedure.

3.2.1 BIM 4D

The 4D in BIM is used for scheduling the different construction phase of the building [19]. A phase is represented as a number in the "creation phase" parameter within the BIM metadata of each part of the building. The ifcBuildingElement (figure 2 – 1) represents the class of each BIM model. It can be a part of the building as a wall with a specific class ifcWall or a door as ifcDoor, or it can be a tool for the operating procedure as a formwork or a scaffolder, but they are represented in a generic class called ifcBuildingProxyElement (figure 2 – 2) based on the standard of IFC [20]. ifcBuildingElement contains metadata as variables such as "ifcID" which would help with unique identification, "creation phase", etc.

Recently the 2D papers procedures (figure 1 – 5) have been enhanced by 3D illustrations from the BIM model (see figure 1 – 2). However, they were only created to obtain more detailed sections and realism in the illustration of what we want to obtain finally on the field. The models are not described step by step but by main phases that can be found in the corresponding 2D procedure to create view boards, see last image in figure 3. For generating the assembly steps in the VR scenario, we propose to use the concept of the 4th dimension by assigning a number on a new parameter "assembly step" in the BIM metadata as the construction sequence of the operating procedure (figure 2 – 2). This manages to not conflict with the construction phase "creation phase" of the building in the proposed system. Figure 3 gives an example based on this approach of the different assembly steps phased in the BIM operating procedure.

3.2.2 Expert knowledge based

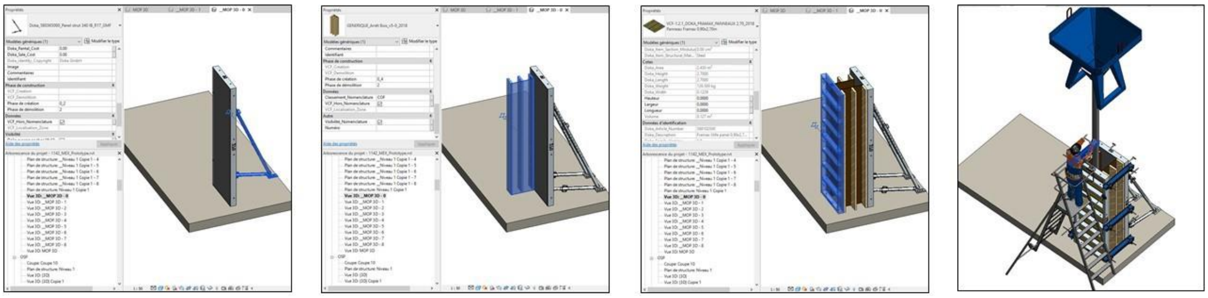

Figure 3. Different assembly steps of a concrete column construction procedure on BIM software [from left to right, assembly step 2, 4, 6 and 42]

The operating procedures are complex and need to be methodologically described. It is also a guarantee of safety for the operator and of quality for the built work. They are used during weekly sessions on the site to explain the operations to be carried out during the day but are also used to constitute the file of the Site-Specific Health and Safety Plan in order to prevent the risks on the building and civil engineering operations. This justifies the need to keep generating static paper version of the operating procedure through our proposed system.

The realization of these procedures implies the collaboration of several experts such as the design office or the QHSE office (see figure 1 – 3). These operating procedures are represented by main phases in 2D sheets illustrated with explanatory drawings (see figure 1 – 5). They also include technical instructions such as "Adjusting the posture using the plumb lines". In addition to the step-by-step instructions, there are color-coded tacit knowledge explanations that refer to quality and safety. To add this knowledge in the scenario of the proposed system, an expert can insert at the 9th step a new step consisting in touching the metal clamping bar with the plumb lines, proceeding as following:

Scenario: insertStep (9, Step)	
Step:	stepDescription ("Adjusting the posture using the plumb lines")
	action (TriggerObject)

TriggerObject:	ifcTool(MetalClampingBar)
	cTool(PlumbLines)

3.3 Procedural scenario generation and VR scene creation

Through the parser, the automatic generation of the scenario is done based on an ifcToolList which store all ifcBuildingElement and be used in the function parseifcToScenario. A list of the needed BIM operating procedure model's ID for the realization of a construction work such as a wall is filled in the related BIM construction work model in its ifcIDsAssemblyList (figure 2 – 1), previously filled by the experts in the BIM software. It helps for attributing the corresponding scenario in the ifcEntityTwin which is its 3D representation in VR as a wall (figure 1 – 6). Each element has its 3D representation in the VR scene and are assigned with the class ifcEntityTwin which store all the element metadata based on the concept of entity twin studied by [14]. At this stage, two different action in VR could be automatically added to the created step depending on the parameter "interactionType" in ifcBuildingProxyElement (figure 2 – 2), previously filled in the BIM software by the experts. If an operator can interact with the object then a DragAndDrop action would be chosen as VR action in the step, if the interaction type is an engine such as the crane, then the action chosen will be an AnimationTranslation action. The steps of a scenario are ordered by the numbers found in the "assembly step" variable of each ifcBuildingProxyElement.

The procedural scenario can be edited by the experts by using the functions in the Scenario class. The scenario and the step classes have a description variable which would be used for the generation of the static paper of the operating procedure. The ConstructionTool class is used for construction tools that are not modeled into the BIM operating procedure such as plumblines, carriages, etc. (figure 2 – 6). A database of 3D objects is available for the experts while adding steps to the scenario for technical or QHSE task. Also depending on the environment these tasks might need different equipment as for operating on the edge of a wall or between different building parts. The associated action is the TriggerObject class that refer to check by touching the right ifcBuildingElement with the designate ContructionTool.

Once the procedural scenario model is ready, the initialization of the VR scene can start. ifcElementTwin are assigned with specific components regarding their metadata. If some ifcElementTwin objects have the value floor as Family's type, then a component Teleportation Area is added to it in the VR scene. Therefore, the operator would use its action Teleportation on any walkable surface in the simulation automatically. Identical for ifcElementTwin objects that have the Family's type Wall or Column, a collider is added to them to consider them as obstacles. Indeed, obstacles can condition the behavior of the operator to perform the operating procedure. Figure 4 shows different views of the VR scene, the blue arrow (figure 4 – 2) indicates the blue and white container where can be found the ConstructionTool objects used for the TriggerObject action.

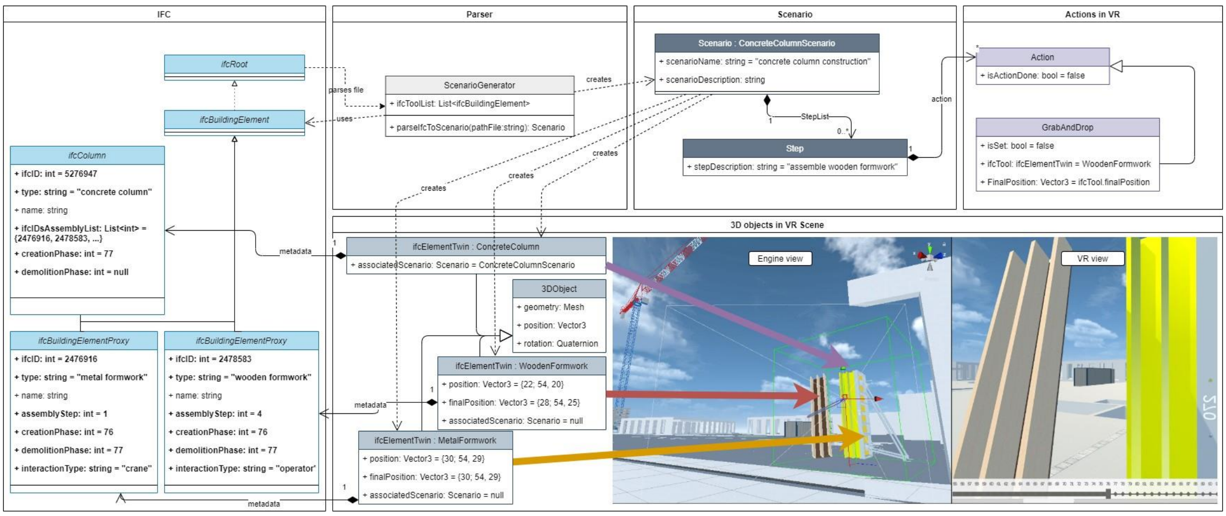

Figure 4. (1) VR view of the worksite at phase 194 of the construction, (2) Engine and VR view of the concrete column procedure

4. USE CASE

Here is presented a use case of a VR training procedure for a concrete column construction in a worksite of a building phased with 200 phases (figure 4 – 1). The VR scene has been created using Unity engine, the OpenXR plugin and an Oculus Quest 2. The 4th dimension is managed by the expert that led the training session and can go through the phases of the building using a slider on the user interface. It shows that operating with evolving environment constraints such as the proximity of the wall in figure 4 – 2 constructed in a previous phase is constraining the operator and would change is behavior while performing the operation in contrast to the clear area in the concrete column construction in figure 5. Figure 5 represents the UML formalism of one step in the concrete column construction procedure in VR. The step is consisting in drag and dropping the wooden formwork at its final position. The purple arrow is designating the future column to construct, the red arrow corresponds to the wooden formwork and the orange arrow to the metal formwork previously assembled by the operator.

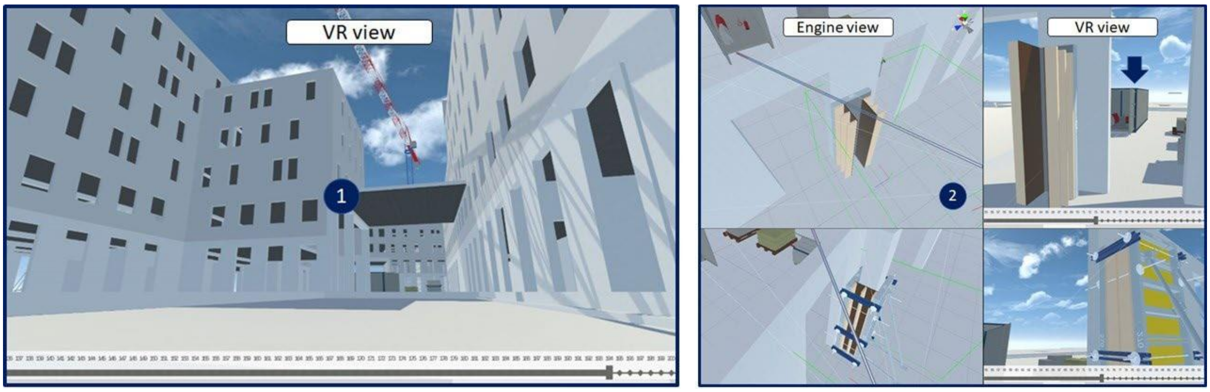

Figure 5. Use case in UML formalism of a step in the concrete column construction procedure

5. CONCLUSION AND FUTURE WORK

This paper introduces a system that could semi-automatically generate a scenario of a construction operating procedure in VR. The issues that this system tried to solve were the representation of tacit knowledge in VR of steps that cannot be modeled in BIM. The realism of the worksite by implementing the environment of the building to consider its constraints over time in the VR simulation using the BIM 4D. And finally, automatic creation of the VR scene and features by reusing BIM metadata and to initialize the VR simulation is performed.

Future work will be to improve the system by associating technical and QHSE edited steps to ifcBuildingElement in previous scenario that would be stored in a database to automatically generating these knowledges in new scenario. For the VR simulation, it would be interesting to study the implementation of paralleled tasks if assembly task numbers are the same in the BIM operating procedure to let more freedom to the operator in his interaction process. Moreover, a multi-user experience of training in operating procedure in VR would be interesting for tasks that need to be done together by multiple operators.

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A SCIENTOMETRIC REVIEW OF REALITY CAPTURE APPLICATIONS IN THE BUILT ENVIRONMENT

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ABSTRACT: *The drive of digital evolution in 4IR require the availability of digital data. The digital revolution in the Global construction industry is made possible by Building information modeling (BIM). The success of BIM implementation relies on digital data. Reality Capture (RC) has made digital data collection possible by using Laser scans and Photogrammetry. RC can provide real-time, up-to-date digital data of site conditions to enhance project performance evaluation. This paper explores the extent of research on reality capture applications in the Built Environment to establish the roadmap for further investigation. A peer-reviewed journal paper of 193 relating to reality capture applications was retrieved through a bibliometric analysis from the Scopus database and analyzed using Scientometric techniques and a VOSViewer software. The study reveals that RC has been extensively applied to digital documentation of cultural heritage buildings, accuracy assessment, project monitoring, building surveys, Construction site progress monitoring, Quality control assessment, etc. However, there is no empirical evidence on Health & Safety, Cost, Labor productivity, and material monitoring. This area has a more outstanding contribution to the project performance, and more research is imperative to explore RC usage. There is a high degree of disparity among researchers in the study area, and there is the need for deliberate attempts to collaborate research for knowledge transfer and sharing. Low research interest in Africa researchers has contributed to the low adoption in the Africa continents. This research has a high level of usefulness to researchers and policymakers when designing areas for further RC applications. And also enhanced project performance delivery in the 4IR. The study has given the research trend on RC applications and future research directions.*

KEYWORDS*: Reality Capture, 3D laser scanning, Photogrammetry, Construction, Built Environment.*

Paper Type- Literature Review

1.0 Introduction

The world is currently experiencing a digital transformation, including the construction industry. The digital transformation improves efficient delivery, productivity, risk reduction, and success in infrastructural development. However, the digitalization journey requires gathering digital data first. Data plays a crucial role in every facet of life, like governance, health, industries, marketing, traveling, institutions, infrastructural development, etc. Professionals also depend primarily on the use of data to improve delivery and productivity. According to Lecia (2018), it can argue that data is potentially valuable than oil due to the insight and knowledge it possesses.

Building Information Modelling (BIM) is among the powerful mediums stirring digital evolution in the Global construction industry. Digitalization of construction projects has been made possible by the BIM, providing a powerful platform for project information sharing and visualization considering design, scheduling, cost budgeting, and variation during the planning and execution life of the project (Jeong *et al.*, 2016). The provision of accurate digital data for the BIM is critical for successful project implementation. Sparking a demand for exact initial site conditions for design and up-to-date digital data for BIM to improve workflow and collaboration among Architectural, Engineering, and Construction (AEC) professionals (Lecia, 2018) requires the use of reality capture.

Reality capture (RC) is a quick and efficient process of getting the precise interpretation of project site conditions using Laser scanners, Photogrammetry, either hand-held, with a tripod or on Unmanned Aerial Vehicle (UAV) to produce a 3D dataset (point clouds or meshes) (Lecia, 2018). Reality Capture is a photogrammetry solution that assists in creating 3D models from laser scans or photographs to immensely advances efficiency, accurateness, value, and safety throughout the project. The 3D models obtained from the digital data through reality capture consist of vital data like building geometry, construction typology, materials properties for BIM processes, offering a better advantage than the traditional construction methods (Almukhtar *et al.*, 2021).

The 3D reality capture permits replicating the physical world into a virtual environment to obtain valuable information. AEC professionals can easily design, monitor progress, and quickly compare as-built models to as-design models, ensuring quality control measures (Mayer, 2019). 3D Laser scanning, also known as LIDAR (Light Detection and Ranging), is an innovative imaging technology that captures complete and exact 3D data for a construction site status. Photogrammetry is defined as a process of obtaining geometric data of an object through measurement on photographs. It creates a precise geometric connection between images and objects. (Turkan *et al.*, 2012). RC is a vital aspect of construction projects' data dynamics, providing a rich image source to support the production control process (McHugh, Koskela and Tezel, 2021).

According to (Lecia, 2018) RC offers the following advantages to the ACE industry;

1. Begin a project with accurate data to reduce project risk.
2. Evade expensive delays and rework because of collaborative sharing of real-time digital data.
3. Constant monitoring progress and visibility for potential risk matters for prompt redress.
4. Provision of digital progress records and evaluation of work against as-planned ensuring the project completed as planned.
5. Ability to share progress project data with all stakeholders.

RC is considered among the prominent technologies for capturing and processing assert or construction project data for various applications in the Built Environment (Almukhtar *et al.*, 2021). However, despite RC's potential for construction projects, the industry has not had the desired impact, especially in developing countries. The current data acquisition process remains laborious, costly, subjectivity, and error-prone resulting in cost and time overruns.

The current study conducts a scientometric review of scientific literature on reality capture usage in the Built Environment (BE) to comprehend the general description of the progressions in the study area over the past 20 years (2000 – 2021). The outcome aimed to offer the researchers a better understanding of the current state of reality capture applications in the BE and identify the potential research directions. There are more publications by Scholars in internationally renowned peer-reviewed journals in reality capture studies. However, a strong need exists to conduct a scientometric review of the existing studies.

2.0 Research Methodology

The systematical methodology is critical for conducting a comprehensive literature review; therefore, a science mapping approach to develop a bibliometric network using a Scopus database source concerning reality capture was adopted. Figure 1 indicates a process review of the framework for the bibliometric exploration using a scientometric analysis and the outcome explanation.

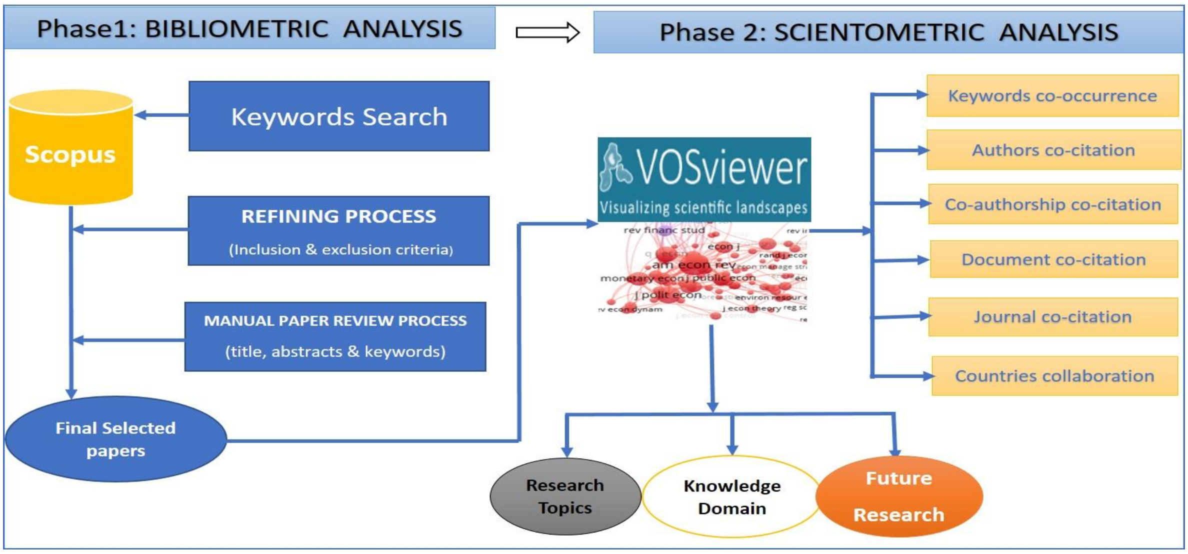

Figure 1: Proposed research methodology

3.0 SCIENTOMETRIC DATA ANALYSIS

Reviewing the number of publications manually is laborious and unreliable because of its subjectivity (Derbe *et al.*, 2020). Yalcinkaya & Singh (2015) added a high tendency to present biased options using a conventional review method. Hence, the introduction of Scientometric analysis for literature review to avoid subjectivity issues (Xu *et al.*, 2021). Scientometric is quantitative research on science improvement that assists in text-mining, citation analysis, and visualization of scholarly literature in the academic area to identify research trends, emerging areas, and gaps for further research (Jin, Zuo and Hong, 2019; Saka and Chan, 2019). Scientometric review is a technique that evaluates the impact of the research, institutes, and journals within an area of study, offer an in-depth comprehension of scientific citation and map the present information and its development in a field established on large scholarly datasets (Yalcinkaya and Singh, 2015; Martinez, Al-Hussein and Ahmad, 2019). This method of review is ideal for the current study since it possesses the ability to identify and analyze the research evolution over some time (Mansuri *et al.*, 2019). A scientometric review is a quantitative approach that supports the research development with visualization and mapping using a largescale bibliographical data through different qualitative indexes (Mingers and Leydesdorff, 2015). Hence, this research proposed a holistic analysis of reality capture in the Built Environment using scientometric analysis.

3.1 Selection of Scientometric tool

Software tools available for scientometric analysis; *VOSViewer* (van Eck and Waltman, 2014), CiteSpace (Chen, 2006) and Gephi (Bastian, Heymann and Jacomy, 2009), BibExcel (Bankar, 2019), CoPalRed (Sangam and Mogali, 2012), Sci2 (Sangam and Mogali, 2012), VantagePoint (Golizadeh *et al.*, 2020). *VOSViewer (version* 1.6.17 released on July 22, 2021) was employed in the current study due to its suitability in visualizing more extensive networks, has a unique feature for text-mining, user friendly, and high usage rate in scholarly review (van Eck and Waltman, 2014; Wen and Gheisari, 2020). In addition, other researchers have used *VOSViewer* in the construction field, i.e., Building information modeling (Olawumi, Chan and Wong, 2017; Saka and Chan, 2019), mapping of digital technology (Mansuri *et al.*, 2019), Virtual human application (Eiris and Gheisari, 2017), virtual reality (Wen and Gheisari, 2020), computer vision application (Martinez, Al-Hussein and Ahmad, 2019), building controls, digital twin application (Ozturk, 2021). Full and fractional counting methods for papers networks visualization can be achieved by *VOSViever* (Jin *et al.*, 2018); however, factional counting methods for author network, co-citation network, co-author citation, document citation, and co-occurring keywords citation were adopted for this study.

3.2 Bibliometric Search Data Collection

Conclusions are based on the selected scientific articles; therefore, data collection of existing literature is essential in this study (Martinez, Al-Hussein and Ahmad, 2019). For this cause, the choice of database and search approach were chosen cautiously. Many available literature databases such as Web of Science, Scopus, Google Scholar, PubMed, etc. (Mongeon and Paul-Hus, 2016). However, Scopus database was chosen as a literature database for the current research due to its comprehensive coverage in the area of construction-related research (Martinze 2019) and a wider range of journal publication compared to other. In addition, most researchers used this database for similar studies. According to Derbe et al. (2020), there is no double citation in Scopus indexed journal articles, and its document citation is highly reliable. Additionally, is one of the most significant peer-reviewed sources of journal articles, conference proceedings, peer-review papers, book chapter, etc. covering the considerable quantity of abstract and citations (Martín-Martín *et al.*, 2018; Derbe *et al.*, 2020).

Existing related publications on reality capture in the Built Environment were retrieved using keywords. The selected keywords were: “Reality Capture” or “3D laser scanning” or “Photogrammetry”; to recover all the publications as per the carefully chosen keywords, the Scopus search engine was set to title/abstract/keywords. The search resulted in 30,407 documents. Redefining was done to the period designated for the investigation was 2000 to 2021, its practical consideration for the development history of Reality Capture in construction-related research. In the screening process, Engineering was selected as a subject area. Final stage Peer-reviewed English journals articles only were included in the refining of the search. Gold and Hybrid Gold Open access publications were added to refine the search. A total of 555 documents were collected from the Scopus database.

The extra purging procedure was manually done by first examining the title, abstract, and keywords to eliminate publications outside the construction industry and, second, unrelated subject area papers before analyzing the bibliographic data retrieved. One hundred ninety-three (193) journal articles relating strongly to the predefined objectives were finally accepted for scientometric analysis after a careful and repetitive manual review of papers. To conduct the analysis, the collected bibliometric publications were transferred with all the essential data like tiles, abstracts, keywords, sources, authors, institutions, citations, and references in a CSV format to the *VOSViewer* for the scientometric analysis. Figure 2 shows the flow diagram of the data retrieval process.

4.0 Data Analysis Result

4.1 Co-occurrence of Author keywords analysis of main research areas

The keywords in the bibliometric network depict main frameworks of previous research and show intellectual teams and organization main topics (van Eck and Waltman, 2014). The core content of the published papers essentially represented the keywords showcasing researched areas within the domain boundaries (Van, Nees and Waltman, 2010). Analysis in co-occurrence keywords network largely depends on the thickness of the links among two keywords depending on the number of publications containing the word (Golizadeh *et al.*, 2020). Fractional counting and author's keywords were selected to create the network (Oraee *et al.*, 2017). *VOSViewer* was employed to obtain the keywords co-occurrence in the research area to build and map the knowledge area between RC and BE. *VOSViewer* is a distanced-based mapping in which the distance indicates the relationship between two knowledge areas (Perianes-Rodriguez, Waltman and van Eck, 2016).

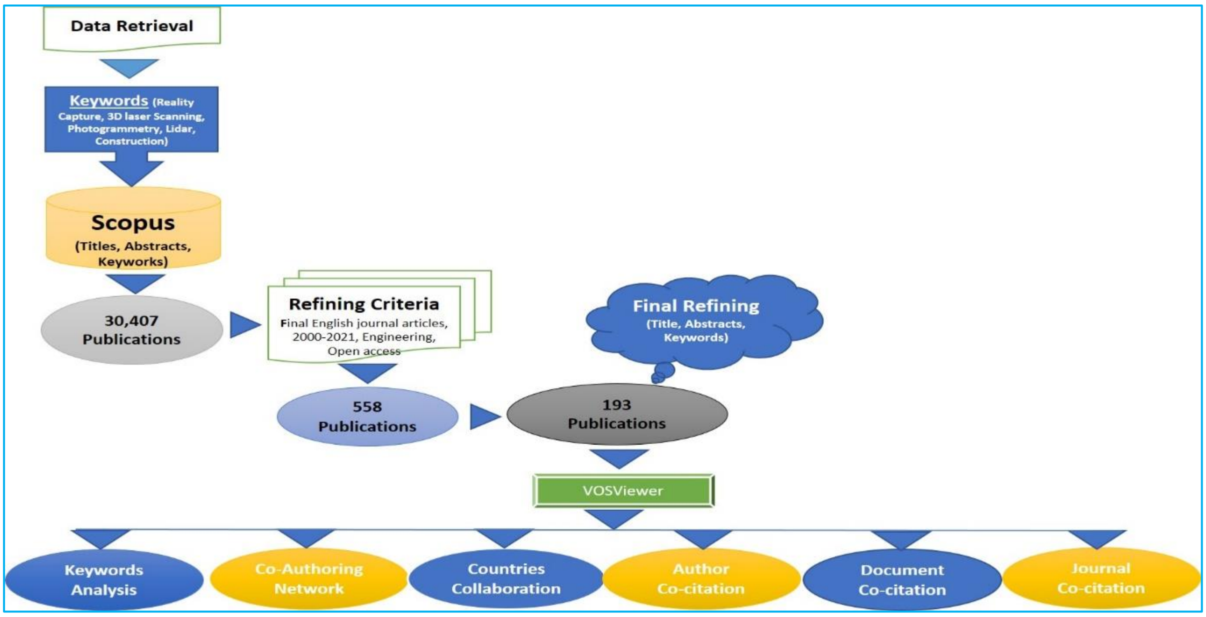

Figure 2: Bibliometric data retrieval Processes

Therefore, the weaker relationship between the two items depicts by the more considerable distances. The label item size also shows the number of journals in which the keywords were identified, and different colors indicate different knowledge domains grouped by *VOSViewer* (Oraee *et al.*, 2017). Keywords were set to 4 times as the minimum occurrence. In the initial result, out of 811 keywords, only 48 met the set threshold. Also, other keywords were with a similar semantic connotation (i.e., "UAV" verse "Unnamed Ariel vehicle" and "BIM" verse "Building Information Modelling" and "3D Laser scanning" verse "Third Dimension laser scanning." in addition, words having exact meaning and plurality differences were identified and sorted out, like (i.e., "Quality control" verse "Quality controls" and "Crack Assessment" verse "Cracks evaluation"). Finally, 38 keywords were selected as indicated in figure 3 and table 1 to show the bibliometric analysis results of the publications, the visualization of the keywords network, and the table of frequency. The top 5 most used keywords in order of magnitude were Photogrammetry, Reality Capture, Unnamed Ariel vehicle, cultural heritage, accuracy assessment. Photogrammetry and Reality Capture show the higher number of occurrences indicating the research level in the subject domain. Unnamed Ariel vehicle(UAV)/Drones is an emerging reality capture technology for ariel digital data capture (Hesam, 2016). Other identified keywords indicating areas of RC application including but are not limited to point cloud, progress monitoring, building survey, 3d reconstruction, construction site monitoring, image processing, quality control. But there is no empirical evidence on RC applications in real-time Health & Safety monitoring, Cost monitoring, Labor productivity monitoring, Materials monitoring, etc. This area has a more significant contribution to the project's success, and more research is imperative to explore RC usage.

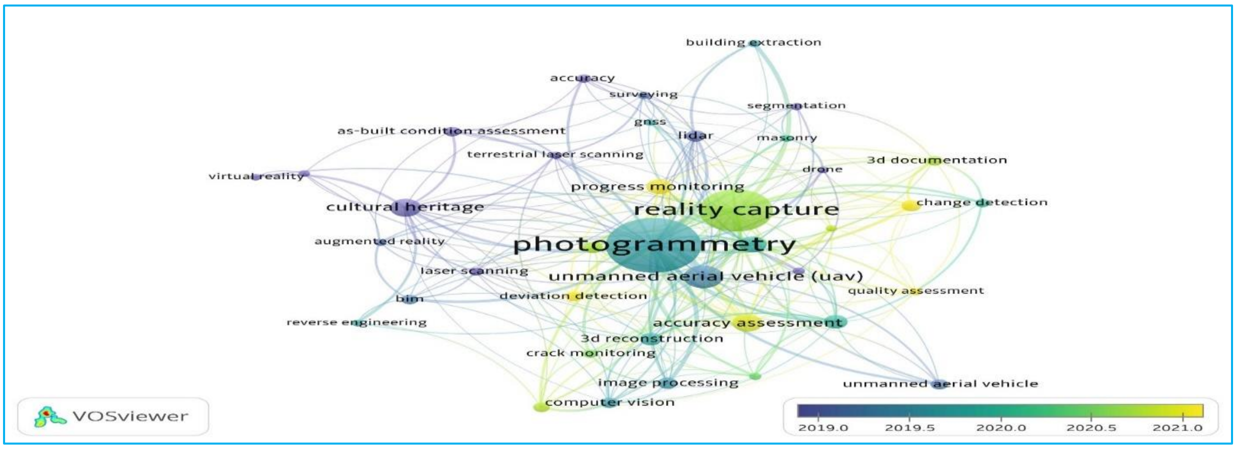

Figure 3: Co-occurrence of Author's keywords

Table 1: Identified keyword in the Reality Capture research domain area.

No.	*Keywords*	*Occurrences*	*Total Link Strength*	*No.*	*Keywords*	*Occurrences*	*Total Link Strength*
1	*photogrammetry*	*83*	*68*	*20*	*accuracy*	*6*	*4*
2	*reality capture*	*58*	*49*	*21*	*change detection*	*6*	*5*
3	*unmanned aerial vehicle (UAV)*	*24*	*19*	*22*	*crack monitoring*	*6*	*6*
4	*cultural heritage*	*17*	*15*	*23*	*laser scanning*	*6*	*6*
5	*accuracy assessment*	*16*	*16*	*24*	*augmented reality*	*5*	*5*
6	*point cloud*	*15*	*14*	*25*	*building extraction*	*5*	*5*
7	*progress monitoring*	*13*	*12*	*26*	*infrastructure inspection*	*5*	*5*
8	*building survey*	*12*	*11*	*27*	*quality assessment*	*5*	*5*
9	*3d reconstruction*	*10*	*8*	*28*	*retrofitting*	*5*	*4*
10	*construction site monitoring*	*9*	*9*	*29*	*segmentation*	*5*	*3*
11	*image processing*	*9*	*8*	*30*	*surveying*	*5*	*5*
12	*lidar*	*9*	*8*	*31*	*terrestrial laser scanning*	*5*	*5*
13	*quality control*	*9*	*9*	*32*	*drone*	*4*	*4*
14	*computer vision*	*8*	*8*	*33*	*GNSS*	*4*	*3*
15	*3d documentation*	*7*	*7*	*34*	*masonry*	*4*	*4*
16	*as-built condition assessment*	*7*	*6*	*35*	*remote sensing*	*4*	*4*
17	*bim*	*7*	*7*	*36*	*reverse engineering*	*4*	*3*
18	*deviation detection*	*7*	*7*	*37*	*virtual reality*	*4*	*3*
19	*object detection*	*7*	*7*	*38*	*visualization*	*4*	*2*

4.2 Co-Authorship Network

To kindle innovative ideas and enhance productivity in a research area, researchers must collaborate (Hosseini, 2018). Citation and author were used to create and visualize the network of co-authorship. In the *VOSViewer* software, minimum research papers were set to two, and only 69 out of 794 authors meet the threshold. Figure 4 shows the network mapping for the 69 authors and table 2 indicates the top 10 most dominant authors contributing to the RC research domain in the BE. Each node indicates an author and the link between the authors indicate the level of association that exists through co-authorship publications. The network indicates a close collaboration link between González-Aguilera D., Burdziakowski P., He H., and Liu Y. confirming their high influence in the research area. According to (Golizadeh *et al.*, 2020), the key to stronger research output that can drive an emerging area is scientific collaboration through a shared experience, findings, and specialties. Burdziakowski has the largest amount of publications in the area with a total of four publications with a total citation of 14. However, Dorninger, P. and Pfeifer, N. having one publication but having the highest citation of 235 whiles Sohn, G., and Achille, C. have two and one publication with 104 and 99 citations respectively as shown in table 3. The degree of disparity indicating in the node is a sign of a lack of collaboration among researchers in this area. This can only reduce through a deliberate attempt to extensively collaborate in the field among researchers. The blue color shows studies carried out in the past three years, green shows one to two years, yellow indicates the emerging studies within the year 2021 (Liu, Habibnezhad and Jebelli, 2021).

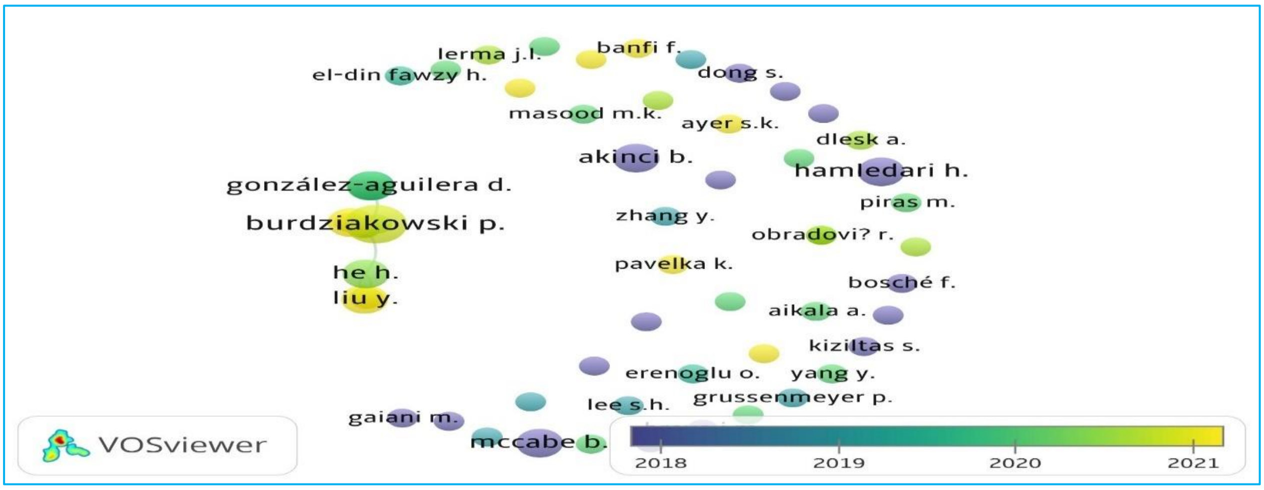

Figure 4: Co-Authorship of Author's Network

Table 2: Top ten most published authors influencing the Reality Capture research

No	Author	Affiliations	Documents	Citations	Total Link Strength	Ave. Citations
1	Burdziakowski P.	Gdansk University of Technology, Poland	4	14	0	4
2	Akinci B.	Carnegie Mellon Univ., United States	3	57	0	19
3	González-Aguilera D.	Universidad Politécnica de Madrid, Spain;	3	41	0	14
4	Hamledari H.	Stanford Univ., Stanford, United States;	3	80	0	27
5	He H.	Guangzhou Urban Planning and design Survey Research Institute, Guangzhou, China	3	8	0	3
6	Liu Y.	Guangzhou Urban Planning and design Survey Research Institute, Guangzhou, China	3	0	0	0
7	Mccabe B.	Univ. of Toronto, Toronto, Canada	3	80	0	27
8	Remondino F.	University of Salamanca, Ávila, Spain	3	21	0	7
9	Rodríguez-Gonzálvez P.	Universidad de Salamanca , Spain;	3	45	0	15
10	Skabek K.	Cracow University of Technology, Poland	3	2	0	1

Table 3: Top 10 most cited authors influencing the Reality Capture research

No.	Author	Affiliations	Documents	Citations	Total Link Strength
1	Dorninger P.	Institute of Photogrammetry and Remote Sensing, TU Vienna, Austria	1	235	1
2	Pfeifer N.	Institute of Photogrammetry and Remote Sensing, TU Vienna, Austria	1	235	1
3	Sohn G.	Department of earth and space science and engineering, York University, Canada	2	104	2
4	Achille C.	Department of Architecture, Built Environment and Construction Engineering, ABC, Politecnico di Milano, via Ponzio, Milano, 31-20113, Italy	1	99	1
5	Adami A.	Department of Architecture, Built Environment and Construction Engineering, ABC, Politecnico di Milano, via Ponzio, Milano, 31-20113, Italy	1	99	1
6	Chiarini S.	Department of Architecture, Built Environment and Construction Engineering, ABC, Politecnico di Milano, via Ponzio, Milano, 31-20113, Italy	1	99	1
8	Cremonesi S.	Department of Architecture, Built Environment and Construction Engineering, ABC, Politecnico di Milano, via Ponzio, Milano, 31-20113, Italy	1	99	1
9	Fassi F.	Department of Architecture, Built Environment and Construction Engineering, ABC, Politecnico di Milano, via Ponzio, Milano, 31-20113, Italy	1	99	1
10	Fregonese L.	Department of Architecture, Built Environment and Construction Engineering, ABC, Politecnico di Milano, via Ponzio, Milano, 31-20113, Italy	1	99	1

4.3 Citation of Documents Network

The document co-citation analysis indicates the number and authority of references cited by publications and also permits underlying scholarly structures of the study area (Martinez, Al-Hussein and Ahmad, 2019). The cited references with the dataset of the research domain are analyzed by the document co-citation network (Saka and Chan, 2019). A minimum of 20 citations was set to visualize the network of 193 documents in the *VOSViewer*, and 24 met the threshold. In figure 5, 24 highly-cited documents in the study area, and the top 10 are shown in table 4. The network of documents co-citation cluster consisting of the total of citations per publication within the domain of the study field. The node stands for the publication, and its label indicates the co-citation relationship existing among the publications. The node size is represented by the number of frequencies. The top 3 most cited documents are Dorninger P. (2008), having 235 citations, followed by Achille C. (2015) with 99, and Shahbazi M. (2015) with 82 citations.

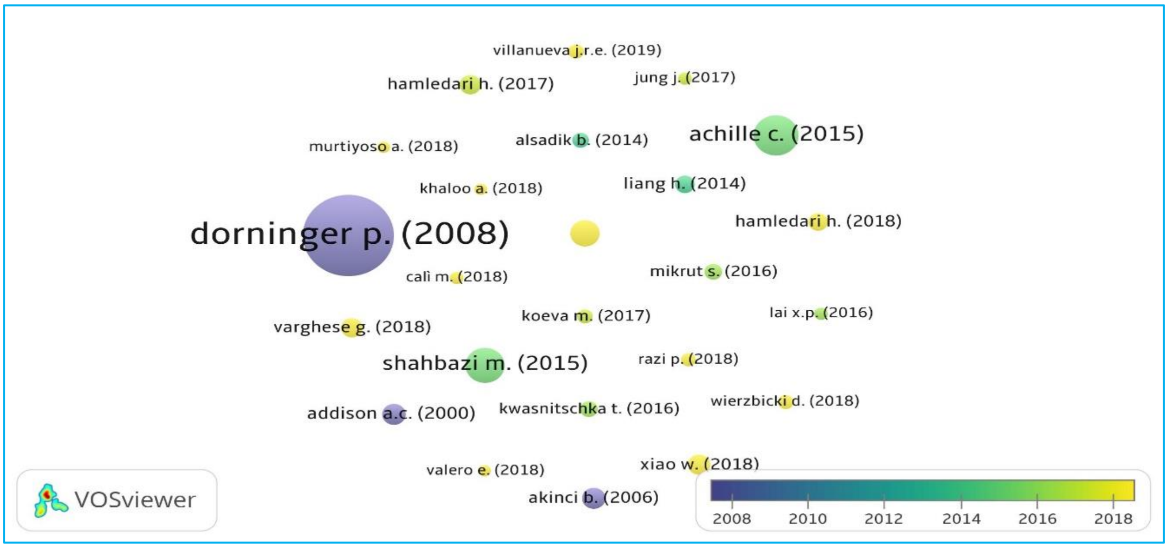

Figure 5: Citation of Documents Network

Table 4: Top 10 most cited documents influencing the Reality Capture research

	Document	*Publication Title*	*Citations*	*Links*
1	*Dorninger P. (2008)*	*A comprehensive automated 3D approach for building extraction, reconstruction, and regularization from airborne laser scanning point clouds.*	*235*	*0*
2	*Achille, C. (2015)*	*UAV-based Photogrammetry and integrated technologies for architectural applications – methodological strategies for the after-quake survey of vertical structures in Mantua (Italy)*	*99*	*0*
3	*Shahbazi M. (2015)*	*Development and evaluation of a UAV – photogrammetry system for precise 3D environment modeling.*	*82*	*0*
4	*Laporte-Fauret Q. (2019)*	*Low-Cost UAV for high-resolution and large-scale coastal dune change monitoring using Photogrammetry*	*57*	*0*
5	*Addison A.C. (2000)*	*Virtualized architectural heritage: New tools and techniques*	*45*	*0*
6	*Akinci B. (2006)*	*Modelling and analysing the impact of technology on data capture and transfer processes at construction sites: A case study*	*43*	*0*
7	*Xiao W. (2018)*	*Geo-informatics for the conservation and promotion of cultural heritage in support of the UN Sustainable Development Goals*	*41*	*0*
8	*Hamledari H. (2017)*	*IFC-Based Development of As-Built and As-Is BIMs Using Construction and Facility Inspection Data: Site-to-BIM Data transfer Automation*	*40*	*0*
9	*Varghese G. (2018)*	*Fabrication and characterization of ceramics via low-cost DLP 3D printing*	*39*	*0*
10	*Liang H. (2014)*	*Remote spectral imaging with simultaneous extraction of 3D topography for historical wall paintings*	*35*	*0*

4.4 Citation of Sources (Articles) network

Articles published in the Scopus database were analyzed with the number of citations, and the document was set to 0 and 2, respectively. A total of 29 publications from 76 qualify the minimum threshold. Figures 6 and 5 indicates that influences in the subject area of publication.

The publisher with the highest number of citations is Sensors (Switzerland) (40 documents and 577 citations).

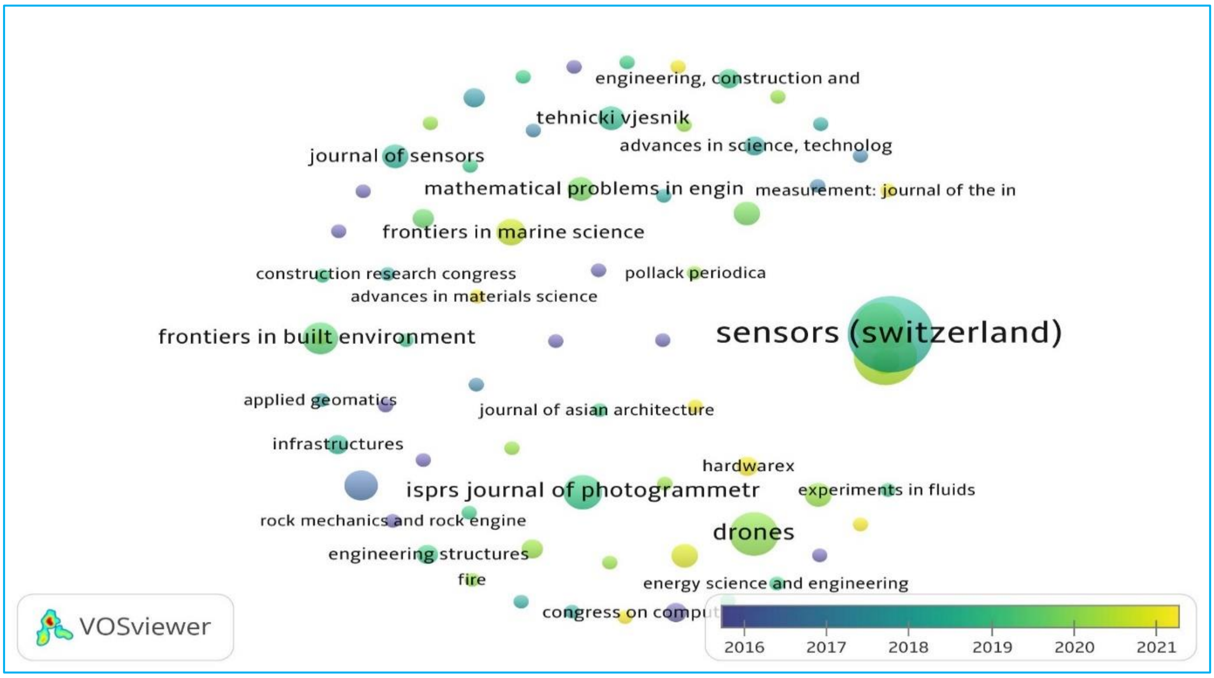

Figure 6: Citation of Sources Network

Table 5: Publication citation influencing the Reality Capture research

No.	*Source of Publication*	*Documents*	*Citation*	*Total Link Strength*	*No.*	*Source of Publication*	*Documents*	*Citation*	*Total Link Strength*
1	*Sensors (Switzerland)*	*40*	*577*	*7*	*16*	*Informes De La Construccion*	*3*	*0*	*1*
2	*Applied Sciences (Switzerland)*	*21*	*69*	*7*	*17*	*Journal of Civil Engineering and Management*	*3*	*26*	*0*
3	*Sensors*	*13*	*240*	*5*	*18*	*Journal Of Sensors*	*3*	*12*	*0*
4	*Drones*	*12*	*67*	*0*	*19*	*Mathematical Problems In Engineering*	*3*	*10*	*0*
5	*Ieee Access*	*8*	*43*	*2*	*20*	*Tehnicki Vjesnik*	*3*	*7*	*0*
6	*Isprs Journal Of Photogrammetry And Remote Sensing*	*7*	*91*	*0*	*21*	*Advances In Science, Technology And Engineering Systems*	*2*	*5*	*0*
7	*Frontiers In Built Environment*	*6*	*46*	*1*	*22*	*Congress on Computing in Civil Engineering Proceedings*	*2*	*4*	*0*
8	*Buildings*	*5*	*6*	*2*	*23*	*Engineering Structures*	*2*	*20*	*0*
9	*Ega Revista De Expresion Grafica Arquitectonica*	*5*	*11*	*0*	*24*	*Engineering, Construction And Architectural Management*	*2*	*5*	*0*
10	*Energies*	*5*	*24*	*2*	*25*	*Hardwarex*	*2*	*0*	*0*
11	*Automation In Construction*	*4*	*31*	*1*	*26*	*Infrastructures*	*2*	*10*	*0*
12	*Frontiers In Marine Science*	*4*	*12*	*0*	*27*	*Journal Of Computing In Civil Engineering*	*2*	*75*	*0*
13	*Advances In Civil Engineering*	*3*	*4*	*0*	*28*	*Journal Of Imaging*	*2*	*13*	*0*
14	*Alexandria Engineering Journal*	*3*	*6*	*0*	*29*	*Journal Of Marine Science And Engineering*	*2*	*57*	*0*
15	*Electronics (Switzerland)*	*3*	*6*	*1*					

4.5 Co-Authorship of Countries

Table 6 and Figure 7 show the dominant countries that are very active in the research domain area. The lower limit of 2 publications and 1 citation was set for analysis. In a total of 53 countries, 34 met the threshold in the VOSViewer scientometric study. Figure 7 and table 6 show that the top 5 countries who have contributed greatly in the research area are United

States (37 articles), China (30 articles), Italy (29 articles), Span (22 articles), and Poland (15 articles). Larger publications indicate that there is more advanced research in the country. Among the researcher published in the study field, one was identified in Africa countries which are challenging for researchers in Africa. Due to the set threshold, the details do not show. A strong link indicates a collaboration between China, Italy, Spain, Poland, UK, and Canada, driving the research in RC as indicated. Researchers in Africa countries must deliberately collaborate with researchers in developed countries to share the experience. Low research collaboration contributes to the low adoption of reality capture in Africa, especially in developing countries, since no researchers are driving the discussion around this emerging technology and its immeasurable benefit to the Built Environments.

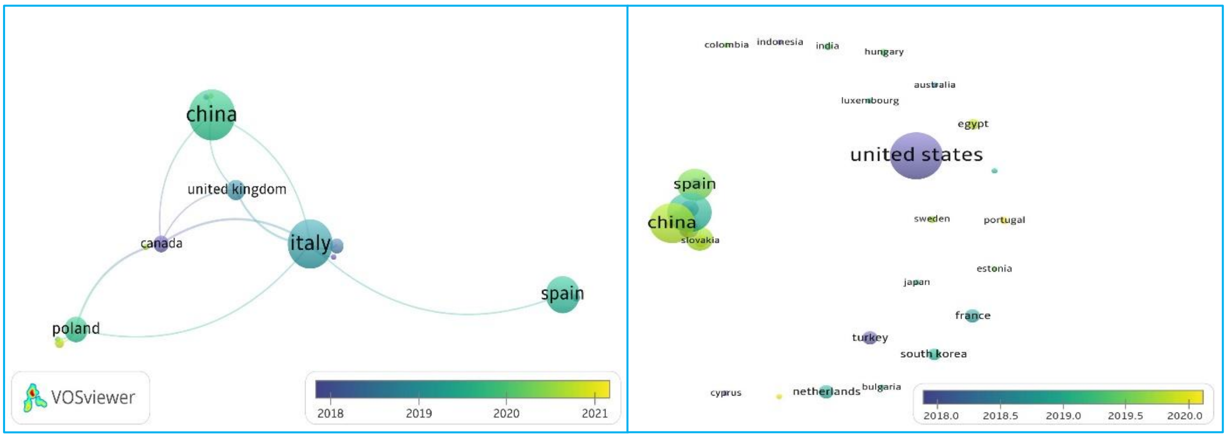

Figure 7: Co-Authorship of Countries Network

Table 6: Publication citation influencing the Reality Capture research

No	*Country*	*Documents*	*Citations*	*Total Link Strength*	*No*	*Country*	*Documents*	*Citations*	*Total Link Strength*
1	*United States*	*37*	*274*	*0*	*18*	*Hungary*	*3*	*2*	*0*
2	*China*	*30*	*126*	*5*	*19*	*India*	*3*	*3*	*0*
3	*Italy*	*29*	*303*	*10*	*20*	*Portugal*	*3*	*3*	*0*
4	*Spain*	*22*	*151*	*3*	*21*	*Slovakia*	*3*	*7*	*1*
5	*Poland*	*15*	*107*	*5*	*22*	*Sweden*	*3*	*20*	*0*
6	*United Kingdom*	*12*	*143*	*4*	*23*	*Australia*	*2*	*11*	*0*
7	*Canada*	*10*	*218*	*7*	*24*	*Austria*	*2*	*235*	*1*
8	*Germany*	*9*	*84*	*2*	*25*	*Bulgaria*	*2*	*27*	*0*
9	*France*	*7*	*113*	*0*	*26*	*Colombia*	*2*	*28*	*0*
10	*Netherlands*	*7*	*62*	*0*	*27*	*Croatia*	*2*	*9*	*1*
11	*Turkey*	*7*	*68*	*0*	*28*	*Cyprus*	*2*	*16*	*0*
12	*Czech Republic*	*6*	*4*	*1*	*29*	*Estonia*	*2*	*4*	*0*
13	*South Korea*	*6*	*21*	*0*	*30*	*Hong Kong*	*2*	*5*	*0*
14	*Egypt*	*5*	*22*	*0*	*31*	*Indonesia*	*2*	*28*	*0*
15	*Serbia*	*5*	*19*	*2*	*32*	*Japan*	*2*	*30*	*0*
16	*Greece*	*4*	*7*	*1*	*33*	*Luxembourg*	*2*	*20*	*0*
17	*Brazil*	*3*	*15*	*1*	*34*	*Saudi Arabia*	*2*	*16*	*0*

5.0 Conclusion

RC is developing technology with a potential contribution to the digital revolution in the construction industry. RC has the driving force for the realization of Construction 4.0 since it practically relies entirely on collecting real-time digital data. The current study proposed identifying the trend of research in RC applications in the Built Environment and finding out the emerging areas and the direction for future research. Quantitative approach through the use of Scientometric analysis and provide a result for the research question.

The findings indicate a high concentration of RC applications in the areas like, digital documentation of cultural heritage, accuracy assessment. Others include but are not limited to point cloud, progress monitoring, building survey, 3d reconstruction, construction site monitoring, image processing, quality control, stakeholder collaborations. However, areas like Health and safety, Cost, Labor productivity, and material monitoring have received less attention from researchers to date. A recent study by (McHugh, Koskela and Tezel, 2021) reveals the RC application on enhancing Stakeholder collaboration and improvements. It is, therefore, imperative for more research to be conducted on other potential applications of RC to realize the immeasurable benefits RC can offer infrastructural delivery in the BE. There is an urgent need to campaign for collaboration of research especially among institutions within developed and developing countries. This would promote the collaboration of researchers to improve discussion, deliberation, and cross-fermentation of ideas and initiatives.

Lots of disparity and fragmented nature is seen among the researchers in this research domain whiles African countries is pintsize represented with only one publication. Lack of the needed resources and logistics, including funding, might the possible cause. This contributes to the low adoption in the Built Environment. Government in Africa Sectors must invest in research and modern technology for the improvement of the productivity and infrastructural delivery, thereby ensuring economic development of the country. The current trend in the 4IR is a digital revolution to improve higher productivity, efficiency, quality processes, quality of life, etc. RC has the potentials to support infrastructural delivery from inception to completion in terms of a gathering accurate and precise digital data to promote visualizing, collaboration, and understanding in the construction project management. It is, therefore, worth exploring other potential RC can offer to the construction industry. Reality Capture has a vital part in the future study of construction since the digital era pushes industries towards digitalization and smart construction using the principle of Industry 4.0.

This research was limited to the Scopus database with past twenty years of publication. There is the need to explore other databases with a different literature review approach to augment the research area.

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DIGITAL ASSET MANAGEMENT: A PROOF OF CONCEPT FOR AN AUTOMATED CHANGE ROADMAP GENERATOR

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ABSTRACT: *In adopting digital asset management (DAM), various technological innovations centred around BIM/DE can be integrated to manage data and information across the life cycle of built assets, to provide the right data and information to the right stakeholder at the right time. Though the great potential of adopting DAM is well recognised in Australia, the uptake of DAM across the industry has been hampered due to various challenges, chef among all being as lack of digital planning and lack of knowledge to manage the episode of change. Based on a grounded theory approach in integration with case study method, this paper offers an account of the initial stages of a research project with the aims of developing a proof of concept (PoC) for an automated roadmap generator, to assist Australian companies in their transition from traditional methods of asset management to digital ones – enabled by BIM and DE – DAM. The PoC offers customised support in the form of action plans, schedules and description of activities and checklists to address the operational needs of shifting to DAM, offering insight into the requirements, activities and resources essential to navigate through the episode of change successfully. In practical terms, this paper contributes to the field through describing the details of a user-friendly, and efficient procedure for managing the change. In terms of theoretical contribution, this paper addresses a conspicuous gap in the body of knowledge, where it speaks to the 'how' question of a transition to digital asset management, as opposed to the dominant discourse that has focused on the 'why' question of transition.*

KEYWORDS: *DIGITAL ENGINEERING, CHANGE MANAGEMENT, FACILITIES, BUILT ASSETS, INFRASTRUCTURE, DIGITALIZATION.*

1. INTRODUCTION

The Australian construction industry is the largest non-services sector of the economy; it generates over $360 billion in revenue annually, produces around 9% of Australia's Gross Domestic Product (GDP) and employs approximately 1.2 million Australians – nearly 9% of the total workforce. The secondary job-creation impacts are also notable as every job in the construction industry creates three jobs in the wider economy. The industry is nevertheless plagued by low efficiency, high error rates, large budget and time overruns (Hosseini et al., 2021). It is through this lens that it is posited: if the Australian construction industry is such an effective vehicle to deliver community and economic benefit – then how can its performance be improved? The answer lies in a transition from traditional to improved methods enabled by digital data-driven methodologies and shifting to digital asset management practices (Gharouni Jafari *et al.*, 2021, State of Victoris, 2021). That is, past research provides evidence that replacing conventional non-digital practices with the integrated management of data throughout the life cycle of assets can resolve many of the cited challenges (Gharouni Jafari et al., 2021). Building Information Modelling (BIM), and its most recent version termed digital engineering (DE and here after also referred to as Digital Asset Management or DAM), presents a significant opportunity to bring a paradigm change to the construction sector (Hosseini *et al.*, 2021). In DAM, various technological innovations can be integrated to manage data and information across the lifecycle of built assets and provide the right data and information to the right stakeholder at the right time (Hosseini et al., 2021). Currently, both state governments in Australia and the private sector have recognised the great potential of adopting DAM (Shemery and Hampson, 2019). In some Australian jurisdictions, like Victoria, the use of DAM is required for all publicly funded projects greater than $10 million (State of Victoris, 2021). Despite the wide recognition of advantages, neither widespread DAM adoption, nor the intended systematic change in the sector have taken place (Matthews et al., 2018, Hosseini et al., 2021). That is because, shifting to DAM resembles adopting a systemic innovation, which needs changes that cut across disciplines, supply chain boundaries and integrated components of an organisation's business (Zomer et al., 2021). Its adoption hence entails practical transformations, which require re-engineering tasks and processes (Akintola et al., 2021).

Available scholarly works and industry sources emphasise the positive aspects of adopting BIM/DE from a strategic perspective. They, however, fail to account for the changes that will occur post-adoption and provide little insight into planning for these changes (Matthews et al., 2018, Hosseini et al., 2021). Current literature is devoted to the 'why' question of change, at the price of the 'how' question (Matthews et al., 2018, Zomer et al., 2021).

Acknowledging the need for an improved approach, this paper describes the details of a proof of concept (PoC) for an automated roadmap generator for assisting companies in their transition from traditional methods of asset management to digital ones – enabled by BIM and DE – DAM. The PoC offers customised support in the form of action plans, schedules and description of activities and checklists to address the operational needs of shifting to DAM, offering insight into the requirements, activities and resources essential to navigate through the episode of change successfully. This provides a user-friendly, and efficient procedure for managing the change, no costs for consultation or engaging change management experts. The PoC is to be underpinned by adjusting change management theories to be more suitably contextualised and customised for Australian construction organisations. Apart from addressing a conspicuous gap in the body of knowledge, in addressing the 'how' question of a transition to digital asset management, the proposed PoC will be of direct appeal to a wide range of practitioners in the Australian construction industry, providing lessons for other countries and settings.

2. CONTEXTUAL BACKGROUND

2.1 The need for a transition

The construction industry is evolving towards integrating people and processes with information across the asset life cycle (Allen Consulting Group, 2010). Developing and operating assets require data and information to be accessible to key actors, including clients/developers, architects, engineers, contractors, suppliers and facility/asset managers (Hosseini, 2018, Chen and Jupp, 2019). Getting the right data and information to the right actor is half the challenge; the other half is getting data and information to actors at the right time. The latter is particularly challenging as infrastructure assets have inherently long lifespans: the 'right actor' may be a future actor in the asset's life cycle. To respond, an effective asset requires: (1) a 'golden thread' of data and information throughout the asset's life – from project planning, schematic and detailed design, to fabrication and construction, to operations, maintenance and decommissioning; and (2) all actors' understanding of the immediate and future data and informational needs (Jupp and Singh, 2016). DAM entails getting the right data and information to the right actor, at the right time, while ensuring future actors' needs and processes are met is the crux of good information management. Good information management underpins effectiveness, utility, productivity and efficiency across the life cycle of an asset (Love and Matthews, 2019). Digital transformation of asset management, centred around the adoption of BIM and DE, has been touted as a remedial solution towards shifting the traditional practices of the construction industry towards one that is more productive and agile.

2.2 Recommendations and policy positions

There is no shortage of recommendations and policy positions for promoting BIM as a panacea for the woes in the Australian construction industry (NATSPEC, 2019). The need for a shift towards digital asset management was first promoted as a reform initiative in the construction industry nearly two decades ago. In 2004, a strategy for digitalisation was introduced by releasing "Construction 2020 – A Vision for Australia's Property and Construction Industry". Of the nine key visions that emerged from the strategy, "Information and communication technologies for construction" and "Virtual prototyping for design, manufacture and operation" were front and centre (Hampson and Brandon, 2004). The 2004 strategy was followed by several papers and policy positions including a 2009 paper (CRC for Construction Innovation, 2009) and a report in 2010 (Allen Consulting Group, 2010). The Australian Institute of Architects, Consult Australia (Holzer et al., 2012), the Australian Institute of Building (AIB, 2013), the Australian Construction Industry Forum, the Australasian Procurement and Construction Council (ACIF and APCC, 2017) and, more recently, the Australasian BIM Advisory Board (ABAB, 2018, ABAB, 2019) are organisations that have all underscored the necessity of a transition to DAM in Australia.

The recent recommendations of '2021 Australian Infrastructure Plan' further highlight the urgent need for shifting towards DAM in infrastructure projects, citing various advantages. It is posited that adopting DAM in infrastructure projects will: improve value for money; reduce uncertainty and risks; increase productivity, embed a culture of innovation; and offer better return on investment in operating and maintaining built assets. Improvements are estimated to be productivity improvements up to 15% and cost reduction of 5%. Despite the various benefits, a transition to DAM is fraught with risks and challenges, as discussed below (Infrastructure Australia, 2021).

2.3 Change as a barrier to transition

Despite the growing interest, past research has acknowledged that the widespread adoption of DAM and the envisaged systematic transition within the Australian construction sector have not occurred (Matthews *et al.*, 2018, Hosseini *et al.*, 2021). Though many large-sized and flagship projects have shifted to digitally-enabled asset management methods, a majority of companies active in the industry still have not achieved large-scale adoption levels. In fact, the BIM and DE markets in Australia have been likened to 'markets not mature enough to reap the benefits of broadscale implementation,' which only materialises when a large number of entities and organisations in the industry shift to digitally-enabled methods in projects (Matthews et al., 2018). A major issue is with small, and medium-sized enterprises (SMEs) lacking the resources and skills to manage the systemic change, which is essential when shifting from traditional methods to DAM-enabled practices, as argued in great length by Hosseini et al. (2016) and Hong *et al.* (2019).

Micro, small, and medium-sized enterprises or 'SMEs' are considered to be the backbone of major economies around the world. In Australia, according to Hong et al. (2019), 97.8 per cent of construction firms are categorised as SMEs, accounting for 70 per cent of Australia's labour force and contributing to 44.6 per cent of the total market value. Given the sheer size of SMEs in the Australian construction industry, even a small incremental improvement would provide substantial benefits for the economy and society (Hosseini et al., 2016). Nonetheless, previous studies show that SMEs are typically lagging behind large-sized enterprises in embracing innovations and usually remain the late adopters of innovative technologies, including BIM-related methodologies (Hosseini *et al.*, 2016, Hong *et al.*, 2019). Past research indicates that around 42.2 % of SMEs in Australia are engaged with BIM to some extent, where over half of them still rely on traditional computer-aided design (CAD) technology (Hosseini et al., 2016), despite the fact that BIM implementation growth rates as high as 115% have been reported in 2015 for Australia, compared against the global average rate of 95% (Hong et al., 2019).

2.4 Australian context: problems and a solution

Various industry reports and scholarly works refer to a poor transition from digital building/ computer integrated construction through to asset management and operation within the Australian context. Moreover, governments, as large asset owners, have not incorporated the benefits of digital delivery into their asset management function, mostly due to a lack of digital content or workflows in the asset management domain (Hosseini, 2018). These issues are inevitably linked to the lack of treasury investment and uncertainty in maintenance budgets leading to state agencies having to continue to divert budget towards more reactive-based repair works. Besides, asset Management is not recognised as a discipline in the digital delivery arena, driving a poor transition from digital building/construction management to asset management and operation. Moreover, governments (departments/ agencies) report that digital delivery is currently managed at a project level, not at an organisation level. This is due to the specialist capability, capacity and resources required for the digital assets to be maintained and kept up to date. Therefore, there is a need to join asset information management teams with digital delivery to integrate data across phases and leverage its value (State of Victoris, 2021).

The risks associated with managing the risk-prone episode of change, coupled with the lack of resources, skills and competency to manage the transition are the major barriers towards broadscale transition to DAM in the Australian construction industry (Rodgers et al., 2015). Indeed, in the absence of tested and proven procedures for a transition and in view of the limited resources available for SMEs, it is unlikely that SMEs will take on the risks surrounding the adoption of DAM (ABAB, 2019). Moreover, failure to adequately identify and fulfil the requirements of the digital asset management journey - that awaits beyond the point of decision to adoption - results in failures in the episode of transitioning to digital asset management approaches (Matthews et al., 2018). Therefore, reliable empirical instructions and clear action plans in the form of roadmaps are key for companies to make the implementation decision and the ensuing successful transition towards digital asset management in Australia (Hosseini *et al.*, 2016, Hosseini *et al.*, 2018). The Australasian BIM Advisory Board (ABAB) as a leading institution have recognised the need. That is, lack of clients' competence, skills and capabilities; risks of disruptive processes during the change that create change resistance; and lack of digital planning among stakeholders are recognised by ABAB as the major obstacles that hamper efforts towards broadscale adoption of DAM across the Australian construction industry (see ABAB (2019) for details).

With the list of challenges identified by ABAB (ABAB, 2019), it stands to reason that a feasible solution to the problem at hand can be an asset management digital roadmap generator to assist both private businesses and government stakeholders in digital planning. Assisting organisations in planning their digital journey and identifying the best digital solution for their specific conditions and visons can be an effective measure towards overcoming the barriers that thwart efforts towards large-scale adoption of DAM across the Australian construction sector. There are a wide range of benefits associated with making a digital roadmap generator available within the Australian context: it reduces the risks of implementing something that may not be useful. Besides, the system concentrates on connecting the implementation directly to business needs, digital ambitions, vision and mission; and it will be a remedial solution for the institutional complexity, information asymmetry, lack of digital content and workflow in asset management practices. So too, it enables asset owners and operators to realise value at any maturity level from digitally-enabled asset information, techniques, analysis and automation by targeting capabilities needed for each value use case.

3. RESEARCH APPROACH

An inductive 'grounded theory' methodological approach combined with case study method directed the present study. Grounded theory is designed to create empirically-derived theories to deal with real-life problems and guide practitioners through understanding the 'black box' of practice (Oktay, 2012). Hence, the outcome(s) of grounded theory is understandable by practitioners in real-life settings, according to Oktay (2012). Grounded theory is an extensive general methodology in Information Systems domain, which relies on integrating various forms of data from different sources with elements of context, process and actions of key players (Fernández, 2004). Two basics assumptions are the tenets of grounded theory: setting aside theoretical ideas; and developing concepts through constant comparison of data, observations of development processes and incidents. The outcome can be a rich conceptualisation of the domain of enquiry, as argued by Fernández (2004). These fundamental building blocks make grounded theory well suited for research involving practice-based organisational/ technical issues and addressing practical problems (Fernández, 2004, Oktay, 2012).

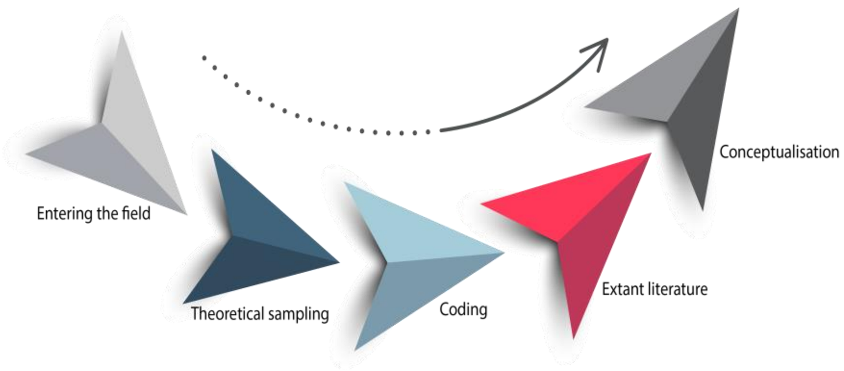

Fig 1: Research design and procedure

3.1 Grounded theory-case study

Grounded theory in the present study was used as the overarching methodology to study data from exploratory case studies and drive data acquisition activities within and beyond the setting of studied cases. The appropriateness of using this approach, namely, grounded theory-case study, was consistent with its advantages to fulfill the objectives of the present study: to generate conceptualisation from practice, little reliance on the literature, explaining organisational complex procedures and practice-oriented research in a previously little studied domain, as argued by Fernández (2004). Besides, the research team had extensive professional experience in the substantive area of the study. The combination of grounded theory-case study was deemed the best fit for dealing with the experiences of the research team, controlling the risk of introducing bias into findings and enabling a rich constant comparison potential for the research team, to compare observations, data and incidents against their extensive knowledge of the domain from various perspectives. Moreover, this created an intimate sense of things in producing conceptualisations that closely mirrored the realities of the field. The research design, followed the procedure, as illustrated in Figure 1.

The first stage was 'entering the field.' The problem for entering the field in grounded theory is discovered from the accounts of practitioners, rather than a precise research question being developed from a review of the literature (Fernández, 2004). Discussions with experts in the domain of BIM and digital engineering in Australia, industry reports like the report by ABAB (2019) and extensive experiences of the research team informed the development of a broad research question with no a priori constructs or guiding theories included. The research question referred to assisting construction companies to manage the episode of changes to DAM as a main theme. The research team had no issue in terms of negotiating with experts in the field and obtaining access to information, given the support offered by the ABAB, position of team members as leading researchers, practitioners of the domain in Australia and a broad network of contacts in the industry, which provided an almost unrestricted access.

The 'theoretical sampling' became possible through unrestricted access to information and data about various documents used by industry practitioners to guide their change to DAM, discussions with key players of change in various case studies and considering the documents from previous change management procedures and processes handled by members of the team. This was a data collection process that continued throughout all the stages of the present study, to allow for taking advantage of emergent themes, acquire data continuously and maximize observation opportunities, all essential elements in the grounded theory approach (Fernández, 2004, Oktay, 2012).

The next stage (see Figure 1) was 'coding' the information and data collected through the methods described as 'theoretical sampling'. This resulted in the creation of various categories, taxonomies and indicators and items to inform the procedure of input, analysis and outputs of the roadmap generators. This stage, in terms of research methodology, was consistent with the recommendation by (Fernández, 2004), where coding stage in a grounded theory approach should create several core themes to guide analysis and further data collection.

The role of 'extant literature' became important after developing the core themes, taxonomies and indicators. Available studies in asset management and change management were reviewed and compared against the developed taxonomies, indicators and themes. The extant literature was treated as an additional source of data to enhance the items generated through coding with improved sensitivity and links with grounded concepts in the body of knowledge, drawing from the procedure proposed by (Fernández, 2004). This was deemed a suitable approach to raise the theoretical level of indicators and outcomes and improve construct definitions.

The 'conceptualisation' stage corresponded to developing a substantial theory of associations among various indicators and items in core themes – input, analysis, output – which entailed a qualitative association rule mining for linking certain pool of input indicators to items of analysis and outputs. This was in fact the a 'middle-range' theory to underpin the procedure of using input items submitted by users of the system to define the best set of suggested roadmap items, proposed by the roadmap generator.

4. THE ROADMAP GENERATOR

4.1 Content and logic

The theoretical underpinning of the roadmap generators, as proposed, alludes to the concept of 'hybrid practices' of adopting BIM/ digital engineering for digitalising the management of built assets, as argued by Davies *et al.* (2017). That is, very few organisations have the skills, knowledge and resources to move fully towards DAM. Smaller business, particularly, struggle to justify the investment required. Contrary to the rhetoric developed around DAM, which criticises its partial uptake, recent studies have established that any transition to DAM needs to be evolutionary and more responsive to the needs and abilities of specific organisations. With this in mind "a variety of hybrid adoption paths are possible" and all deserve to be supported (Davies *et al.*, 2017, p. 79). The roadmap generator is therefore designed to enable asset owners and operators to realise value at any maturity level from any digitally-enabled asset information scenario, techniques, analysis and automation by targeting the specific capabilities needed for each value use case.

Input and output for each stage of the procedure can be defined through predefined taxonomies and indicators for users, where users need to search through a list of items and select the one that best describes their vision, maturity state, digital category that defines their target, etc.

Table 1: Number of items available at each stage

	Aim	Number of available items	Description
Step 1	Providing input	7 roles (user profiles) 28 areas/units	The user selects the role/s and unit/s they are looking to add DAM. This is based on the asset management industry overview which includes roles from policy and strategy through to process improvement and knowledge management.
Step 2	Providing input	155 divided across the 7 roles and 28 sub-roles	The user selects an asset management element and the digital category under the role and area in which they need assistance

			with implementing DAM. This is based on the asset management industry requirements for that role and the digital categories established from research and industry workshops.
Step 3	Analysis	2 backwards to review selections or forwards to continue	The user understands the areas of concentration their selections have indicated and can go back and alter their answers if they feel the analysis isn't representing their business needs.
Step 4	Providing input	155 divided across the 7 roles and 28 sub-roles 4 options per selected element	The user selects the digital sub-categories that they are looking for digital guidance. The sub-category is establishing if the user needs to identify, specify, cost, or collect the data to inform their DAM.
Step 5	Providing input	8 widgets 155 divided across the 7 roles and 28 sub-roles 4 options per selected element	The user selects their preferred approach from the 8 widgets which show varied levels of detail. A widget that provides the following can be selected. • a roadmap, • checklists, and • task sheets Each widget gives users the option to add or remove the detail of the roadmap generated, hence the need for 8 widgets. If users have not selected items that are a prerequisite of an implementation, they will be notified at this stage to consider ticking those extra boxes to detail those prerequisite steps.
Step 6	Output	4 back, save, export, export as a selected file format	The user selects if they are wanting to revise the last set of selections or if they want to save or export the guidance generated.

Potential users will provide input to the system in four stages, receive an analysis of their status quo in core areas in one stage and will be offered a report as a roadmap in the sixth stage. The number of alternatives – items – along with the content and logic of each step are tabulated in Table 1, while Figure 2 illustrates an example of the user journey.

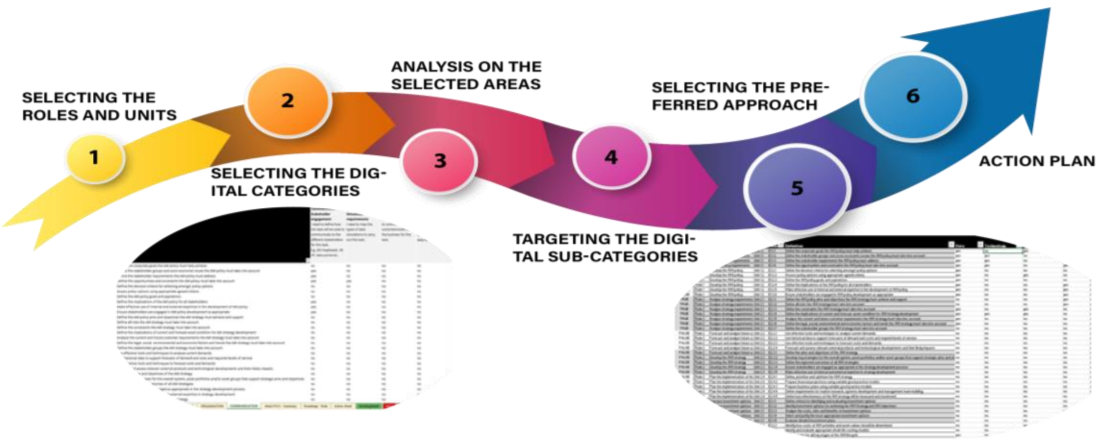

Fig 2: The user journey and examples of the items included in the spreadsheet

4.2 User journey

The interaction of potential users with the roadmap generator begins with login to the system. The formality of the login is required so that users can save or export the results. Step 1 will entail users searching through the list and select the key role and units of work that users intend to achieve.

As discussed, there are many recommendations within industry, however those recommendations are overarching and difficult for independent roles and asset management functions to connect with. The roadmap generator therefore concentrates on the business needs of its users according to their role and the function of the role as determined by their industry competency. The roadmap generator therefore users with their digital asset management needs, that is, using roadmap generator, users develop an understanding of what digital asset management means to their role as they walk through the steps.

Step 2 is about selecting the element and the detail of the digital category that users need assistance with to achieve the task. Various categories are included to assist users in making their intentions and the vison for DAM clear. The element is based on what the asset management function has described as a task a specific role should be able to do. When a user selects this element, they then select what digital category they feel they need guidance on to achieve the tasks required to deliver that element (see Figure 3).

Fig 3: Step 2 – Selecting the digital categories

In Step 3, an analysis is given to users, in the form of an overview of the selections the user made up to this point. The analysis provides users with an opportunity to go back and change their selection, edit the input and rectify any error in their input to the system. The reason for adding this step is users will often stop filling in forms or answering questions if they do not receive insight or gratification within a few clicks.

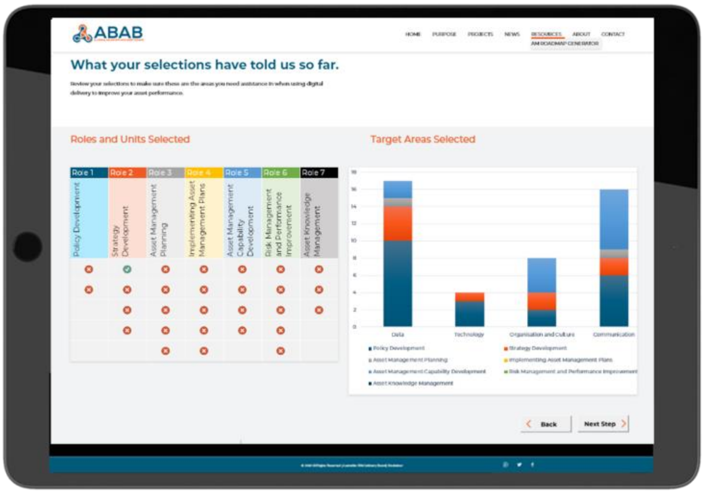

Fig 4: Step 3 – Analysis on the selected areas

This step is added for the user acceptance of their selections and to provide a 'prize' to keep them engaged for taking the next steps, as illustrated in Figure 4. Step 4 will entail selecting the digital sub-categories, where the details of the digital categories needed to complete the task are to be selected. This level of granularity is added to the questions to ensure the roadmap can create a level of detail about how to achieve the digital category their DAM requires. As an example, the user may have selected data to achieve the tasks required for that element. The platform needs to understand what aspect of data the user needs assistance with e.g., is it to identify, specify, cost, or collect the data to inform their DAM.

In Step 5, users will review the results and select the approach they wish to take to discover the recommendations. As we noted earlier in this paper, the objective is to create a roadmap generator that helps all levels of digital maturity. To be able to achieve this, step 5 displays a dashboard of widgets that a user will instantly connect with and drive them towards guidance at a level they require. To make this work there are three levels of granularity from a sound level of maturity (1) to a low level of maturity (3).

1. Roadmap with a simple overview and Gantt chart
2. A checklist/action plan with a paragraph that outlines the requirements and can be the starter for a business case.
3. A task sheet with workflow maps and detailed actions sheets.

Step 6, as illustrated in Table 1 and Figure 2 is about generating the output of the system.

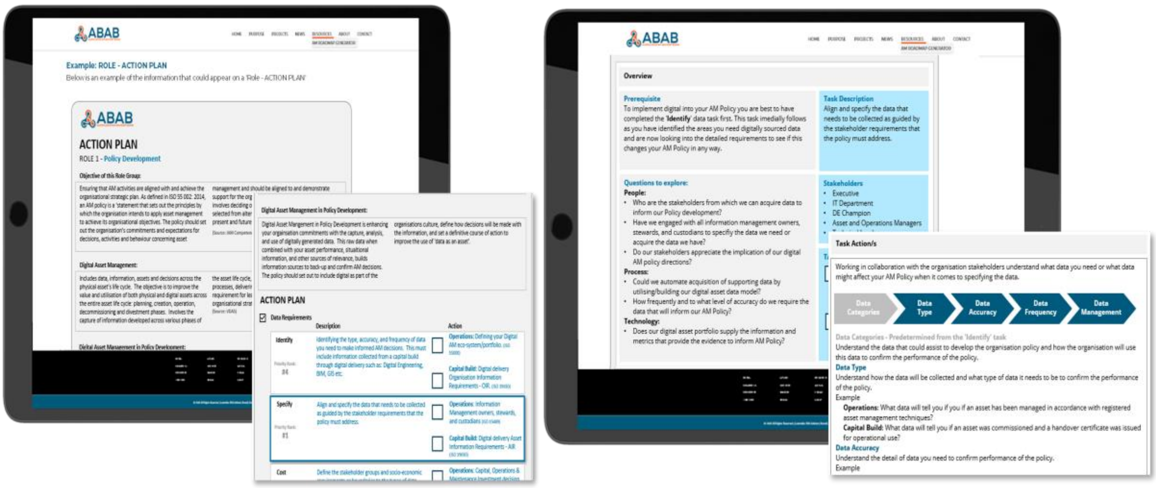

Fig 5: Step 6 – Actions plans and details

Based on the input provided by the users and according to the logical operators included in the system, the most fit-for-purpose scenario for achieving the vision of DAM is proposed by the system. At this step the user is deciding whether to save their journey for future review or export their guidance to a specific file format.

5. DISCUSSIONS

The roadmap generator contributes to the field and offers novelty in several ways. First, as a constant data collection platform, the roadmap generator project will be one of the first macro level empirical studies – at the industry level – on the adoption process of DAM, which creates macro level knowledge and will reveal the 'needs state' of the market. The knowledge, ideas and insights collated by the roadmap generator will provide researchers and practitioners with a sound basis for further research, policy making and designing interventions that enhance the chance of success in a transition to DAM across the construction industry in Australia. The proposed roadmap generator will also provide lessons for other contexts and countries and creates a blueprint for future research into the adoption journey of other technological systemic innovations across the construction industry.

Second, addressing the 'how' and 'when' and 'by who' questions, rather than the 'why' question of BIM/DE adoption and transition to DAM have remained under-researched areas (Akintola *et al.*, 2021, Zomer *et al.*, 2021). Providing the field with the roadmap generator can be likened to moving beyond the deterministic and prescriptive discourse around BIM/DE adoption and DAM. It extends the realm of adoption from the current exclusive focus on 'why' a transition is needed to a 'how' and 'when' and 'by who' a transition needs to be planned and managed for successful adoption.

Third, the use of change management theories to move from explanation to intervention in BIM/DE adoption is described as a gap in the body of knowledge (Matthews *et al.*, 2018, Zomer *et al.*, 2021). The use of established theories in BIM/DE adoption literature has been limited to applying the "innovation diffusion theory" in exploring the factors that affect adoption. Studies devoted to the topic of a change to BIM/DE and DAM remain entirely descriptive in the use of change management theories to analyse what takes place during transition. Providing the roadmap generator offers novelty in going beyond this point, through synthesising major change management theories as its theoretical underpinnings, to chart pre-existing conditions; identify the prerequisites for successful change through considering interactions among key components that participate in the change; and characterise areas in need of intervention to enhance the capacity of identified components, including individuals as well as non-human actors.

Moreover, in Practical terms, the roadmap generator is novel in linking change management theories, BIM/DE and DAM adoption and enhancing capacity in both organisation and individual levels alike. The novelty here lies in providing a new frame of reference to approach the journey of DE/BIM and DAM adoption. The uniqueness relates to moving away from an exclusive focus on technology-oriented view to one informed by socioeconomic aspects of individuals' and organisations' capacities for going through the change successfully.

6. CONCLUSION

This paper provides the first account of an ongoing research project with the aim of creating an automated roadmap generator, to expedite and facilitate a transition from traditional methods and practices of asset management from traditional to BIM/DE-enabled one, namely, digital asset management (DAM). Offering this automated roadmap generator is deemed a response to the well-recognised need in the market, to address the major barriers that have hampered efforts for a broadscale uptake of DAM within the Australian construction industry: a lack of digital planning, lack of awareness of effective practices to manage the episode of change, and resistance to change due to perceived latent risks of transition to digital methodologies.   a needed intervention within the Australian construction industry.

Through in its initial stages, the automated roadmap generator is designed to be enhanced through the integration with artificial intelligence (AI), as the next step towards a fully-automated roadmap generator. Within the next phases, the knowledge collected through the constant use of the platform will be merged with the feedback from users, to learn from past experiences in recommending effective future actions plans, as a fertile area for the next phase of this research project.

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From BIM student to BIM professional: How work-ready are Australian Universities BIM graduates?

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ABSTRACT: *BIM offers numerous benefits to the Australian Construction Industry, yet its uptake remains slow. A lack of suitably qualified BIM professionals is understood to be the main barrier to widespread BIM adoption. In response, Australian Universities have made some attempts to integrate the teaching of BIM into construction curricula, but with limited success. The main impediment is conjectured to be a mismatch between what universities offer and what industry actually needs. Yet, the exact nature and extent of that mismatch has to date remained unresearched and undescribed. This study addresses that knowledge gap. It assesses both the current status of BIM competencies among university graduates and explores how BIM education at Australian universities may be further improved to deliver BIM Work Readiness (BWR), as required by the industry. A qualitative research methodology was adopted, relying on 17 semi-structured interviews of BIM industry experts. Findings reveal that graduates are generally competent regarding the use of BIM software. However, employers not only expect graduates to demonstrate software skills, but to also have the capability to implement BIM as a process. Graduates appear to be significantly deficient in matters of BIM protocols, collaboration and coordination, information workflows as well as completion and handover procedures. As a recommendation, this study proposes the concept of the "T-shaped BIM professional" as a learning outcome to be pursued though suitable improvements in university BIM education courses.*

KEYWORDS: *Digital engineering; Digital asset management; Academic forum; University education; BIM roles; Tertiary education*

1. INTRODUCTION

BIM has been widely praised as a new paradigm and the next digital transformation in the AEC industry, towards one that is more productive and agile (Oraee et al., 2019). Despite the growing interest, past research has acknowledged that neither widespread BIM implementation, nor the envisaged systematic transition with the AEC sector have occurred. That is, while many large-sized and flagship projects are already using BIM, the industry still has not achieved a large-scale implementation of BIM. This is particularly a problem in Australia, where the BIM market has been likened to not mature enough to reap the benefits of broadscale implementation, which materializes when a large number of entities and organizations of the AEC industry use BIM in projects (Matthews et al., 2018). Within the relatively emerging BIM market in Australia, BIM adoption is increasing; more businesses implement BIM and so demand for professionals with BIM competence is exponentially increasing (Hosseini *et al.*, 2018). To accommodate short-term BIM-related skill demands, AECO businesses can engage internal staff or outsource expertise. However, from a longer-term perspective, a sustainable pipeline of competent BIM graduates supplied by higher education institutions is urgently needed (ABAF, 2021). University students constitute a significant part of the future industry workforce, therefore, BIM skills and competencies are needed to solve future problems confronting the sector (Hong *et al.*, 2019).

The latest literature on BIM education within the Australian context has not explored the impacts of BIM education on the working environment of graduates of universities (Casasayas *et al.*, 2021). Despite the significance of assessing student perceptions, the impacts of BIM education on graduate's career and employer perception on BIM education provided to graduates is still not fully explored (Wang *et al.*, 2020). Moreover, a more detailed investigation is vital to decide the best educational methodology to incorporating BIM in curriculum (Sacks and Barak, 2010). To bridge the gap, this research explores how BIM education in Australian universities assists graduates in their career path by investigating employer perceptions. Assessing BIM education through the lens of employer will provide a clear image of what happens after graduation and helps with measuring learning outcomes in real working life. In fact, it provides an assessment of BIM education quality in Australian universities, as argued by Dicker *et al.* (2019). The main question for this research is: How BIM education offered by Australian universities affects graduates work readiness for BIM-related jobs?

The following questions were set as the aim of this research:

Research question 1: What are the perceptions of employers regarding graduate BIM-related work readiness?

Research question 2: What solutions can be offered to improve BIM education practices to enhance graduates BIM competences towards higher employability?

As one of the first of its kind, this paper provides a picture of the current landscape of BIM education at Australian universities, from the vantage point of employers and industry practitioners. Findings will unearth the chasm between 'what universities offer' and 'what the industry needs.' Besides, findings will provide a point of reference for data-informed improvement of BIM-related courses and subjects at Australian universities. For policy makers and practitioners, findings offer insight into the requirements of the industry in terms of skill demand and talent acquisition.

2. LITERATURE REVIEW

Building Information Modeling (BIM) is now ubiquitous within the construction industry. Reliance on BIM has brought with it a dramatic increase in demand for employees with BIM capabilities and skills. Research studies confirm that the construction industry now requires its team members to be able to participate in BIM processes and utilize BIM tools (Hosseini *et al.*, 2018). Moreover, the wide and growing acceptance of BIM in the construction sector has sparked a transition from traditional roles and positions on construction projects to newly defined roles and responsibilities that are highly dependent on technology-based skillsets. Specifically, the recently evolved role of BIM manager (BM) has emerged to safeguard the success of BIM-enabled construction projects and facilitate BIM use.

The observed increase in BIM adoption is a global trend and BIM adoption in Australia is no exception, accelerating exponentially in the last two decades. This growth is attributed to a concerted government push towards wider Industry 4.0 adoption that seeks to engender smart and more sustainable cities and infrastructure. Despite this promising advancement, Australia faces many barriers to BIM implementation on projects. Of these barriers, lack of knowledge and, BIM education and training are identified as primary causes (Puolitaival and Forsythe, 2016, NBS, 2019). Given this demand from the AEC industry, Australian universities have made some progress in fostering BIM education and/or have offered compelling rhetoric that they are BIM enabled (Casasayas *et al.*, 2021).

The main purpose of BIM education is to facilitate the spread of technology by equipping current and future graduates with competencies required by industry (Succar *et al.*, 2012). An overview of current BIM education at Australian universities has been reported by NATSPEC and ICIS (2020). According to the report released by the Australian BIM Academic Forum (ABAF), 23 universities out of 43 have integrated BIM within their curriculum. The earliest courses were introduced only six years ago, while none to date can be considered synchronized with the broader curricula in which they are embedded.

In 2018, however, Australian universities established the ABAF to update BIM curriculum and align with government demands for the adaption of BIM/DE, designed to enhance graduate readiness for BIM related jobs (NATSPEC and ICIS, 2020). Despite some success, further work is still required to improve BIM skills and knowledge (ACIF and APCC, 2017). Consequently, a stream of studies has emerged on the barriers that impede BIM educational outcomes at Australian universities (Forsythe *et al.*, 2013, NATSPEC and ICIS, 2020, Casasayas *et al.*, 2021), or they have assessed the perceptions of students regarding the quality of BIM education they have been offered (Zou *et al.*, 2019). Some researchers have also tried to identify the shortfalls of BIM education in Australian universities and have recommend improvements (Baradi *et al.*, 2018).

3. RESEARCH METHODS

This research investigates the value of BIM education in the labor market by examining graduates' readiness for BIM-related jobs. The best paradigm for this research is social constructivism (Guba and Lincoln, 1994). Based on Amaratunga *et al.* (2002), this type of research required a qualitative method and inductive approach to understand phenomena related to human experience in a specific context. This approach will assist in a deep understanding and describing phenomena of human practice in real life (Amaratunga *et al.*, 2002). In addition, the qualitative approach has the potential to obtain rich data and uncover complexity (Amaratunga *et al.*, 2002). Therefore, to explore the BWR of construction-related graduates, employer perception will provide a clear image of the real working life of graduates. The semi-structured interview is the primary method because it is a multilateral and powerful qualitative technique especially for addressing specific aspects and giving a space for participants to add new knowledge and ideas to the research topic.

3.1 Semi-structured interviews

Thirty-three firms in the Australian construction industry that utilize BIM were identified, and an invitation to participate in this study was sent out through LinkedIn to 46 potential participants. Each was a BIM/Digital expert with at least five years' experience in construction. 17 valid semi-structured interviews were collected, which serve as the data set to this study.

3.2 Theoretical framework

This research utilizes the concept of Person-Organization (PO) fit. PO fit seeks to establish the compatibility between "demand" and "ability" (Kristof, 1996). Compatibility refers to features of an organization's demand of employees, such as skills, knowledge, pace, effort, etc., and compares these with what employees actually deliver. PO fit is said to be achieved when at least one side of this model provides what the other side needs (Kristof, 1996).

Measuring PO fit between "demand" and "ability" can be assessed indirect by establishing "explicit comparisons" between the individual and the organization, and this can be undertaken by a researcher (Kristof, 1996). Specifically, the researcher treats the organizational characteristics as one side of the model, while the other side requires an examination of individual employee characteristics, and in so doing identify the level of congruence (Chatman, 1989).

4. DATA ANALYSIS

Interview findings reveal graduates' "Ability" as compartmentalizing into two major themes:

- BIM software
- BIM as a process

4.1 BIM software

Based on interviewees perception, most respondents (14 of them to be specific) agreed that graduates are skilled with BIM software packages. Especially with tools related to 3D modelling and parametric design. For example:

"Many students are very good with the tools, sometimes even better than the people on the projects in real life already" (Interviewee C).

"Grads are coming out with skills that the older generations could not even fathom" (Interviewee C).

4.2 BIM as a process

Students and new graduates appear to share a gross misunderstanding of BIM as a process. They tend to think of BIM merely as a software tool. All participants referred to this point, and the consensus is reflected in this comment:

"Graduates have a very limited understanding of what it [BIM and Digital engineering] actually really means, and a lot of the time I asked a simple question of the graduate, what is your interpretation of BIM, and a lot of the time they will come and say Rivet, as an application, which is totally wrong" (Interviewee I).

Graduate application of BIM as a process reveals weaknesses across four components:

1. Lack of awareness on industry standards.
2. Unprepared for collaboration and coordination.

3. Lack of understanding for information workflows.

4. Lack of understanding project deliverables.

4.3 BIM competencies required by employers

When asking participants about the major expectations related to BIM work readiness of graduates, respondent's answers formed the "demand" list. These can be classified into four broad categories. See Figure 1.

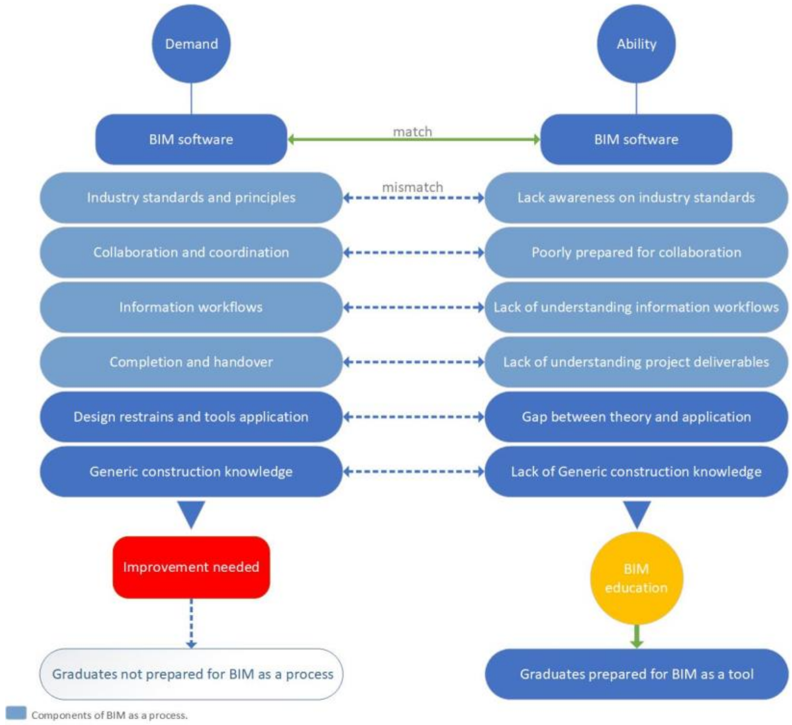

Figure 1. Person-Organization (PO) fit model of the findings

1) Utilization of BIM software

Based on interviewees perception, the minimum requirement expected from graduates is to know BIM software. Graduates are required to be skilled with BIM software linked to their disciplines. So, *"they can produce whatever they need to produce for their discipline"* (Interviewee A). One of the interviewees stated that: *"Fundamentally we expect you [graduate] to know a software"* (Interviewee E).

2) Understanding BIM as a process

All interviewees argued that understanding BIM as a process is more important than BIM as tool. The broad term of "BIM as a process" implies the awareness of the following interpretation points as perceived from interviewees:

- Industry standards and principles: particularly ISO 19650 series.
- Collaboration and coordination: Graduates are required to understand the concept of sharing and managing information within project teams.
- Information workflows: Understanding work progress and data management during a project lifecycle.
- Completion and handover: graduates are recommended to have knowledge about types of documentation related to BIM and digital engineering and how project is handed over to client.

3) Design restrains and tools application

One of the important requirements as perceived from interviewees is understanding the application of BIM tools.

Employers expect graduates to acquire technical and structural knowledge as an essential pre-requisite. As articulated by (Interviewee O): *"I am concerned the design skills and construction knowledge and all other practical theoretical knowledge related to the industry is more important than actually having skills in operating one of those tools. Because, within two or three or five years there will be another tool".* Similarly, (Interviewee E) emphasized that: *"You need to make sure your foundation of skill for design … are well converse and well equipped with that technical knowledge".*

4) Generic construction knowledge

In successfully leveraging the BIM and digital work environment to maximize productivity, graduates must also demonstrate strong communication skills, problem-solving and clash detection skills, creativity, critical thinking, self-management, as well as the ability to deal with clients and clients' needs. One of the interviewees stated that: *"We want our graduates to be … really open to communicate" (*Interviewee L). (Interviewee C) stated that: *"Industry is all about problem solving and working together as a team, and that is what BIM is all about, so you need to have a good understanding of active problem solving"*. Other interviewee said: *I expect them to run their own self checks and clash detection"* (Interviewee A).

5. DISCUSSION

Based on the Person-Organization (PO) fit model (Figure 1), A match between "ability" and "demand" appears to exist for BIM software skills. graduates are mostly prepared for BIM software. Their ability to contrast 3D models, dealing with parametric design, using software for scripting and coding is the most components addressed by interviewees. Therefore, employers are most likely satisfied with BIM software competencies possesses by graduates, especially for design-related tools. This could be the result of what BIM education offers to students. The reports indicate that BIM education in Australia concentrates more on BIM authoring tools than it does on the BIM process (NATSPEC and ICIS, 2020). Moreover, design-oriented courses in Australian universities are more disposed to utilize BIM for visualization purposes (ABAF, 2021).

On the other hand, a mismatch appears to exist for BIM as a process in addition to the knowledge on design restrains and generic construction knowledge.

The following are the discussions of employers' expectations.

5.1 BIM as a process

BIM competencies should encompass the ability to use software (BIM tools) and the capability to implement the BIM process (Abdirad and Dossick, 2016). Based on employer perceptions, understanding the BIM process is more important than knowing the tool. This statement disagrees with the prior requirement of industry professionals surveyed by Wu and Issa (2014), that ranked BIM software skills at the top of the desired list of student learning outcomes. In the traditional academic environment, students can easily be trained in BIM software skills. However, segregation between construction-related disciplines prevents from simulating the collaborative working environment required of industry.

5.2 Industry standards and principles

Knowing a process in BIM should be endorsed with understanding the BIM guidance as argued by Hjelseth (2017). BIM guidance consists of all "documents describing how defined parts in specified standards". The purpose of developing BIM guides and any BIM-related standards is to support the utilization of BIM and to manage information exchange between both the stakeholders and throughout the life cycle of the project (Hjelseth, 2017). BIM-related standards have gotten global attention to boost the achievement of BIM benefits. Therefore, ISO 19650 series that initially established based on British BIM principles- to provide international standards for BIM implementation.

5.3 Collaboration and coordination

Most employers have pointed out that graduates are still working in isolation without understanding the role of sharing data with other disciplines. They have limited knowledge of what data needs to be shared and when to share it with certain team members. This indicates that a holistic appreciation of the necessity for collaboration and coordination in the BIM environment is still absent among graduates. This could be due to the fact that universities do not provide adequate collaborative teamwork while teaching BIM. According to ABAF (2021) report, BIM education in Australia has limited approaches for collaborative and teamwork work environments. Moreover, recent studies have revealed that the integration of a collaborative environment in traditional education is one of the significant challenges that face BIM education in Australia (Casasayas *et al.*, 2021).

5.4 Information workflows

BIM usage within the industry has become more mature and clients are increasingly demanding. Thus, BIM is no longer limited to geometrical models. It is now used to manage information flows between different parties to a project, such as designers, clients, contractors, suppliers, and others (Sampaio, 2021). Consequently, a lack of experience in implementing BIM for asset management, combined with an insufficient ability for collaboration among graduates, hinders Australian construction organizations from leveraging the benefits of BIM (Oraee *et al.*, 2019).

5.5 Generic construction knowledge

According to the analysis of BIM-related jobs criteria done by Barison and Santos (2011), successful applicants should have good levels of communication skills and critical thinking as well as BIM software skills and processes. Zhao *et al.* (2015) argued that the technological and dynamic industrial practice requires a mixture of BIM technical knowledge and skills such as innovation and collaboration. However, training graduates to be prepared for the industry is challenging for education. Because a well-prepared graduate should attain technical and practical knowledge and education usually provide the technical side of knowledge that does not certainly transfer into practice in the working environment.

5.6 Specialization and accreditation

According to the literature, accreditation will additionally offer a chance to old professionals to be integrated into the BIM environment and redevelop their skills by getting enrolled in BIM specific training (Agostinelli *et al.*, 2019). Moreover, accreditation aims to set the standards for BIM job placements (Wu and Issa, 2014). Succar *et al.* (2013) argued that defining and classifying BIM competencies in relation to specific tasks in BIM in the industry would benefit both the industry and education. For the industry, this can facilitate the measurements of competency of individuals, define and meet project requirements and for the education, such classification would assist with the design and development of BIM curricula and facilitate the measurements and assessment of student competencies.

5.7 Employer recommendations and the "T-shaped BIM professional"

When asking interviewees what components should be added to BIM education curriculum to enhance graduate BIM competencies, the following recommendations have been gathered:

- The philosophy of BIM/digital engineering and the logic behind it.
- BIM software and tools capability.
- Industry standards and National strategies
- Bridging the gap in inter-discipline communication
- Add specialties and accreditation to BIM education.
- Supporting future competencies through digital engineering education.
- Benefit from advanced BIM education in other countries in Europe and Asia.
- Industry and education collaboration

Based on employers' recommendations, the concept of the "T-shaped BIM professional" is proposed.

5.7.1 Proposed "T-shaped BIM professional"

Over the last decade, the industry 4.0 revolution promises smarter and more efficient productivity. Moreover, with accelerating technological advancements combined with increasingly savvy stakeholders, the need for well-developed professional competencies is more essential than ever (Lasi *et al.*, 2014). Therefore, education should offer graduates appropriate knowledge in preparing them to respond to an ever-demanding technological environment (Oskam, 2009). However, evidence shows that BIM education at Australian universities has failed in preparing graduates for BIM-related roles (Casasayas *et al.*, 2021).

In response, recent research identifies the remedy to be the "T-shaped BIM professional" (Martek *et al.*, 2021). Karjalainen *et al.* (2009) argues that "T-shaped persons are experts in specific areas (T's vertical stroke) while the 'know-how' of their discipline interacts with others (horizontal stroke). Suwal and Singh (2018) suggested that the inclusion of BIM in education should be through vertical and horizontal integration. Whereas vertical integration should focus on promoting students' awareness and capabilities of BIM, horizontal integration should focus on multidisciplinary collaboration, simulating real work scenarios. See Figure 2.

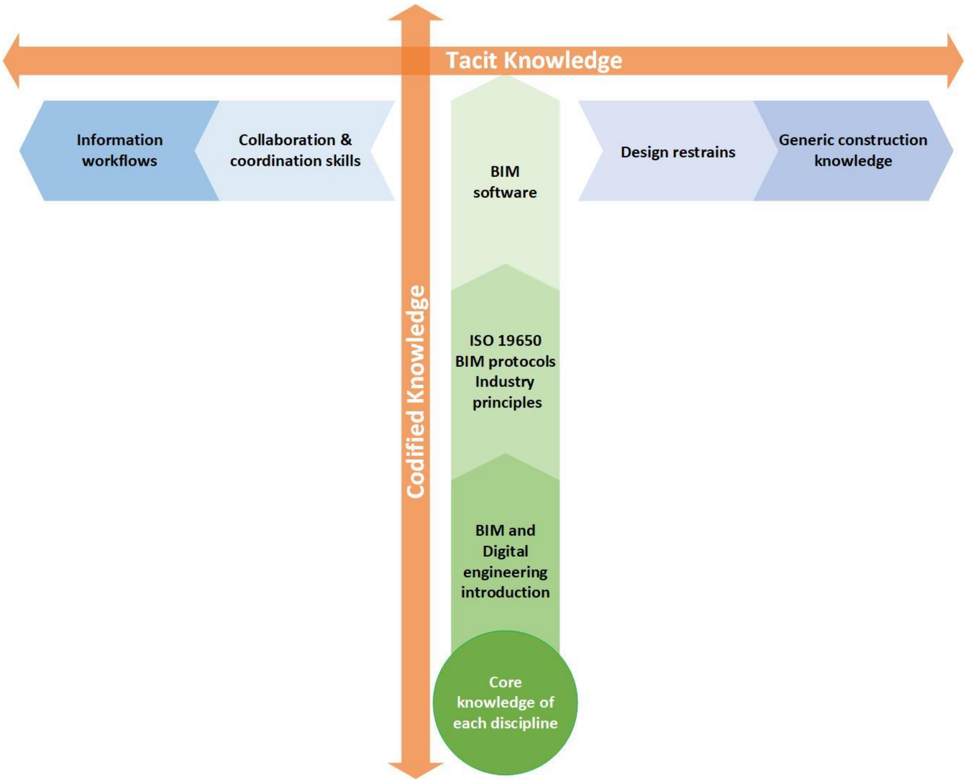

Figure 2. Proposed components of the "T-shaped BIM professional"

Vertical axis of the "T-shaped BIM professional"

Based on the improvement recommendations suggested by employers, each student should possess core specialized knowledge. Christenson (2006) argues that successful users of BIM software should have an adequate understanding of construction technology. Therefore, core construction-related knowledge is required as fundamental and complementary to BIM knowledge. Employers have highlighted the importance of providing students with fundamental knowledge of industry standards (ISO 19650 series), BIM protocols, Industry Foundation Classes (IFCs) and the importance of developing BIM Execution Plan (BEP). It is also recommended that BIM education should introduce different types of BIM collaborative contacts, such as contracts for partnering and for alliancing and how the process of working and procurements should be connected and driven by contracts. Current literature emphasizes the need to understand the diversity of BIM aspects among students and the importance of integrating this knowledge into education to facilitate the transition of BIM knowledge into action in the BIM work environment (Budayan and Arayici, 2021).

Horizontal axis of the "T-shaped BIM professional"

The horizontal axis of the "T-shaped BIM professional" consists of collaboration and management knowledge on BIM that education should consider to better prepare students for the BIM working environment. This knowledge is categorized under tacit knowledge because it cannot be easily taught in traditional education classes, whereas it should be gained during practice (Martinez-Brawley and Zorita, 2007). Higher education programs have usually followed the approach of engraving information in students' minds, with limited chances to test what they have learned in practice (Kolb and Kolb, 2005). Literature indicates that BIM education has overlooked BIM collaborative and management aspects (Abdirad and Dossick, 2016, NATSPEC and ICIS, 2020). The development of collaborative aspects depends on coordination and communication skills in which the shared information in a project is not limited to geometric properties, however, it should include "information about functions, constraints and the design rationale" (Wong and Sriram, 1993). Therefore, Bozoglu (2016) suggested that BIM education should offer an opportunity for students to learn by doing to allow them to progress from a theory to a project-based application. In line with the recommendations by employers to engage students in a working environment that is similar to the real work-life in BIM. Moreover, (Matthews *et al.*, 2018) revealed that the essential understanding of collaborative and management BIM aspects is achieved by practice.

6. CONCLUSION

Employers' perspectives on graduate readiness for BIM-related tasks are explored in this study. Findings reveal that BIM education at Australian universities prepares students for BIM software, but not for BIM as a process. BIM education fails to provide students with sufficient knowledge in industry principles, Furthermore, graduates lacking knowledge on design restrains and unskilled with generic construction knowledge such as communication skills and problem-solving. Latest studies. Employers expect graduates to have BIM software skills and have the capability to implement BIM as a process.

The uniqueness of this study relies on its focus on identifying expected BIM competencies by employers and comparing them with current graduate BIM competencies. Via applying matching theory, this research highlighted the valuable BIM competencies in the working environment and paved the way for improving BIM education. The findings of surveying employers identify the professional BIM competencies that universities should equip students with to enhance their work readiness. Employers' recommendations enable this study to propose the "T-shaped BIM professional" and formulate BIM education components of the vertical and the horizontal axes of the T- shaped to be considered during the improvement of BIM education courses.

With a relatively low amount of literature on graduate BWR, this study represents a step towards understanding what to emphasize at universities when it comes to BIM competencies. Since graduate BWR is a worldwide concern, further research is needed to pinpoint specific uses of BIM in industry and cluster BIM competencies accordingly. Moreover, future research should investigate BWR for the different BIM roles in the industry to assist universities in developing BIM specialties and accreditations. With the increasing presence of digital engineering in the industry, there is a call to professionalize the role of digital engineering in the industry to facilitate the development of digital engineering education.

The contribution of this study, coupled with our suggestions for future research in BWR, will provide significant benefits to educators, industry, and graduates to form professional BIM skills that support the implementation of BIM and digital engineering in the industry.

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TOWARDS A SEMANTIC COMMON MODEL LIBRARY FOR WATER INFRASTRUCTURE ASSETS

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ABSTRACT: *Product information capture and validation in the United Kingdom's water industry is primarily a manual process that relies on utilising spreadsheets to describe very detailed asset information. The designer would specify the required product information in a spreadsheet that is then submitted to the relevant supplier for population. Prior to this, asset specification comparison for choosing the right product is rather primitive and does not utilise the level of detail of asset specification. The current practices lack specifications comparison, and automated data exchange and validation mechanisms resulting in inefficiencies in terms of quality, time, and cost. Nonetheless, as this has been a persistent practice by the United Kingdom's (UK) water industry, a consensus has been reached to develop these spreadsheets into a common form called the Product Data Templates (PDTs). This issue of using static documents for product information exchange is prevalent in the literature, as suppliers' involvement in the information life cycle is usually disconnected. This issue is further amplified for the infrastructure sector, as exhaustive non-geometric data is of more importance for Operations and Maintenance (O&M).*

This paper uses Semantic Web Technologies to address this issue by proposing a common-model semantic library for phase-specific data exchange. Presented in this paper's use case is the knowledge representation of water industry's product data that must fit within current industry practices, provide logical consistency, and account for future technological advancements. Subsequently, an ontological common model was designed using Web Ontology Language (OWL) to represent the knowledge for a phase-specific data exchange scenario, as part of the common model library. Although, OWL is a powerful language for knowledge representation and inference, it is not designed for setting constraints on the data. Therefore, the Shapes Constraint Language (SHACL) was applied to the model using Apache Jena APIs to set constraints on and validate product data. This paper presents the use of such system by demonstrating the system architecture with an example and proposes future recommendations.

KEYWORDS: *Product data exchange, Product Data Templates, Water industry, Semantic Web Technologies, Common model library, Product library, Data validation.*

1. INTRODUCTION

The construction industry is large and diverse, as it spans across several domains and requires multiple parties (stakeholders) collaborating to deliver a project. Therefore, it is wise to break down the industry based on classification systems into smaller blocks that would facilitate tackling its issues. One of these issues is the comparison, acquisition, and validation of product manufacturer data across different domains. The collaborative involvement of manufacturers in Building Information Modelling (BIM) is usually hindered due to the lack of dynamic links between their product catalogues and the BIM model (Costa and Madrazo 2015). Additionally, once product information is captured, the compliance checking of this information to requirements forms another issue in the construction industry. This forms part of the wider compliance checking process that takes place across the project's life cycle (Amor and Dimyadi 2021). These issues of product information comparison, acquisition, and validation are particularly prominent in the infrastructure sector, where rich and technical product information is more important than 3D data (Bradley et al. 2016) and is still communicated using static documents (Rasmussen et al. 2019).

This paper addresses the water infrastructure in the United Kingdom, which uses spreadsheets, dubbed as Product data Templates (PDTs), to exchange product information. The information structure (product attributes) in the PDTs have been agreed upon by several water companies in the UK. The input and output processes from and to PDTs, respectively, are manual. This would introduce issues such as inaccurate data, missing data, wrong-format data, as well as time and cost inefficiencies. Additionally, product data information pertinent to the water industry are only available upon request from product suppliers' websites, resulting in a lengthy negotiation process to compare and obtain the information.

A central repository for building related concepts has been proposed and standardised by the ISO 12006 International framework for Dictionaries (IFD) (BSI 2016), which has reported benefits for the building domain

(Beetz and de Vries 2009). This paper borrows the concept of a central repository to represent water products information. However, as descriptive and technical information is dominant in the infrastructure sector, knowledge representation is critical for describing products, and so, each product would have a model that describes it, resulting in a product model library or common model library. Many researchers have investigated knowledge representation using Semantic Web Technologies (SWT) and reported tangible benefits. In addition to knowledge representation, SWT help integrating multiple data sources, and hence, achieve Linked Data (LD).

The objective of this paper is to present some of the work that has been done on modelling product information for a submersible pump for the UK water infrastructure sector.

2. PRODUCT INFORMATION MODELLING

Modelling product data has been a topic of research for decades across all industries. However, inefficiencies still exist in the construction industry due to its size, variety of products, as well as the high customisability of products.

Synergising different parties along the supply chain is a challenge due to social, economic, or technical difficulties (Pandit and Zhu 2007). During the product design phase, the process of decision making involves many factors such as performance, quality, safety, product certification, etc. Thus, having all these factors available during the decision making is critical (Pandit and Zhu 2007). For product procurement in the water industry, most of the information provided by these factors are provided by the suppliers, and hence, supplier integration in the product procurement process is important (Costa and Madrazo 2015). Poor coordination and communication due to the scattered design environment are the main reasons for poor supplier integration. Therefore, Pandit and Zhu (2007) recommended an effective computerised collaboration environment. Although Building Information Modelling (BIM) was developed for such tasks, product catalogues integration with BIM was reported by Costa and Madrazo (2015) to be lacking. This problem is more pronounced in the infrastructure sector, where static documents are still used for product procurement and the adoption of BIM is lacking overall (Bradley 2016; Kamunda et al. 2020; Pidgeon and Dawood 2021).

A digital solution starts with modelling - a detailed representation of - product data. Several standards exist that may aid when modelling products such as ISO 10303, IEC 62264, ISO 15926, ISO 23386, and ISO 23387 as well as several research papers. However, product information requirements differ by project nature, project phase, and utility company (Alani et al. 2021). In the UK, PDTs, although under development, are ought to form a consensus on the product information requirements by several water companies. Also, due to the importance of the operational phase for utility companies, choosing the best product to match the requirements and importing all its relevant data to the asset management system is of major benefit.

Tursi et al. (2007) stated that a product is an interoperable system as it stores all relevant information about itself, that can be structured in a common formal model, which can be mapped to networked enterprises. Ontologies are formal models by definition; “an explicit specification of a shared conceptualisation” (Gruber 1993). Therefore, product ontologies are expected to contribute to the interoperability solutions between assets and asset management systems (Tursi et al. 2007). However, the use of ontology applications by manufacturers is not fully mature (Fraga et al. 2020).

There is plenty of research in managing heterogeneous information coming from different sources/stakeholders. However, choosing the right information to import is an issue that needs attention. As per Barbau et al. (2012), developing an interoperable product model is a challenge due to 1) the variety of information to be represented and the interaction between this information, and 2) the abstraction principles needed to model such information. Therefore, knowledge representation is important for interoperability and decision making. In the context of ontologies, the logical inference and proofs is one of major benefits of knowledge representation (Pauwels et al. 2017).

3. MODELLING A SUBMERSIBLE PUMP

3.1 Knowledge representation

Within the UK water sector, product data exchange must be phase specific (Alani et al. 2021). This is due to the differing requirements between project phases. Therefore, this research considers the stage where product requirements are fully mature. During the O&M phase for instance.

In the field of ontology development, the Web Ontology Language (OWL) is a common ontology development language, Protégé is the ontology modelling tool, and Jena is the Application Programming Interface (API) (Fraga et al. 2020). Description Logic (DL) which is a subset of OWL, i.e., OWL-DL helps modelling product life cycle information, both from an information requirements aspect and abstraction principles aspect (Fiorentini et al. 2008).

Figure 1 shows the axioms involved in describing a submersible pump that were manually extracted from the PDT of a submersible pump. This model forms part of the Asset Specification Ontology (ASO) presented in Alani et al. (2021). The arrows in blue represent object properties, i.e., properties that lead to other instances of a class as their range. The arrows in green represent data-type properties, i.e., properties that lead to literal values as their range. OWL provides axioms that modellers can use to describe properties as "functional", "inverse functional", "transitive", "symmetric", "asymmetric", "reflexive", or "irreflexive". These axioms were also utilised to describe the properties in this model where applicable. For example, "hasComponent" was asserted to be of type owl:TransitiveProperty to indicate that a component of an impeller that belongs to the submersible pump, for instance, is a component of that submersible pump. In addition to these properties, a submersible pump inherits other properties from its parent (super) classes, which are Pump and UniclassPreparatoryProduct.

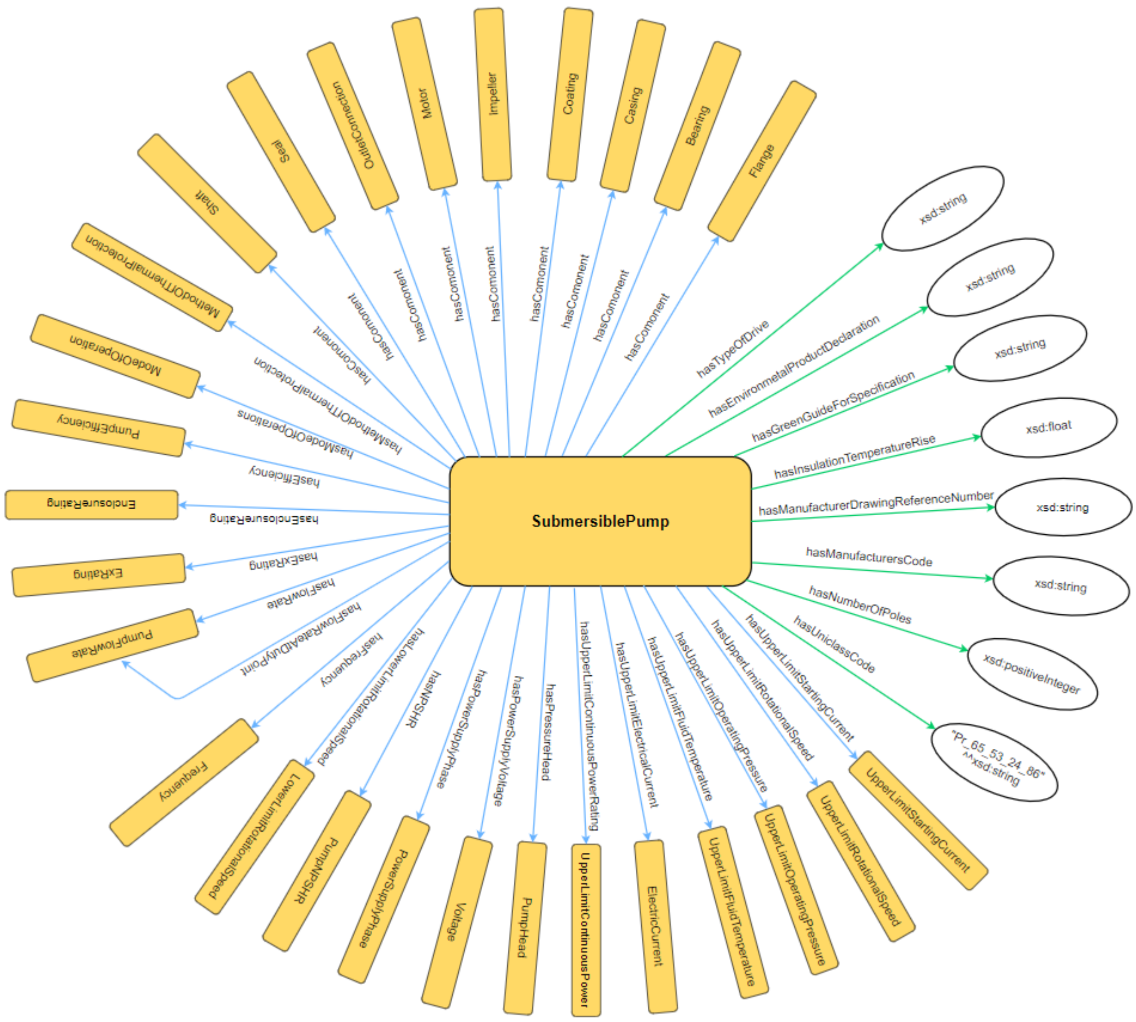

Fig. 1: Simplified representation of a submersible pump model.

From figure 1, these relationships (axioms) provide the data structure for the model. Of course, figure 1 is rather simplified for understanding, as it omits OWL class restrictions that were used to create these relationships. The relationships do not provide validation driven constrains on the data, but rather inference driven reasoning. For example, there is a cardinality restriction on the property "hasPowerSupplyVoltage" stating that it must have exactly one value from the class “Voltage”. If the incoming data, e.g., from a supplier asserted that a certain member of class “SubmersiblePump” has two values for property “hasPowerSupplyVoltage” and that they are members of class “Voltage”, the reasoner would then infer that these two members are in fact the same using “owl:sameIndividualAs”, rather than reporting a violation. Additionally, interactions between these properties cannot be directly modelled in OWL. For example, the pump’s shaft power (UpperLimitContinuousPowerRating) is represented by the following equation

$P\_s = Q\rho gh/\eta\_p$

Where,

Q is the flow rate (PumpFlowRate),
ρ is the fluid density (constant),
g is the gravity acceleration (constant),
h is the head produced by the pump (PumpHead), and
η_p is the efficiency of the pump (PumpEfficiency).

This relationship cannot be directly represented in OWL-DL but is necessary for the consistency and validity of the data. Therefore, the Shapes Constraint Language (SHACL) was added to the model for providing constraints on the data, and hence, user customisability. A SHACL constraint is added to every property in the model presented in figure 1. SHACL constraints were also used to validate interactions between properties, such as the mathematical relationship presented earlier, which was done using the SHACL-SPARQL extension. Therefore, constraints would compose the *submersible pump shape*. Listing 1 shows an example, where SHACL shapes were used to check the validity of sample data using Apache Jena in Eclipse. The example shows that the data about the pump’s power supply phase is missing as shown by the “sh:resultMessage”. In addition to data validation, the use of SHACL is also useful for building user interfaces, generating code, or ensuring data integration (Knublauch 2021).

```
[ a              sh:ValidationReport ;
  sh:conforms   false ;
  sh:result     [ a                                  sh:ValidationResult ;
                  sh:focusNode                       aso:SubmersiblePump1 ;
                  sh:resultMessage                   "What is the power supply phase?" ;
                  sh:resultPath                      aso:hasPowerSupplyPhase ;
                  sh:resultSeverity                  sh:Violation ;
                  sh:sourceConstraintComponent       sh:MinCountConstraintComponent ;
                  sh:sourceShape              []
                ]
] .
```

Listing 1: Example of SHACL data validation results.

3.2 Logical consistency

Figure 2 shows the logical constraints used for describing a submersible pump. A submersible pump is a subclass of a restriction (restriction 1), which defines a particualr function or aspect of a submersible pump. Modelling this function this way – rather than asserting the submersible pump to be equivalent to restritcion 1 allows for future expansion of the definition of a submersible pump, as this model only defines part of a submersible pump. This is because in DL a class can have more than one parent class, and hence, more than one definition. In this regard, the submersible pump is a subclass of a uniclass preparatory product, meaning that it should also inherit the definition of a uniclass preparatory product. Since the definition of a Uniclass preparatory product is set by the PDTs – i.e., the minimum attributes that a product must have to be considered a Uniclass preparatory product – it has been modelled as an equivalent class to restriction 2. Therefore, based on DL reasoning for an instance to belong to the class of submersible pumps it must satisfy restriciton 1 and restriction 2. Thus, a submersible pump for the UK water industry must be a Uniclass preparatory product. Consistency of the submersible pump Asset Specification Ontology (ASO) was validated using the Jena’s API’s as shown in Listing 2.

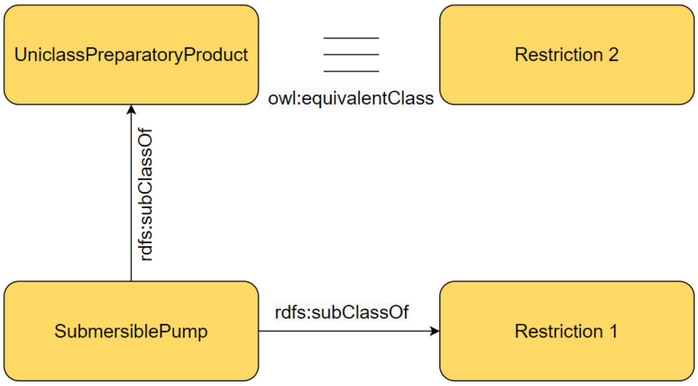

Fig. 2

```
import org.apache.jena.ontology.OntModel;
import org.apache.jena.ontology.OntModelSpec;
import org.apache.jena.rdf.model.ModelFactory;
import org.apache.jena.reasoner.ValidityReport;

public class SubmersiblePumpOntology {
        public static void main(String[] args) {
        OntModel model = ModelFactory.createOntologyModel( OntModelSpec.OWL_DL_MEM_RULE_INF ) ;
        model.read("C:/Users/yasir/OneDrive - Teesside University/PhD/Ontologies/XMLSubmersiblePumpOntology.txt") ;
        ValidityReport validity = model.validate() ;
        if (validity.isClean ()) {
                System.out.println("Okay") ;
        } else {
                System.out.println("Conflicts") ;
                }
        }
}
```

Listing 2

3.3 Future compatibility

Using logic for modelling is beneficial; assuming that logic does not change, logical modelling can form the basis for future development (Allemang and Hendler 2011).

The submersible pump model presented here was created from the PDT of a submersible pump and results from focus group sessions - presented in Alani et al. (2021) – using Description Logic. To ensure logical consistency and future compatibility, the model ensures that definitions are clear and precise. For example, as per this submersible pump model, a submersible pump is an instance of a class that has all the properties presented in figure 1, and therefore, missing one of those properties disqualifies the model from being a submersible pump – from a definition point of view and not from a validation point of view due to the Open World Assumption (OWA). It is worth mentioning, however, that some Semantic Web systems are not targeted at provable correctness, due to the nature of the web (Allemang and Hendler 2011), which again justifies the need for incorporating rule language such as SHACL for precise modelling.

4. COMMON MODEL LIBRARY

This research focuses on the modelling aspects of utility companies' products, as their information requirements are more complicated than buildings products. The aspiration here is to have a SHACL-based information retrieval from the OWL graph database. Information retrieval based on SHACL validated graphs is lacking in the literature, as incorporating Natural Language Processing (NLP) with graph-based querying is no trivial task (Styperek et al. 2015).

However, an issue is that there are no means of knowing what properties of a product outweigh others. User preference or intent is therefore another research problem. In this regard, future work is ought to ask industry practitioners in the UK to evaluate the importance of a submersible pump's attributes to understand their preferences in terms of information indexing. Indexing helps user queries in generating a ranked list of documents (Mohd 2011). Such indexing is not supported by SPARQL.

Using SHACL only for modelling the product data would indeed fulfil validation requirements, however, the semantic meaning would be lost. For example, filling a SHACL form via the user interface would only restrict the results to what is specified by SHACL constraints. If a user decided to search for instances of a UniclassPreparatoryProduct in figure 2, SHACL may not include SubmersiblePump(s) in the results. Therefore, OWL semantics and inferencing capabilities are very important in this context.

Generally, the aspiration is to demonstrate over the next phases of the research the process of retrieving submersible pump's data from the model presented in this paper.

5. CONCLUSION

This paper has presented part of an ongoing research, which addresses the issue of supplier integration in the process of product data capture for the water industry in the UK. Some of the main properties that define a submersible pump product were presented. SHACL was also added as a rule language to model restrictions and introduce rules into the model. Apache Jena APIs were used to manipulate the model, with brief examples presented.

From the modelling issue in this paper, using Description Logic is no trivial task, as it requires deep understanding of the language by the modeller, particularly with predicting the implications of certain axioms in the future. On the other hand, OWL-DL introduces modelling flexibility that would help accounting for future extensions, which is one of benefits of using logic in general. For example, if one was to add to the definition of a submersible pump, they can simply assert more parent classes to the submersible pump class.

From a data validation perspective, despite that OWL, and consequently DL, are not enough for modelling complex product information (Alani et al. 2021), modelling in OWL is generally more efficient and easier than creating the entire model in rule-based systems (Allemang and Hendler 2011). Therefore, combining OWL with rules brings the best of both worlds.

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The development of an adaptable outcome-focused measurement and management methodology, incorporating risk mitigation assignment in support of Collaborative BIM

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ABSTRACT: This research explores the current availability of BIM measurement systems, processes, and toolsets as well as their limitations and opportunities for development through the utilization of a two-phase data collection and analysis approach. The design of the study initiates phase one with a thematic review of underpinning literature alongside a focus group survey questionnaire as part of the data collection exercise which included 15 BIM experts from both academia and industrial environments respectively. The second phase of the study explores and analyses the existing underpinning literature supporting for the implementation of adopted BIM measurement and management methodologies and practices.

Following the exploration and data collection phases, analysis of the findings show that existing measurement systems developed by both academia (63.89%) and industry (36.11%) to support the measurement of BIM are represented by 36 dominant methodologies, with a heightened yet limiting focus on providing the ability to measure BIM performance (42%), followed by BIM maturity (30%) and BIM competency (28%) which are mostly aligned with measuring the standardized compliant approach to BIM implementation. Furthermore, due to the subjective nature of collaborative BIM on a project-by-project basis, issues were raised such as the complexity of implementing and measuring BIM in a manner that best positions people and teams to harness their abilities and thusly increasing the likelihood of achieving the required outcome(s) progressively throughout and across the entire BIM project.

In response to these gaps and opportunistic findings, a novel measurement and mitigation methodology was developed to support the measurement, management, and implementation of collaborative BIM for a range of diverse practitioners, focused on ascertaining the complexity, confidence and impacts alongside risk mitigation that the task/objective may inherit. Further, this approach enables practitioners to move away from static and restrictive high-level BIM measurement and towards an active BIM management methodology for implementation across a heterogenous range of BIM project types, at varying stages of their lifecycle.

KEYWORDS: *Building Information Modelling, Measurement Techniques, Collaboration, Project Delivery, Decision Making.*

1. INTRODUCTION

Building Information Modelling (BIM) is a collaborative process driven framework that supports the digital delivery of projects, supported by technology and applications (Eadie et al, 2013; Kirby-Turner and Whittington, 2018), through the integration of teams of people focused on delivering specified outputs utilising a single source of truth (Vanlande et al, 2008; Vernikos, 2016). Regarding the latter, Common Data Environments (CDE's) holds the data that a project produces, exchanges and archives in order to create information clarity and certainty supported by stage gates and assurance workflows following the check, review, approve methodology (Forcael et al, 2020). Adding to these points, Singh et al (2010) research defines that almost all of the complexities of collaborative multi-disciplinary activities are visible across a range of AEC projects, which is where in theory the prospect of BIM holds potential value as it can aid in removing ambiguity and information silos (Azhar, 2011) and positions clients and their supply chain with a robust way of understanding their requirements and aspirations in delivering outputs in an efficient, digitally focused and collaborative manner (Harty, 2005). However, and adding to the simplified outline above and of the intent of BIM (Oh et al, 2015), the qualitative and quantitative measurement of BIM is typically an elusive and ambiguous area (Howard and Björk, 2007; Doloi, 2013; Hicks, 1992;), with items such as Return On Investment (ROI) being consistently difficult to ascertain and represent (Eadie et al, 2014), alongside seemingly insufficient tangible, unified and connected methods to capture the rate of delivered progress (Da Silva et al, 2019) against the information requirements or client expectations respectively, in a clear and succinct manner (CIOB, 2020) and at an agreed implementable level. Further, Iyer and Jha (2005) reaffirm that for projects to be truly measurably successful, a clear approach to delivery must be agreed and adopted by all parties, together alongside project managers and client stakeholders, respectively. Therefore, in light of the above, this research study as outlined in the developed sections which follow explores further the existing applied measurement methodologies, processes and frameworks with a focus on evidencing how they effectively manage and deliver the expectations and aspirations at a delivery level, from an achieving outcomes biased perspective. Latter sections state the opportunities to learn and develop these further through the creation of a new adaptable measurement process across all stages of the project lifecycle (Glick and Guggemos, 2009) and by a diverse range of stakeholders.

2. METHODOLOGY

The methodology and principles set out as part of design of this research are summarized below, in terms of the progressive workflow order.

1) Explore and assess through a systematic literature review the current state of BIM in respect to its implementation nuances, across academic and industrial literature.
2) Investigate the existing and thus developed measurement methodologies, tools and processes that are readily available to support BIM execution of projects, across academic and industry literature.
3) Undertake a semi-structured electronic questionnaire with a predetermined focus group, including 15 BIM experts from academia and industry, to expose their knowledge and experience of how BIM is currently measured and how it could be improved.
4) Review and compile a consolidated list of existing measurement methodologies, processes and tools that are available to support the implementation and management of BIM projects.
5) Summarize and review the gaps, opportunities and reference to existing measurement systems from data collected from the 15 BIM expert focus group participants.
6) Analyze the findings post literature review and data collection of how BIM is measured, managed, and delivered through academic and industry data collection.
7) Develop a novel alternative measurement methodology that is biased towards achieving qualitative and quantitative proactive outcome assignment and measurement of collaborative BIM due to the opportunities presented, including risk mitigation; and
8) Conclude, apply limitations, and outline future works.

2.1 AIM AND OBJECTIVES

The key aim, objectives and methods used as part of the design of this research are stipulated below in Table 1, following the developing research 'aims and objectives model' proposed by Thomas and Hodges (2010).

Table 1: Aim and objectives of the research study (Thomas and Hodges, 2010)

Aim	**Objectives**	**Methods**
To develop a novel approach to measuring both qualitatively and quantifiably the outcomes of BIM objective implementation, following a systematic and thematic exploration of academic and industry literature alongside a semi-structure questionnaire of BIM experts (academic and	Undertake a review of the underpinning theoretical literature, as well as industry practices and advances.	Systematic and thematic review of academic and industry literature.
	Develop and execute a semi-structured survey questionnaire to understand further the currently available and adopted measurement systems and toolsets.	Utilise an electronic questionnaire platform (Microsoft Forms) to facilitate the mixed methods of data.

industrial).	Outline the core gaps between current measurement methodologies and future opportunities for BIM.	Through analysis of the research findings.
	Propose an alternative measurement system focused on simplicity and adaptability of use for both qualitative and quantitative data for collaborative BIM delivery.	Develop a novel measurement methodology based upon existing gaps and opportunities presented by the conclusive evidence.

2.2 PROCESS FLOW METHODOLOGY

To further support the thematic analysis approach to this research (Attride-Stirling, 2001), a process methodology flow developed by Braun and Clarke (2006) for the socially led exploration of research has been utilized as shown in Figure 1 below, as part of the schema design. This four-stage process enables in order of flow 1) discovery of information 2) review of collated evidence 3) a proposal based on the key outcomes and 4) conclusive formalization on the thematic themes, feedback, and findings.

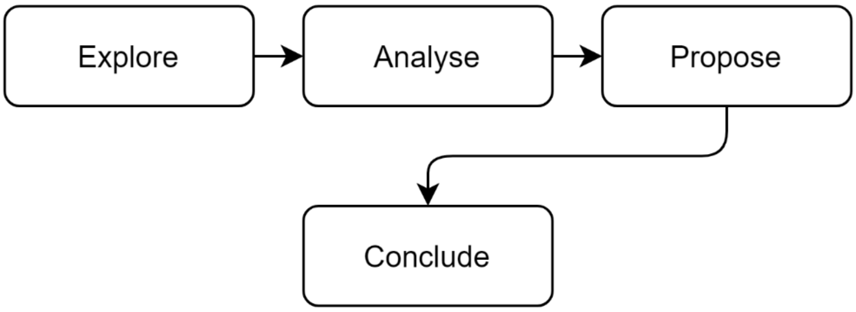

Figure 1: High-level process flow methodology (Redrawn from Braun and Clarke, 2006)

Presenting the developed methodology of this research more clearly and visually, a flow diagram has been created in Figure 2 below which represents the process leading towards the research's ultimate aims in developing an alternative outcome focused measurement and management methodology.

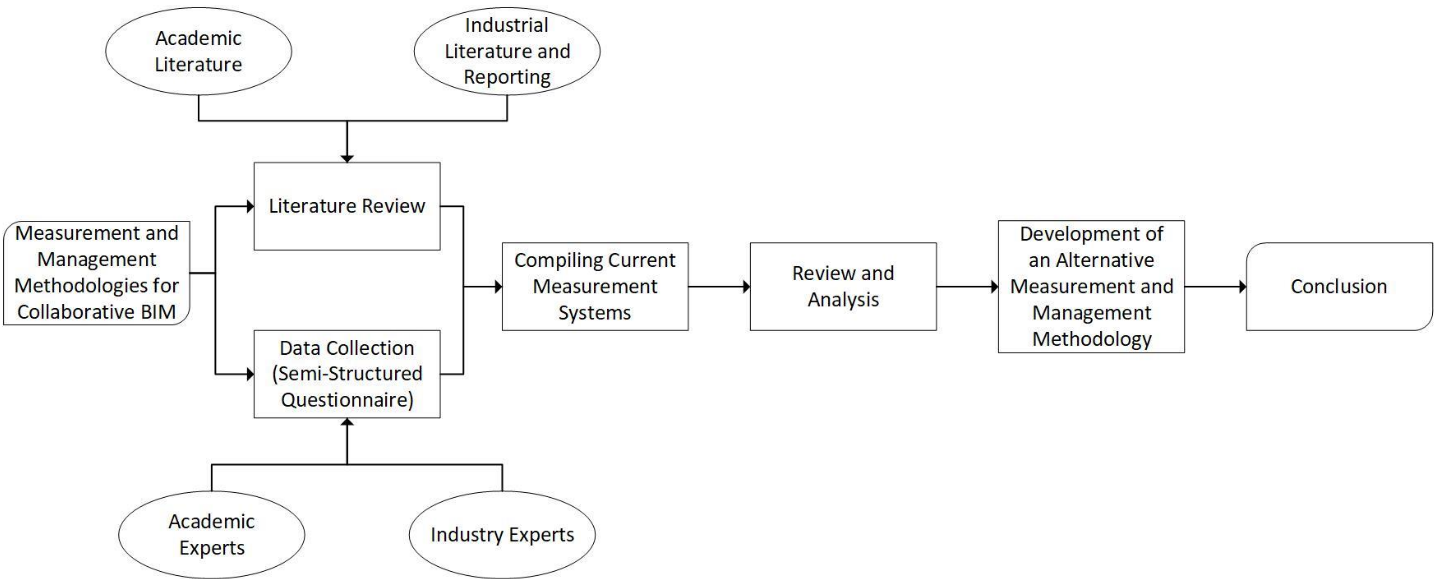

Figure 2: Visual research process methodology

2.3 STAKEHOLDER INCLUSION

In order to facilitate, capture and incorporate data from a range of diverse, experienced and educated participants, fifteen BIM experts were invited from both academic and industry background to support the thematic data collection process (Attride-Stirling, 2001). Furthermore, this predetermined focus group was a prolongation of participants designed and developed from previous research by the author (Pidgeon and Dawood, 2021a), with their continued utilization to create consistency from a focus group perspective; gathering expert opinions, experiences, and perspectives from their collective average experience of almost 23 years (as described below in Table 2).

Table 2: Stakeholder participants, expertise, and experience

Function	Participant Reference	Experience	Average Experience	Expertism bias	% Split
Professor	P1	20	c. 23 years	Academia	33%
Professor	P2	28		Academia	
Professor	P3	33		Academia	
Professor of Construction Management	P4	40		Academia	
Professor of Digital Construction	P5	12		Academia	
BIM Manager	C1	22		Construction	33%
Senior Project Manager	C2	22		Construction	
BIM Consultant	C3	35		Construction	
Project Manager	C4	30		Construction	
Deputy Regional Chief Engineer	C5	17		Construction	
BIM Consultant	D1	12		Design	33%
BIM Manager	D2	10		Design	
Project Information Manager	D3	10		Design	
Operations Director	D4	21		Design	
Business Unit Director	D5	30+		Design	

3. RESULTS AND ANALYSIS

This section and sub-sections which follow capture the data collected via the focus group BIM experts (15no.) spanning academia and industry, using the semi-structured questionnaire survey technique, to better understand which measurement systems are currently adopted, their successes and any opportunities that may be presented from their opinions and knowledge due to their poor usefulness and gaps they bring. Additionally, this was complimented by a thematic literature review of the currently available underpinning literature produced by academic and industry respectively, with a focus again on the developed measurement and management systems specifically focused towards supporting BIM.

Further, the specific area of interest and thus exploration across both survey and literature review explore the existence of these measurement systems (both theoretically and practically) in order to provide a further detailed insight towards the current state, availability, benefits and disadvantages of available BIM measurement systems and thusly, opportunities for developing an alternative approach to support collaborative BIM implementation and execution.

3.1 SURVEY DATA COLLECTION TECHNIQUE

To gain further knowledge into the existing measurement methodologies which are currently available to support the implementation of collaborative BIM which have equally successful and unsuccessful elements, three questions were designed and distributed to the focus group via a semi-structured questionnaire to understand further how BIM outcomes were measured, their success and failures as well as proposals for alternative practices that could benefit the BIM operational environment further.

Moreover, three questions were positioned to the participants as part of the survey questionnaire to gain a wider detailed perspective towards understanding how the existing applied methodologies were structured, what trends they share, their advantages and as well as inefficiencies and outlining any opportunities for improvement. These questions are part of the design in response to the former items were as follows.

1. How are BIM criteria and alternatives currently measured?
2. What are their successes and disadvantages?
3. How do you propose this could be alternatively measured and/or undertaken in the future?

In response to the assigned items above, Table 3 below outlines in summary the conclusive observations and commonalities stated, which has been summarized by the author in response to the participants feedback received through completion of the interview questionnaire.

Table 3: Stakeholder participants, expertise, and experience

Participant reference	**Observations by the author to the responses**
A1	- Current methods are aligned more to PAS1192 and equivalent standards. - No directly referenced/actively used measurement systems at the BIM execution stage.
A2	- Requests for Information are largely the benchmark for successful collaboration. - No directly referenced/actively used measurement systems at the BIM execution stage.
A3	- Return On Investment metrics are rarely implemented. - No directly referenced/actively used measurement systems at the BIM execution stage.
A4	- No directly referenced/actively used measurement systems at the BIM execution stage.
A5	- Reduced clarity on how measurement is practically undertaken. - Evidenced a vast range of theoretical tools developed as part of a research study but reduced data on implementation referencing. - No directly referenced/actively used measurement systems at the BIM execution stage.
C1	- Compliance is documented but not measured (quantifiably) - No directly referenced/actively used measurement systems at the BIM execution stage.
C2	- No directly referenced/actively used measurement systems at the BIM execution stage.
C3	- Development, at a project and organisational level, of measurement methodologies towards better clarity on implementation themes would be beneficial to a range of team members. - No directly referenced/actively used measurement systems at the BIM execution stage.
C4	- Disconnected teams despite active BIM

	- Procurement and contracts supporting information exchange are required. - Silos of what is to be delivered, when and by whom is sometimes mysterious. - User friendly and understandable interfaces to the benefits as well as making clear the negatives would be advantageous. - No directly referenced/actively used measurement systems at the BIM execution stage.
C5	- Regular metrics reported as part of organization operating model but disconnected from direct project activities and inconsistently produced. - No directly referenced/actively used measurement systems at the BIM execution stage.
D1	- Limited to zero tools available to practically measure active delivery/task outputs. - Success typically driven and perceived as cost alignment (on time, on budget) - Information clarity and quality should be a driver for useful measurement. - No directly referenced/actively used measurement systems at the BIM execution stage
D2	- Lack of client understanding of BIM requirements and therefore importance factors. - Applying understandable focus for and from the client towards output requirements and goals would be advantageous. - No directly referenced/actively used measurement systems at the BIM execution stage
D3	- No measurable input or out from, by or with the delivery partners. - Completion as well as way points checks required to support outcomes (and get them back on track). - No directly referenced/actively used measurement systems at the BIM execution stage.
D4	- As goals aren't typically measured but stated there are reactive measures taken to gain realignment which is disruptive and costly (time, cost, reputation etc.). - Applying a system that focuses on right first-time approach would reduce rework and thus improve efficiencies of collaborative BIM. No directly referenced/actively used measurement systems at the BIM execution stage
D5	- Measurement systems require friendliness to them so all can use and gain benefits, steer and guidance on how to achieve tasks/reduce risks. - Risk reduction and performance output driven approach would be valuable. - No directly referenced/actively used measurement systems at the BIM execution stage.

3.2 EXISTING MEASUREMENT AND MANAGEMENT METHODOLOGIES

Complimenting the survey questionnaire feedback responses as evidenced above in Table 3, a thematic literature review of the existing BIM measurement systems from both academic and industry literature was undertaken towards further understanding the available systems developed to achieving the expected outcomes for collaborative BIM. These findings as part of the thematic literature review are shown below in Table 4, along with a categorization of their bias and whether they have been developed by industry or academia.

Table 4: Stakeholder participants, expertise, and experience

Methodology	**Categorization (bias)**	**Academic or Industry developed**	**Citation**
BIM Assessment	Maturity	Academia	Pennsylvania State

			University, 2013
BIM Maturity Measurement	Maturity	Industry	Arup, 2015
BIM Benefits Management	Performance	Industry	Transport for London, 2017
BIM Return on Investment Tool	Performance	Industry	CDBB, 2019
CPIx BIM Assessment	Competency	Industry	CPIx, 2011
Project Management Process Maturity Model (PM2)	Performance	Academic	Kwak and Ibbs, 2002
BIM Measurement Methodology (BMM)	Performance	Industry	PwC, 2018
BIM Value Management	Performance	Industry	NATSPEC, 2019
Interactive Capability Maturity Model (I-CMM)	Maturity	Academic	Suermann et al., 2008
BIM Excellence Online Platform (BIMe OP)	Competency	Academic	Succar et al, 2013
BIM Maturity Measurement Tool	Maturity	Industry	ICE, 2014
BIM Maturity Assessment	Maturity	Industry	National Federation of Builders, 2019
BIM Benefits	Performance	Academic	University of Cambridge, 2018
BIM Performance Benchmarking	Performance	Academic	Sebastian and Berlo, 2010
NBIMS CMM	Maturity	Industry	NBIMS, 2007
Business Process Orientation Maturity Model (BPO)	Competency	Academic	Lockamy and McCormack, 2004
COBIT Model	Competency	Academic	Lainhart, 2000
Vico BIM Scorecard	Competency	Industry	Vico, 2019
IU BIM Proficiency Index	Competency	Academic	Indiana University, 2012
BIM ROI Framework	Performance	Academic	Giel and Issa, 2013
BIM Competency Assessment Tool (BIMCAT)	Competency	Academic	Giel and Issa, 2014
i-BIM Maturity Model (Level 0-3)	Maturity	Academic	Bew and Richards, 2008
Capability Maturity Model Integration for Development (CMMI-DEV)	Maturity	Industry	SEI (2006)
Lean Enterprise Self-Assessment Tool	Maturity	Academic	Nightingale and Mize, 2002
BIM Quick Scan	Performance	Industry	Sebastian and Berlo, 2010

Portfolio, Programme and Project Management Maturity Model (P3M3)	Performance	Academic	OGC, 2008
BIM Assessment Profile	Competency	Industry	CIC, 2012
BIM Cloud Score (BIMCS)	Performance	Academic	Du et al, 2014
Construction Supply Chain Maturity Model (CSCMM)	Performance	Academic	Vaidyanathan and Howell, 2007
VDC Scorecard	Performance	Academic	Kam et al, 2014
Owner's BIMCAT	Competency	Academic	Azzouze et al, 2015
BIM Characterization Framework	Maturity	Academic	Gao, 2011
BIM Maturity Matrix	Maturity	Academic	Succar, 2010
Five Performance Metrics for BIM	Performance	Academic	Succar et al, 2012
Knowledge Retention Maturity Levels	Competency	Academic	Arif et al., 2009
Interorganizational BIM	Performance	Academic	Fox and Hietanen, 2007
Total BIM Measurement and Management Methodologies		**36**	

Summarizing on Table 4 above, Figures 3 and 4 which follow highlight the percentage share of existing measurement and management methodologies, as well as a graphical representation of their dominance of focus and developed areas.

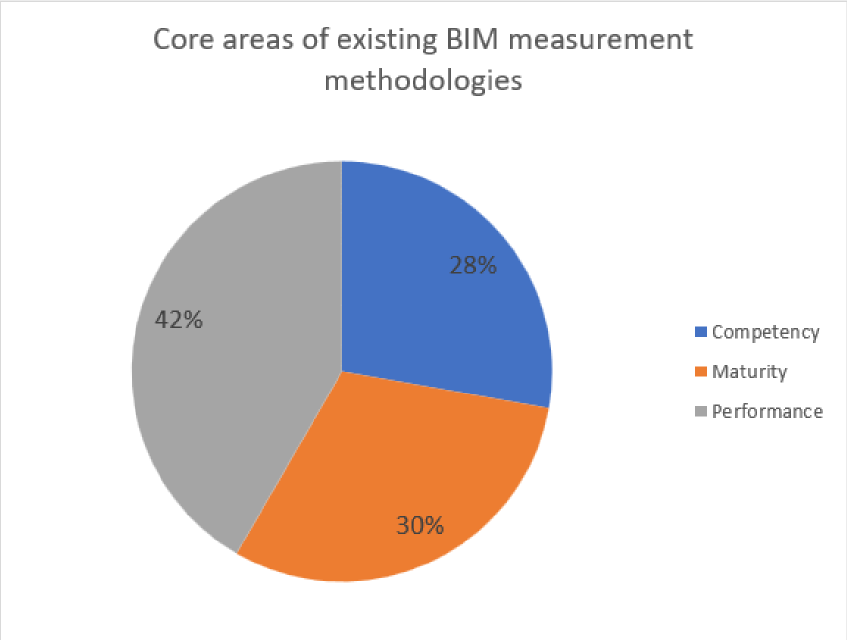

Figure 3: Existing BIM measurement and management focus

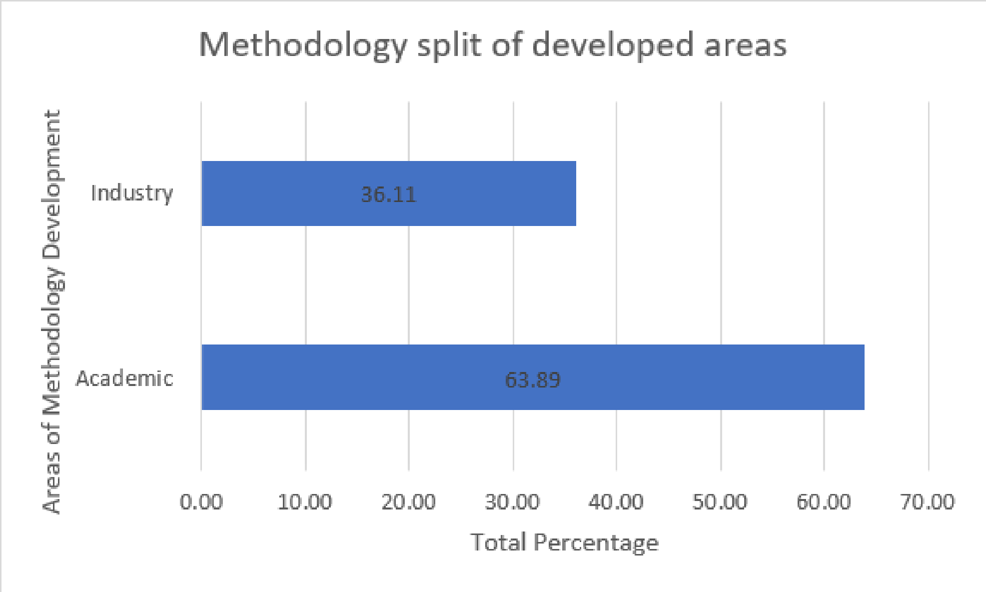

Figure 4: Analysis of dominant development areas

4. DEVELOPMENT POST ANALYSIS

Following analysis of the focus group feedback in response to the semi-structured questionnaire alongside a thematic literature review of existing academic and industry measurement and management methodologies to support the delivery of collaborative BIM, a novel methodology has been produced in Table 5 below, provided by the gaps, opportunities, limitations, and inefficiencies that the existing methodologies present and of course inhibit. This newly developed system advancing on from core findings from the existing underpinning literature focus along extrapolation of data provided through the mixed method survey collection technique focuses on both qualitative and quantitative application and reasoning from user input towards achieving specific BIM goals and objectives and risk mitigation.

Table 5: Developed measurement and management methodology proforma

Confidence, Complexity, and Impact (CCI) Measurement and Management Framework				**Total Sum**
Focal Point (objective)	Confidence (in being able to deliver the task)	Complexity (of the task/goal)	Impact (on wider objectives if not achieved)	
A	1=high 2=medium 3=low	1=non-complex 2=complex 3=highly complex	1=low 2=medium 3=high	C + C+ I
B	1=high 2=medium 3=low	1=non-complex 2=complex 3=highly complex	1=low 2=medium 3=high	C + C+ I
C	1=high 2=medium 3=low	1=non-complex 2=complex 3=highly complex	1=low 2=medium 3=high	C + C+ I
Risk Factor (from total sum above)				
Low	1-3			

Medium*	4-6
High*	7-9
What (needs to be undertaken or utilized to improve the likelihood of success?)	
A	
B	
C	
Who (needs to support the task for effective delivery?)	
A	
B	
C	
When (will this start, be re-evaluated i.e., monthly, and finish?)	
A	
B	
C	
***Mitigations (if risks are 'medium' and/or 'high')**	
A	
B	
C	

Mathematically, the formula for calculating each sum for the Confidence, Complexity, and Impact (CCI) factor as defined by each practitioner or team for their particular focal point(s) is shown below.

$$\sum_{i=1}^{3} a_1 + a_2 + a_3$$

Where each element is:

a_1= Confidence factor

a_2= Complexity factor

a_3= Impact factor

5. CONCLUSION

This research study was designed to expose the existing measurement and management methodologies that support collaborative BIM via a systematic and thematic literature review of academic and industrial literature, as well and alongside the inclusion of a BIM focus group inclusive of 15 academic and industry experts. Findings show that although there are 36 dominant and available measurement methodologies, they are primarily attentive to three core areas of focus: performance (42%), maturity (30%) and competency (28%). Additionally, existing methods are heavily focused on high-level compliance with standards (such as ISO19650) and aim to confirm the ability of a project or person to be able to deliver performance to said standards and/or protocols. The development of an alternative measurement approach as defined as part of this research is intended to be implemented across a broad range of diverse stakeholders throughout various stages of the BIM lifecycle of a project, and thus unrestrictive and adaptable. Moreover, a three pillar approach of confidence, complexity and impact (CCI) has been developed in light of these findings, allowing objectively focused outcomes to be assigned quantitative and qualitative values in a simplified manner and measured in a progressive form, complimented by risk management and mitigation fields which can be defined, populated, remeasured and even used as escalation mediums to increase the likelihood of BIM goal attainment, seek continual improvement and benefit from risk reduction in achieving successful collaborative BIM outcomes.

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AUTOMATED DETECTION OF LEARNING STAGES AND INTERACTION DIFFICULTY FROM EYE-TRACKING DATA WITHIN MIXED REALITY LEARNING ENVIRONMENT

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ABSTRACT: *The fourth industrial revolution promises to usher the construction industry into an era of reduced waste, augmented productivity, and improved quality through the adoption of innovations and sensing technologies such as laser scanners. This trend has prompted additional demand for competent workforce for deploying such technologies in the construction industry. However, as access to the jobsite continues to be an issue in construction education, equipping the future workforce with the required experiential skills becomes challenging. To match the skill demand in the industry, the authors explored the potentials of virtual environments such as mixed reality as an alternative learning environment for laser scanning. However, to promote seamless learning, the mixed reality learning environment must be proactive and intelligent, which can be achieved via integrated automated classification models. Hence, the study explored the use of eye-tracking and think-aloud data to demonstrate the potentials of machine learning for detecting learning stages and interaction difficulties from eye-tracking data during the usability study of laser scanning in the mixed reality environment. The study adopted multiple machine learning classifiers on fixation durations, fixation positions, fixation distance, and fixation start time from eye-tracking data. The classification models demonstrated high performance, with Neural Network classifier showing the superior performance (accuracy of 99.9%) during the detection of learning stages, and Ensemble showing the highest accuracy of 84.6% for detecting interaction difficulty during laser scanning in the mixed reality learning environment. The findings revealed that eye movement data possess significant information about learning stages and interaction difficulties. The classification models will help detect users who require additional support to acquire the necessary technical skills for deploying laser scanners in the construction industry and inform the specific training needs of users to enhance seamless interaction with the learning environment.*

KEYWORDS: *Learning stages, Interaction difficulty, Eye-tracking, Usability study, Supervised learning.*

1. INTRODUCTION

As the construction industry continues to advance technically, there is a high rate of adoption of sensing technologies such as laser scanners, cameras, and radiofrequency identification devices (Ogunseiju et al., 2021b). Compared to other sensing technologies, laser scanners are one of the most adopted, but institutions are lagging behind in equipping students with the technical capabilities of laser scanning (Ogunseiju et al., 2021b). This could be due to limited access to the construction site for hands-on learning, the high up-front cost of these technologies, and unformalized competencies. One way to address this is by adopting alternative and captivating learning environments such as mixed reality (MR), where students can perform hands-on implementation of laser scanners for authentic and constructive learning experiences (Yusoff et al., 2010) without exposure to jobsite hazards.

In a previous paper, the authors (Ogunseiju et al., 2021a) presented an MR environment for learning sensing technologies, with an example of laser scanning. However, to implement such learning environment as a pedagogical tool in construction education, a usability study was conducted. The usability study employed eye-tracking and think-aloud protocol as measures of evaluating the quality of the learning experience in the environment. This is because learning is usually informed by the perception of stimuli and information in the environment (Andrzejewska and Stolińska, 2016). While the think-aloud protocol provides immediate feedback on the environment, learning and cognitive activities can often be inferred by exploring learners' eye-tracking data (Andrzejewska and Stolińska, 2016). Since learning can vary based on individual needs and abilities (Toker et al., 2014), detecting cognitive stages, and human-computer interactions can provide opportunities for designing dynamic and intelligent virtual learning environments in construction. However, eye-tracking data is highly multi-dimensional, and manual comparison of different eye metrics can be computationally expensive, and time-consuming. For instance, Lee et al. (2019) explained that while it is visually possible to assess scanpaths for two images, it becomes more challenging to compare multiple scanpaths. Zemblys et al. (2018) explained event detection from eye-tracking data as challenging when conducted manually. Hence, advanced techniques such as machine learning are required to further provide deep insights from eye gaze patterns.

In this paper, we present machine learning models that employ eye-tracking data for detecting learning stages and users' interaction difficulty during laser scanning activities in a mixed reality environment. The findings revealed that eye movement data possess significant information about learning stages and interaction difficulties. The classification models will help detect users who require additional support to acquire the necessary technical skills for deploying laser scanners in the construction industry and inform the specific training needs of users to enhance seamless interaction with the learning environment.

2. BACKGROUND

This section presents a review of MR environments in education and eye-tracking as a usability measure of virtual environments. This section also provides a review of machine learning for providing insights into eye-tracking data.

2.1 MR/AR Environments in Construction Education

MR and AR environments have been widely adopted in the construction industry for enhancing safety (Moore and Gheisari, 2019), facility management (Ensafi et al., 2021), and design communications (Chalhoub and Ayer, 2018). Likewise in construction education, MR has been employed as a learning environment for simulating construction activities in the classroom. For example, Shanbari et al. (2016) employed MR to project environmental contents and constraints of construction processes. The study revealed the efficacy of MR in improving the memorability of roofing and masonry work. Bosché et al. (2016) presented the potentials of MR for simulating difficult construction conditions such as work-at-height. With an example of a wood framing lab, Wu et al. (2018) presented the potentials of MR for acquiring tacit knowledge and revealed its efficacy for design comprehension and for technical skills acquisition for building wood-frame structures. Despite the opportunities of MR environments in construction education, reports for acquiring hands-on experiences of currently adopted technologies are scarce. As such, the authors in a previous paper (Ogunseiju et al., 2021a), presented the potentials of an MR environment for learning different sensing technologies currently adopted in the industry. It is also imperative to conduct a usability test for evaluating its capability to enable users to achieve specified goals with effectiveness, productivity, and satisfaction.

2.2 Eye-tracking for Usability Studies

Several measures such as usability questionnaires, think-aloud protocol, and eye-tracking are often used for procuring data during usability studies. While usability questionnaires and think-aloud protocol often provide subjective data, eye tracking is often employed for assessing usability evaluations of virtual environments and user interfaces involving cognitive activities and human-computer interactions. For example, visual attention from eye-tracking was used to analyze end-user's satisfaction with construction design (Mohammadpour et al., 2015). Similarly, eye-tracking data revealed users' preferences and performance during engineering design reviews (Satter and Butler, 2015). Eye movement data such as fixations have also been explored for inferring cognitive processes during steel installation in an AR learning environment (Wang et al., 2018). In construction safety, Ye and König (2019) employed eye-tracking data such as scan path and heatmaps for hazard identification in a virtual environment. However, inferring high-level cognitive activities and interaction difficulties is imperative for reducing cognitive load and designing intelligent and dynamic virtual learning environments in construction education, and this has not been explored in these studies.

2.3 Machine Learning for Understanding Eye-Tracking Data

Machine learning has been effective in detecting users' cognitive states, performance levels, and learning stages from eye-tracking data. For example, Eivazi and Bednarik (2011) employed machine learning techniques on eye-tracking features and labeled high-level behaviors to predict cognitive states for intelligent user interfaces. By assessing think-aloud protocol data, five cognitive states: cognition and evaluation, intention, planning, and concurrent move were classified (Eivazi and Bednarik, 2011). The study revealed that while cognition was difficult to predict, the performance level of participants during the cognitive activity was predicted more accurately. By assessing eye-tracking data, Toker et al. (2014) employed machine learning techniques for predicting users' learning phase during a visualization task. Users repeated experimental tasks twice, and the model was trained to predict the 'before skill acquisition' phase (first trial) and 'after skill acquisition' phase (second trial) owning to a statistical difference in the task completion time during both trials. Likewise, Conati et al. (2020) predicted users' cognitive abilities using eye-tracking and users' interaction data. Notably, fixation was the common eye-tracking metrics adopted in the reviewed studies, although the adopted machine learning classifiers varied. For example, Eivazi and Bednarik (2011) adopted Support Vector Machine (SVM), Toker et al. (2014) adopted Logistic regression (LR), and Conati et al. (2020) adopted Boosted LR and Random Forest (RF) for developing their classification models. In the same vein, Lagun et al. (2011) employed both LR and SVM for detecting cognitive impairments during behavioral tests, and Salminen et al. (2019) adopted Neural Network (NN) and RF for inferring users' confusion levels from eye-tracking data. However, the main obstacle to exploring machine learning for eye-tracking data is getting the appropriate data inputs and machine learning methods (Bednarik et al., 2012, Eivazi and Bednarik, 2011). To this end, literature was reviewed to investigate eye-tracking features and user-level data commonly adopted for machine learning systems. Conati et al. (2020) explored only fixations for training their classification model, which generated a high accuracy. However, the more the eye-tracking data inputs, the better the classification's performance. For example, Lagun et al. (2011) reported an increased classification performance when all eye-tracking data was employed for training the classifiers than when the baseline feature (Novelty preference) was used. However, different eye-tracking data inputs such as fixation duration, and fixation start time often possess different underlying information and should be selected based on the embedded cognitive information and impacts on improving classification performance during machine learning. For example, fixation duration has been revealed to carry significant information and insights to usability studies. Goldberg and Helfman (2010) explained that longer fixation duration may infer confusion of the perceived information. Similarly, fixation duration increases as the mental effort and information processing for a task increases or becomes more demanding (Shojaeizadeh et al., 2019, He and McCarley, 2010). Also, fixation positions can also reveal cognitive processes in the mind, and indicate users' task. Since learning was performed in two different scenes, fixation positions can provide more insights for the classification model. The fixation distance provides further validation of the fixation positions as this is computed as the Euclidian distance of the fixation positions. In addition, fixation start time creates a continuous time sequence that could better improve the classifier's performance. Salminen et al. (2019) revealed that data inputs creating sequence and connections with preceding data can improve the performance of classification models. Hence, to achieve a robust training dataset, this study employed fixation duration, fixation start time and fixation positions, and fixation distance (Table 1).

2.4 Theoretical Framework

The development of the holographic scenes was guided by the cognitive apprenticeship theory. The theory posits that cognitive development happens when learners' previous knowledge is enhanced through the reification of cognitive activities (Hennessy, 1993). Collins et al. (2018) explains that learning can be enhanced through modeling, scaffolding, coaching, fading, articulation, and reflection on their problem-solving skills. Hennessy (1993) further explained that in a classroom setting where cognitive apprenticeship is adopted, students seek help from adults or other more knowledgeable peers, but with the advent of digital learning environment, scaffolding can be achieved via guided participation in social activity. In particular, '*Scaffolding refers to the help which thereby enables learners to engage more successfully in activity at the expanding limits of their competence, and which they would not have been quite able to manage alone, i.e. within the 'zone of proximal development'* (Vygotsky, 1980). The zone of proximal development often referred to as ZPD is the distance between the "potential level of development" (determined by the tasks that can be solved with 'help') and the "actual level of development" (which can be determined by the tasks solved independently) (Veresov, 2004). Guided by this theory, and to ensure knowledge is scaffolded, the learning environment was developed as three learning scenes: (1) explore jobsite scene, (2) sensor tutorial scene, and (3) sensor implementation scene. The explore jobsite scene provides a learning platform for situating students in their domain. Students can explore different construction activities and identify the risks and construction resources for these activities, and selectively explore tasks, operations, resources involved and workspaces. After interaction with the explore jobsite scene, students can proceed to the sensor tutorial scene. It is assumed that at this stage (sensor tutorial scene), students are at the level of potential development of skills for implementing sensing technologies on construction projects. According to Lunsford (2017), Vygotsky posits that students often possess the inherent ability to learn which can be fostered through assistance and learning strategies.

Hence, 'help' was provided via learning in a less-congested environment (that is exclusion of other construction activities irrelevant to the learning-in-progress), and a guided interface that outlines the required steps for accomplishing the cognitive tasks (Fig. 1a). After interacting with the sensing technologies in the sensor tutorial scene, students can proceed to the sensor implementation scene where similar cognitive tasks for each sensing technology can be performed without the 'help' in the Sensor tutorial scene (Fig. 1b). The authors posited that at this stage (sensor implementation scene), students are at the stage of actual development of technical skills for implementing laser scanning on construction projects.

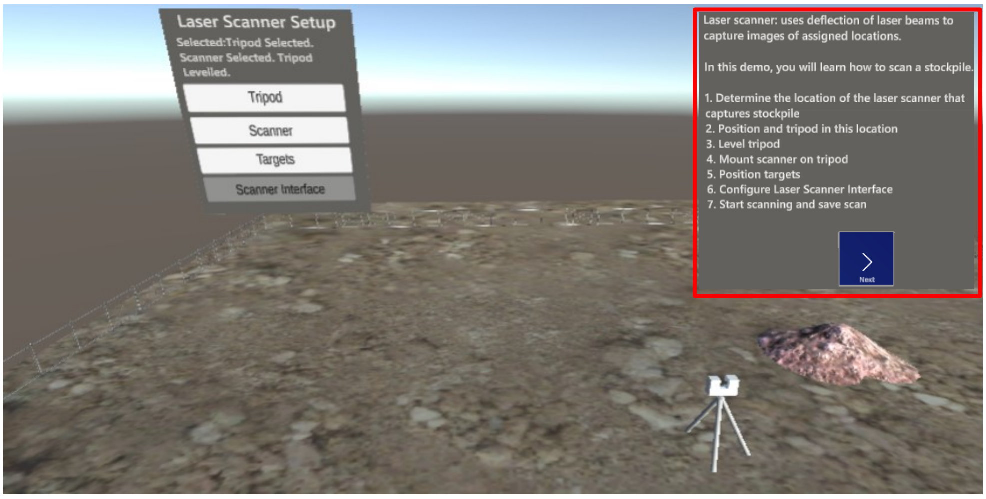

Fig. 1a: Sensor tutorial scene.

Fig. 1b: Sensor Implementation scene.

Fig. 1: Sensor tutorial and sensor implementation learning scenes.

2.5 Research Gaps

Despite the opportunities offered by machine learning, eye tracking data from usability studies in construction education are still often analyzed manually which might become time-consuming especially when multiple eye-tracking data must be compared. Machine learning helps computers learn and understand patterns, and make predictions from multi-dimensional data without explicit programming (Simon, 2013, Lee et al., 2019). Also, machine learning can extract relevant relationships between eye movements and human cognition for inferring deep insights such as cognitive stages and interaction difficulties with a virtual learning environment. Based on the significance of the sensor tutorial and sensor implementation scenes, and the distinct design features in each scene, this study presents the utilization of machine learning to automatically learn features from eye-tracking data for predicting when learners are in potential development and actual development stages and predicting interaction difficulties in the learning environment.

3. MATERIALS AND METHODS

This section details the adopted methodology in this study. As outlined in Fig. 2, data collection was performed during the usability evaluation of an MR environment for learning laser scanning. During the experimental tasks, eye-tracking data were collected through the embedded eye tracker in the AR head-mounted device (HMD), and a think-aloud protocol was employed to procure immediate feedback on the interaction difficulties in the learning environment. The eye-tracking data and think-aloud protocol were then analyzed and utilized for developing the classification models.

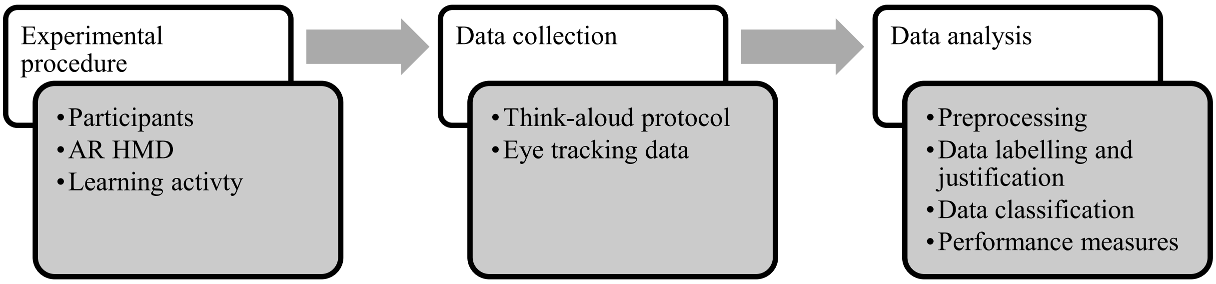

Fig. 2: Methodology overview.

3.1 Experiment Procedure

3.1.1 Participants

Participants of the usability study were 18 students (15 males and 3 females) of Virginia Tech with an average age and standard deviation of 28years (± 7). Based on the objective of the learning environment, only participants with construction backgrounds were recruited for the study. The participants were required to sign two consent forms before proceeding with the experimental tasks: one pertaining to in-person research during COVID-19, and the other entails consent to participate in the study. Participants were then introduced to the AR HMD and briefed on the experimental tasks.

3.1.2 AR-HMD

The AR HMD adopted for this study was the HoloLens 2, which is a see-through device that allows natural communication between users, by overlaying the virtual environment on the real world. The HoloLens 2 displays on a field of view of 52 degrees, a resolution of 47 pixels per degree at the rate of 60 frames per second. The device also has an embedded eye-tracker, which was leveraged for the study.

3.1.3 Learning environment and activity

After collecting the consent forms, participants were immersed in the learning environment through the AR-HMD. All participants were required to calibrate their eye-gaze for procuring accurate eye movement data. The experimental activity entailed the performance of similar laser scanning tasks in the “sensor tutorial” and “sensor implementation” scenes. The laser scanner in the learning environment was modeled after Faro Focus M70 and Trimble X8. Guided by the menu interface, the laser scanning activity entails basic steps of the laser scanning activity for taking scans of a stockpile in the simulated construction site. The ‘laser scanner setup’ menu interface (Fig. 3a) provides a sequential guide for setting up the laser scanner components, while the ‘laser scanner interface’ provides a sequential guide for interacting with the settings of the laser scanner.

Hence, guided by the ‘laser scanner setup’, participants were required to interact with the laser scanner components (tripod, scanner, and targets 1, 2, and 3) such as positioning and leveling tripod (Fig. 3a), mounting scanner on the tripod, and positioning targets in the desired location (Fig. 3b). The targets are an important aspect of laser scanning as they allow for stitching of two or more scans. After interacting with the laser scanner components, participants were required to set up the scan settings (such as scan coverage, resolution, quality, color, and profile) by interacting with the ‘scanner interface’ menu (Fig. 3c). For example, on selecting the coverage button, the participants could set up the required scan coverage (Fig. 3d) by interacting with the horizontal and vertical sliders. To provide an engaging learning experience, the selected coverage was visualized as a ‘red light beam’ (see Fig.

3d). This guided their knowledge of the extent of the selected scan coverage.

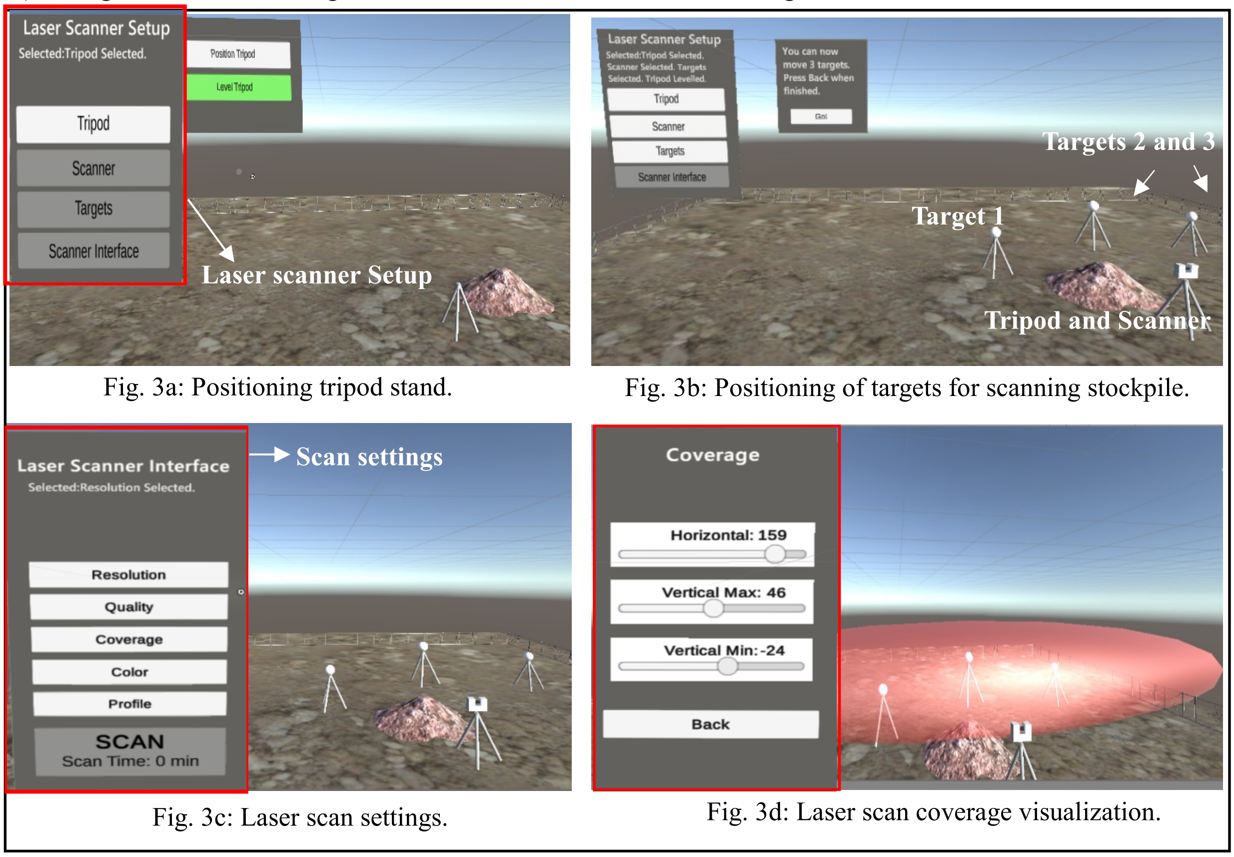

Fig. 3a: Positioning tripod stand.
Fig. 3b: Positioning of targets for scanning stockpile.
Fig. 3c: Laser scan settings.
Fig. 3d: Laser scan coverage visualization.

Fig. 3: Illustration of laser scanning activity.

3.2 Data Collection

During the experimental procedure, eye-tracking data was procured to investigate the cognitive activities while the think-aloud protocol provided immediate feedback on the interaction difficulty during the experiment. To validate the data from the think-aloud protocol, 'HoloLens capture' was employed to video-record the interactions with the learning environment. The data collection procedure is described further in the subsequent sections.

3.2.1 Think-aloud protocol

The study adopted a think-aloud protocol during the experimental procedure to procure immediate feedback on the interaction difficulty during the laser scanning activities. During the think-aloud protocol, participants were asked if they experienced difficulties while interacting with the environment. This question prompted further responses and comments on their interaction difficulty with the laser scanner components, which were audio recorded. For example, when conducting laser scanning of a stockpile, participants were required to pick up and move laser scanner components like the tripod stand and targets to their desired location. During this process, some participants had trouble interacting with the laser scanner components, while others did not. The responses and comments served as classification labels for the interaction difficulty in the learning environment.

3.2.2 Eye-tracking data

The eye-tracking data from HoloLens 2 provides eye daze duration, eye origins and hit positions, head origins and positions at 30 frames per seconds. Fixation duration for each participant during the "sensor tutorial" and "sensor implementation" scenes were extracted from the eye tracking data based on a minimum duration of 75ms. However, eye tracking data for a participant was incomplete and hence excluded from the study.

3.3 Data Analysis

3.3.1 Preprocessing

Think-aloud protocol: The think-aloud protocol was analyzed using thematic coding and validated with video analysis to extract participants who had difficulty interacting with the laser scanner components in the learning environment. Two researchers judged the coding, and an interrater reliability test was performed using Cohen Kappa. The inter-rater agreement between the judges was good (Cohen's Kappa = 0.7).

Eye-tracking: The total task completion time during both scenes was extracted from the eye-tracking data and statistically analyzed using one-way ANOVA. Based on the significance of the fixations for developing machine learning systems, the study adopted fixation duration, fixation positions, fixation distance, and fixation start time (Table 1). While the other data inputs were extracted from the eye gaze data, the fixation distance was computed as the Euclidian distance of the fixation positions (Equation 1).

$$\text{Euclidian distance} = \sqrt{x^2 + y^2 + z^2} \qquad \text{(Equation 1)}$$

Table 1: Data Inputs and their description.

Data Inputs	Description
Fixation duration	Fixation time measured in milliseconds (ms)
Fixation positions	The coordinates (X, Y, and Z) where the fixations focused
Fixation distance	Euclidian distance of the fixation positions
Fixation Start Time	Fixation start time (ms) measured from the beginning of the experiment

3.3.2 Data labeling and justification

Learning stages: Recall that the sensor tutorial scene was posited as the stage of potential development, and 'help' was provided to scaffold students learning in this scene. The sensor implementation scene on the other hand served as the actual development stage. A prior analysis of the usability data (based on ANOVA) revealed a significant effect (p = 0.002) of the learning scenes on task completion time (Fig. 4). This result demonstrates that users performed the cognitive tasks significantly faster when engaged in the sensor implementation scene. This was similar to the findings of Toker, Steichen [34] where trial order significantly affected task completion time. Hence, training data labels were provided based on the learning scenes. Eye-tracking data corresponding to sensor tutorial and sensor implementation scene were labeled as potential development (PD) and actual development (AD) respectively.

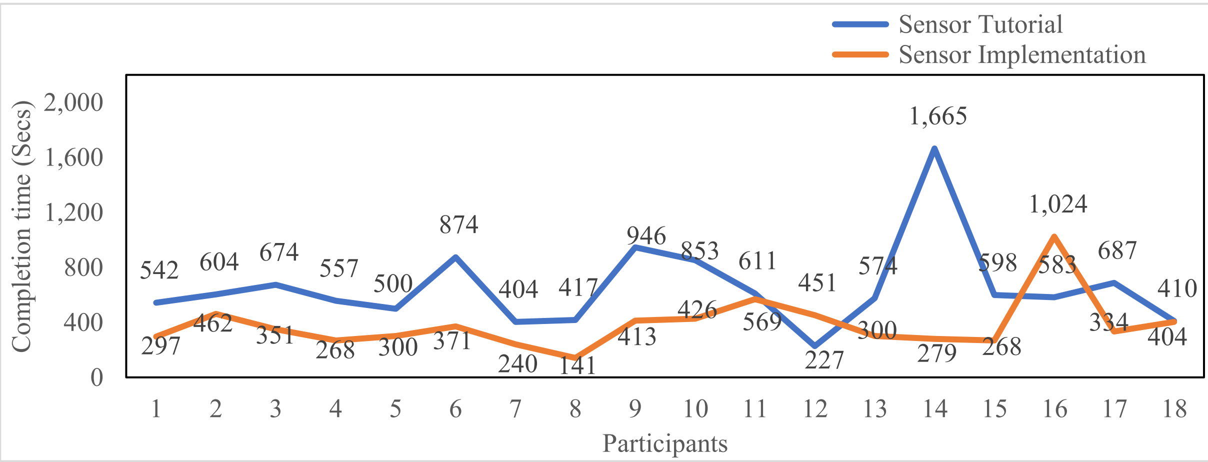

Fig. 4: Task completion time across both learning scenes.

Interaction difficulty: The input data for the machine learning training was labeled based on the think-aloud protocol data. Table 2 details the number of participants who experienced and did not experience difficulty interacting with the laser scanner components in both learning scenes. By adopting machine learning and eye tracking, a classification model that automatically identifies interaction difficulty can be developed. The training data can be labeled based on whether difficulty was expressed during the think-aloud protocol as explored in Salminen et al. (2019).

Table 2: Difficulty level of participants in both learning scenes.

Learning scenes	Difficulty	No Difficulty	Total
Sensor tutorial	3	14	17
Sensor Implementation	3	14	17
Total	6	28	34

3.3.3 Data classification

The classification model was trained on data from seventeen participants owning to missing fixation position data for a participant. The adopted machine learning classifiers varied for the reviewed papers, thus all the established classifiers for supervised learning were employed for training. The multiple algorithms employed in this study includes K-nearest neighbor (KNN), Support Vector Machine (SVM), Neural network (NN), Ensemble, Naïve Bayes, Decision Tree, Logistic Regression, and Kernel (Li et al., 2020). It is observed from this study that NN, KNN, SVM and Ensemble were the top classifiers to understand the learning of the end users. (Witten et al., 2005) provides an in depth explanation of the employed classifiers. Once trained five-fold cross-validation was employed for testing the trained model since the sample dataset is small. Cross-validation is an iterative subset splitting that creates data inputs for training and testing exclusively (Mierswa et al., 2006, Bednarik et al., 2012). Hence, the training dataset was divided into five parts. In each cross-validation iteration, some data were used for training, and unseen dataset was used to validate (test the performance) the classification. For training the model, data features were extracted from the input data (fixation duration, fixation distance, fixation position, and fixation start time). Common statistical data features were chosen to be extracted, which included the mean, median, mode, standard deviation, maximum, minimum and sum to capture the attributes of the input data (Eivazi and Bednarik, 2011, Conati et al., 2020, Toker et al., 2014, Li et al., 2020). As a result, a total of 42 features was used for training the classifiers.

3.3.4 Performance measures

To evaluate the performance of the classifiers, accuracy, sensitivity (recall), and specificity (precision) (Chatterjee et al., 2011) were employed as performance measures. The sensitivity of the model was measured by examining the rate of true positives, while the specificity revealed the rate of true negatives of the model. The harmonic mean of the model's sensitivity and specificity were evaluated using the F1 score. When the dataset is unbalanced, the accuracy of the classifier may be misleading when adopted as the only performance measure (Egan and Egan, 1975, Bednarik et al., 2012). Hence as adopted by several studies (Egan and Egan, 1975, Bednarik et al., 2012), the Area Under ROC Curve was employed as an additional classifier evaluation in addition to accuracy, specificity, sensitivity and F1 score. The more the area under the curve, the lesser is the impact of the unbalanced distribution of the class labels in the classifier (Bednarik et al., 2012).

4. RESULTS

The supervised recognition from the previous section was executed using MATLAB and implemented on a server equipped with a 4.6 GHz Intel(R) Core(TM) i7 9700K CPU, an NVIDIA(R) GeForce RTX(TM) 2080 GPU, and 64 GB RAM. This section focuses on the results of the study, wherein the confusion matrix for the top classifier is explained and the performance of the top three classifiers are compared using the afore-discussed performance measures (Table 3).

4.1 Performance Evaluation of Learning Stages Classification Model

The classification algorithm for the development stages performed very well, with the highest accuracy being 99.09% for Neural Network. Whereas the accuracy for models succeeding is 99.70% for KNN and SVM. A total of 14040 data samples were employed in the study. As shown in Fig. 5, the confusion matrix for the top classifier successfully classified 8350 of the sample data as actual development and 5680 as potential development. Only 10 misclassified data samples were wrongly predicted as potential development. The model registered a very high specificity for actual development, which is 1 whereas for potential development (PD) it is 0.998. The model's sensitivity for actual development is 0.999 whereas for potential development it is 1. This is reflected in the F1 score, which is 0.999 for both the stages. Also, the area under the curve further supports the high performance of the NN with a high value of 1. The area under the curve is consistent for all the top three classifiers showcasing high performance. The specificity, sensitivity and F1 score of KNN and SVM for both learning stages are similar but lesser than those of NN.

Table 3: Performance measures of classification models

Classifications	Classifier		Accuracy	Specificity	Sensitivity	F1 score	AUC
Learning Stage	Neural Network (NN)	Actual Development	99.90%	1	0.999	0.999	1.00
		Potential Development		0.998	1	0.999	1.00
	K nearest neighbor (KNN)	Actual Development	99.70%	1	0.995	0.997	1.00
		Potential Development		0.993	1	0.996	1.00
	SVM	Actual Development	99.70%	1	0.995	0.997	1.00
		Potential Development		0.993	1	0.996	1.00
Difficulty Level	Ensemble	Difficulty	84.60%	0.848	0.530	0.652	0.87
		No Difficulty		0.845	0.965	0.901	0.87
	KNN	Difficulty	83.80%	0.800	0.541	0.645	0.87
		No Difficulty		0.846	0.949	0.895	0.87
	NN	Difficulty	81.40%	0.625	0.684	0.653	0.80
		No Difficulty		0.879	0.863	0.871	0.80

4.2 Performance Evaluation of Difficulty Levels Classification Model

For the difficulty level, the performance of the classification models was high with the highest accuracy of 84.60% for Ensemble classifier which is followed by KNN and NN with 83.80% and 81.40% respectively. The difficulty level training was carried out with 13560 data samples. The confusion matrix (Fig. 5) showcases that the Ensemble model correctly classified 1960 and 9510 of the data samples as Difficulty (D) and No Difficulty (ND) respectively. In addition, 350 and 1740 of the data samples were misclassified as D and ND respectively.

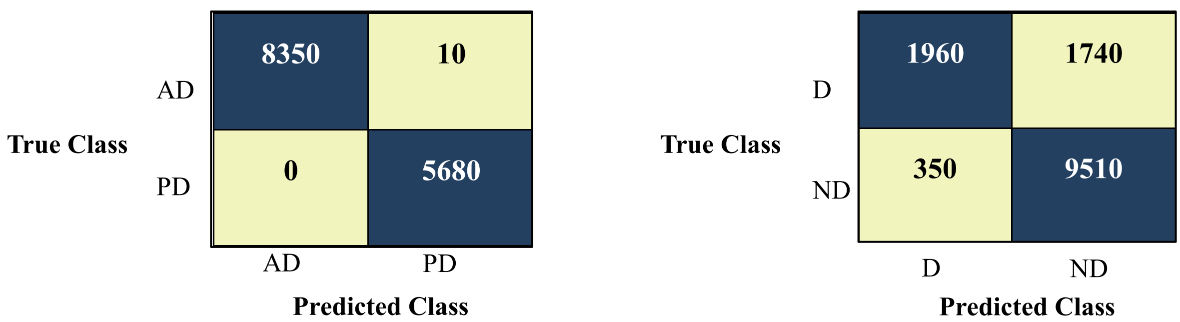

Fig. 5: Confusion matrix of the classification models.

This could be due to the unbalanced nature of the dataset wherein ND samples were more than D samples, however the classifier performed well. This is further supported by the high specificity of Ensemble for D (0.848) which is the highest amongst the top three classifiers. Even though the specificity for ND was lowest for Ensemble (0.845), the sensitivity was the highest (0.965) followed by KNN (0.949) and NN (0.863). The F1 score for 0.901 (Ensemble) for ND which is the highest demonstrates a high harmonic mean, whereas for D, it was 0.652 which was right after NN (0.653). Furthermore, a high value (0.87) of Ensemble for the area under the curve exhibits good performance of the classifier, which is also the greater compared to NN (0.80). Overall, the performance of the model was better for D than ND as evident from the F1 score of three classifiers, which could also be attributed to the unbalanced data set.

5. DISCUSSION

With the promises of MR environments for construction education, there is a need to explore the efficacy of designing an intelligent MR learning environment that can automatically detect learning stages and human-computer interactions. As a first step, a comprehensive review of literature was conducted to assess the potentials of eye-tracking data and machine learning techniques for designing effective classification models. Hence, this study adopts a supervised machine learning approach to detect learning stages and users' interaction difficulty from eye-tracking data during laser scanning activities in a mixed reality environment. The performance of the top three classifiers for both classification models was presented. The results revealed that the eye-tracking data was effective in detecting learning stages with the adopted classification algorithms (Table 3). The NN classifier showed superior performance with an accuracy of 99.9%. This was closely followed by KNN and SVM (99.7%), which have been revealed as effective for detecting classes from eye-tracking data (Zhu et al., 2020).

However, the classification model for detecting interaction difficulties performed lesser with the Ensemble classifier revealing the highest accuracy (84.6%). Similar to the study of Salminen et al. (2019) and Eivazi and Bednarik (2011), the results confirm the efficacy of think-aloud protocol beyond qualitative analysis and highlight its effectiveness as input for detecting interaction difficulties in an MR learning environment. While the model was effective in predicting participants with no interaction difficulties, the performance was low for classifying participants with interaction difficulty, which can be due to the unbalanced dataset for this model. The AUC reveals the expected performance of each class and has a statistical equivalent to Wilconxon test of ranks for ranking classification models (Hand, 1997, Batista et al., 2004). As such, a classification model is effective when the AUC is greater than 0.9 (Li et al., 2020). Hence, despite the unbalanced dataset for predicting interaction difficulties, the classification models can be interpreted as effective in classifying the learning stages and difficulty levels.

6. CONCLUSIONS AND FUTURE WORKS

Mixed reality environments are currently being applauded for their efficacy in providing interactive and experiential learning experiences in construction education. But to achieve an effective learning environment, it is important to design intelligent systems for seamless learning experiences. With the efficacy of eye-tracking to provide instantaneous behavioral evidence of users' visual and cognitive processes, this study presents classification models that can reliably predict learning stages and interaction difficulties from users' eye movement data during laser scanning in an MR environment. Such classification models will help detect users who require additional support to acquire the necessary technical skills for deploying laser scanners in the construction industry and inform the specific training needs of users to enhance seamless interaction with the learning environment.

However, there are some limitations in this study that should be addressed. The dataset for detecting interaction difficulties was unbalanced, and as such impacted the performance of the model. Future works will explore data augmentation methods for providing a robust dataset for the classification model. Likewise, it is important to assess the data inputs with the highest impact on the classification model. For example, exploring the effects of only fixation duration for training the classifiers, and a combined effect of fixation durations and fixation positions. This will inform the choice of training data in the absence of a robust eye-tracking dataset.

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ACTIVITY RECOGNITION FROM TRUNK MUSCLE ACTIVATION FOR WEARABLE AND NON-WEARABLE ROBOT CONDITIONS

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ABSTRACT: *The physically demanding nature of construction work exposes workers to a variety of risks, which could affect their productivity, safety and health. Recognition of construction workers' activities is critical for performance and safety management. Previous studies have largely employed kinematic data, which are inadequate for inferring workforce safety and health risks. Advances in ergonomics research have provided evidence of relationships between activations in one of the trunk muscles, the erector spinae, and the movement of the hands. Given that human actions are largely performed with the hand, this relationship is yet to be explored for detecting construction workers' activities. This study presents the potential of automatically recognizing construction workers' actions from activations of the erector spinae muscles. A lab study was conducted wherein the participants (n=10) performed rebar task, which involved placing and tying subtasks, with and without a wearable robot (exoskeleton). The intent of studying both conditions is to understand if activity recognition models for workers without exoskeletons can be adapted to workers wearing exoskeletons. Muscle activations for both conditions were trained with nine well-established supervised machine learning algorithms. Hold-out validation was carried out and the performance of the models was evaluated using accuracy, precision, recall, and F1 score. Results show that the classification models performed well for both experimental conditions with Support Vector Machine having the highest accuracy of 83.8% for the exoskeleton condition and 74.1% for the 'without exoskeleton' condition. The performance of the classification model for the exoskeleton condition paves the way for the future of smart wearable robotic technology that can respond to the required muscle activations of the body during construction activities.*

KEYWORDS: *Activity recognition, Machine learning, EMG, Rebar task, Wearable robot.*

1. INTRODUCTION

Construction projects are labor-intensive, often involving tasks that are physically demanding and repetitive. As a result, construction workers suffer from low productivity and are exposed to safety and health risks (Sherafat et al., 2020). Automated recognition of workers' actions is increasingly recognized as one of the requirements for assessing these risks. Information obtained from the assessment improves the awareness of project stakeholders and enhances decision-making. Existing methods for automated recognition of workers' actions and activities can be categorized into vision and wearable sensor-based methods. Vision-based methods infer information about workers' activities from image or video data using computer vision techniques. Such data obtained from cameras, are sensitive to environmental factors and could be computationally expensive to analyze. Wearable sensor-based methods include kinematic (e.g., inertial measurement unit, gyroscopes, and accelerometers) and surface electromyography (sEMG) sensors. Previous studies have utilized inertial measurement units (IMU) and smartphones attached to the wrist, arm, waist, and thigh to capture acceleration and angular velocities of workers performing a variety of activities e.g., sawing, hammering, carpentry, bricklaying, and drilling (Akhavian and Behzadan, 2016, Joshua and Varghese, 2014, Joshua and Varghese, 2011, Antwi-Afari et al., 2020). These studies employed supervised and unsupervised machine learning techniques to recognize workers' actions from kinematic data. While good recognition accuracies has been achieved from kinematic data, their potential for also inferring safety and health risks is limited (Mudiyanselage et al., 2021, Nouredanesh and Tung, 2019, Bangaru et al., 2021, Diaz, 2020).

sEMG sensors measure the electrical activity of muscles, which can be used to understand movements and investigate triggers of health conditions e.g., muscle disorders and fatigue (Lariviere et al., 2002). Data from sEMG sensors attached to different body parts (e.g., hands, legs, and trunk) have also been used for recognizing activities (Wang et al., 2021, Young et al., 2014). A key motivation for utilizing sEMG data for activity recognition is that specific patterns of electromyographic activity are observed in the muscles when certain body parts are moved (Friedli et al., 1988, Hodges and Richardson, 1996, Zedka and Prochazka, 1997). These patterns have been found to correlate with the direction and extent of movement of the associated body part (Hodges et al., 1999). Sánchez-Zuriaga et al. (2009) provided evidence of activations in the erector spinae, one of the trunk muscles, resulting from repetitive movement of the hands. During tasks involving bending and lifting, the erector spinae muscles generate large extending activations to help raise materials and keep the upper body in an upright position (Dolan and Adams, 1993). Despite this evidence, there are few studies exploring the potential of sEMG sensors for classifying workers' actions and activities. Since the hand and arm are key body parts for performing construction tasks and that construction tasks involve significant bending and lifting, this study hypothesizes that when construction workers perform work, specific activation patterns are triggered in the erector spinae muscles, which can facilitate detection and classification of construction activities. However, the extent to which these patterns can be distinguished by machine learning algorithms in order to recognize workers' actions is unknown.

According to the United States Bureau of Labor and Statistics (BLS), the rate of non-fatal injuries (i.e. work-related musculoskeletal disorders) among construction workers is about twice the rate in other industries (BLS, 2020). This has triggered increasing awareness and interest in the adoption of wearable robots and postural assist devices (i.e. exoskeletons) for preventing work-related musculoskeletal disorders (WMSDs) amongst construction workers. Kim et al. (2019) reported that the use of an exoskeleton for construction work could improve workforce productivity and safety. In a more recent study, Antwi-Afari et al. (2021) assessed a passive exoskeleton during manual material handling tasks and reported reduced discomfort and muscle activity at the back and improved work performance. Ogunseiju et al. (2021) also investigated a postural assist exoskeleton for manual material handling tasks. The use of the wearable device reduced range of motion and discomfort at the back and also improved task performance. However, studies (Madinei et al., 2021, Gonsalves et al., 2021) have shown that exoskeletons have unintended consequences such as restricting movements. Workers would need to alter their regular work postures to perform work. This makes activity or action recognition models developed for workers without exoskeletons unsuitable for workers using exoskeletons. In other words, it is possible that the relationship between the activation patterns in the erector spinae muscles and the hand movements will differ for workers wearing and not wearing exoskeletons.

The objective of this research was to investigate automatic recognition of construction workers' activities from activations of the erector spinae muscles measured with a wearable sEMG. To achieve this, an experimental study was performed to collect activations of the erector spinae muscles during a simulated rebar task performed with and without a wearable robot. Rebar task is chosen given that it exposes workers to multiple ergonomic risk factors such as prolonged static and awkward posture (e.g., squatting and back bending), and repetitive movement. Thus, making rebar workers good candidates for exoskeleton use. Supervised machine learning is performed on the muscle activity data to recognize the subtasks involved in rebar work. The main contributions of this research are to: (1) propose an automated approach for recognizing construction workers' activities based on muscle activation data; and (2) determinate the extent to which activations of the erector spinae muscles can distinguish actions of workers performing construction work without and with wearable exoskeletons.

2. METHODOLOGY

The method adopted in this study is shown in Fig. 1. Muscle activity data was collected from participants performing simulated rebar tasks with and without an exoskeleton using a wearable sensor. Collected muscle activity data were segmented and several features were calculated. Each segment was labeled based on the corresponding rebar subtasks. Nine supervised machine learning classifiers were trained to detect and classify subtasks involved in rebar work performed in the laboratory. All data processing was performed using MS Office Excel 2021 and MATLAB Release 2021a (Matlab, The MathWorks Inc., MA, USA).

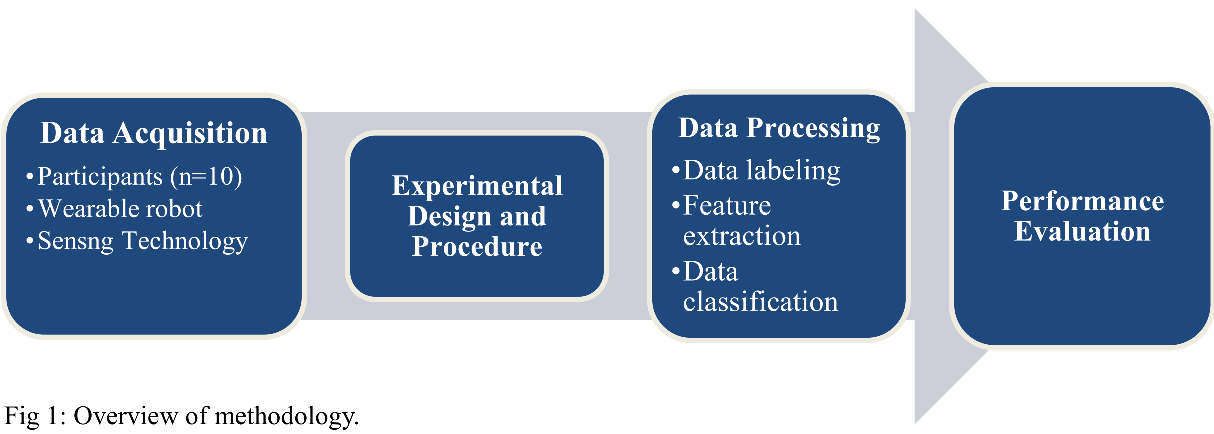


Fig 1: Overview of methodology.

2.1 Data Acquisition

2.1.1 Participants

The study adopted a convenience sample size of ten participants from Virginia Tech. All the participants were male with no prior experience of the task and signed the informed consent form approved by Virginia Tech Institutional Review Board (IRB). None of the participants reported any health issues or prior musculoskeletal disorders which could impact their task performance. The demographics of the students in mean and standard deviation is age = 23yrs ± 1.99, weight = 155.70 lbs. ± 22.51 and height = 173.40 cm ± 4.97.

2.1.2 Wearable robot

A passive back support exoskeleton, BackX™ S from SuitX industries (https://www.suitx.com/backX), was employed in this study. BackX is designed to reduce the stress from the workers' lower back during forward bending, squatting, lifting, and stooping tasks. The exoskeleton weighs 3.4 kg and comprises of a harness and a frame that provides up to 13.6 kg of support to the lower back. The harness consists of straps (shoulder, chest, and leg), a chest pad, and a hip belt whereas the frame has a chest plate, thigh pad, and a torque generator which acts as the actuation point for the exoskeleton. The frame connects with the harness via the hip support as shown in Fig. 2.

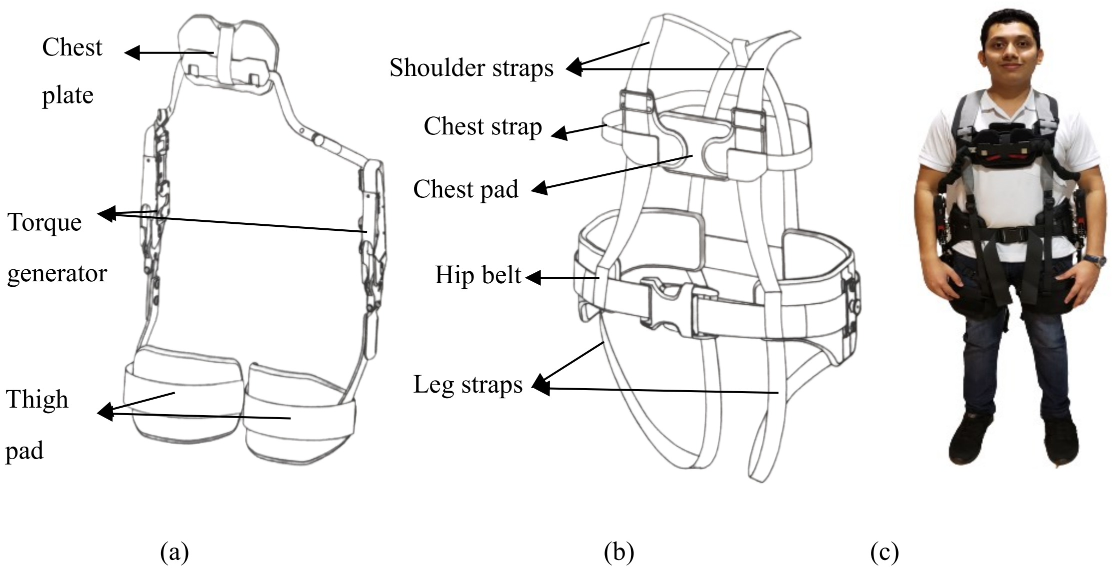


Fig. 2: BackX exoskeleton (a) frame (left), (b) harness (middle) and (c) complete exoskeleton (right).

2.1.3 Sensing technology

A wearable device called Cricket (Fig. 3a), developed by Somaxis Inc. (https://www.somaxis.com/), was used to collect EMG data from the erector spinae muscle group (i.e., left and right erector spinae muscles) (Fig. 3b). Cricket is a wearable device that consists of an EMG, electrocardiogram (EKG), electroencephalogram (EEG), and one 6-axis IMU sensor (3-axis for acceleration and 3-axis for gyroscope). The device weighs approximately 0.18 kg and contains a rechargeable lithium-ion battery, which according to the manufacturer, can last for 11 hours at continuous live-streaming at 1000 samples/sec (for EMG, EKG, and EEG data) and 30 samples/sec (for IMU data). The device is attached to the body using a disposable patch as shown in Fig. 3a. The patch also serves as an electrode that provides access to one channel of data from the sensors. The data from the EMG is transmitted in real-time to local or cloud storage via Bluetooth Low Energy (BLE) wireless connection and recorded by an application developed by Somaxis Inc. The Cricket device has been reported as having an acceptable accuracy when employed for other applications such as recreation (Boddy et al., 2018).

Fig 3: (a) Cricket wearable device (left); (b) Cricket devices on the left and right erector spinae muscles (right).

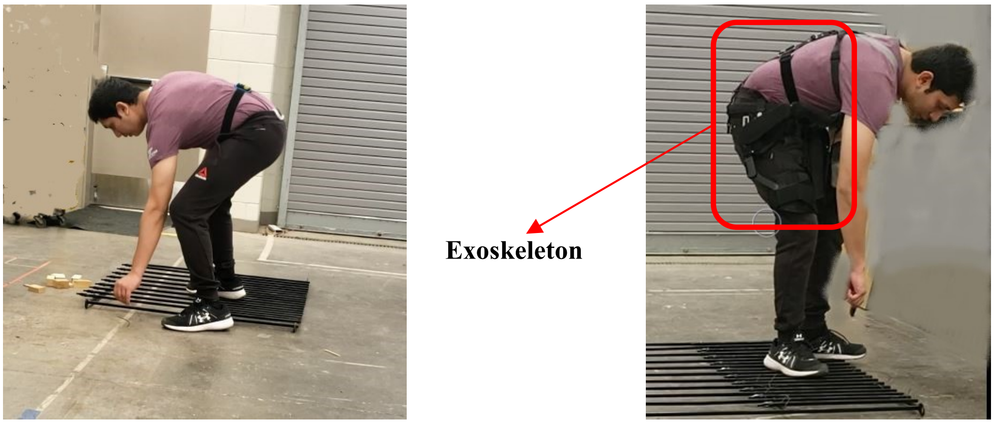


Fig. 4: Performing simulated rebar task: (a) NoExo condition; (b) Exo condition.

2.2 Experimental Design and Procedure

Post signing the informed consent, the rebar task was explained to the participants since they didn't have any prior experience and they were allowed to practice multiple cycles of the task. Once comfortable with the task, the Cricket devices were placed directly on each participant's skin bilaterally on the erector spinae muscle group by exercising the placement technique identified in Florimond (2009). Prior to placing the devices, each participant's skin was cleaned with alcohol to remove impurities. Thereafter the participants performed the rebar task without the exoskeleton (Fig. 4a) and were allowed to rest for 15 mins to avoid fatigue. Subsequently, the functioning of the exoskeleton was introduced to the participants. Once comfortable with the exoskeleton, the participants performed the rebar task using BackX (Fig. 4b). A prefabricated assembly was utilized to simulate the rebar task. The assembly comprises of #6 rebars placed at 127mm on center (both ways) with 600mm by 400mm cross-sectional dimension. Four cycles involving placing and tying subtasks were performed with and without the exoskeleton (i.e., Exo and NoExo conditions). For each cycle, the participants placed one prefabricated assembly on the ground during the placing subtask and subsequently they tied the joints using a plier and pre-cut ties. The participants were video recorded while performing the experimental tasks to identify the subtasks' durations.

2.3 Data Analysis

2.3.1 Data preparation and labeling

During the rebar task, the time-stamped raw EMG data was collected at a frequency of 500 Hz and extracted using the accompanying device. The timings of the placing and tying subtasks were identified by comparing the time-stamped EMG data with the recorded videos. Thereafter, the data was sorted into subtasks using a Python script and the non-productive data was discarded. The data for the placing and tying subtasks were separately combined for all the participants for both the left and right erector spinae muscles. The total number of data samples is 2,729,400 for the NoExo condition and 2,141,500 for the Exo condition. The raw EMG data was progressively filtered between 20-450 Hz with 4th order Butterworth band-pass filter (De Luca et al., 2010). The filtered data was subsequently transposed into rows, with each row having 100 columns. Once transposed, the data for the placing and tying subtasks were structured using concatenation and each row was labeled to correspond to the correct subtask. All the data extraction, structuring, and processing were performed using MS Office Excel 2021 and MATLAB Release 2021a.

2.3.2 Feature extraction

Feature extraction was performed to transfigure the raw input data into features that contain useful information about the data. Time-domain features were employed for the feature extraction. Time-domain features are widely used for classifying EMG data because the resulting classifications contain a reduced amount of noise and the processing time is lower than that of the frequency domain features (Toledo-Pérez et al., 2019). Seven features such as mean absolute value (MAV), integrated EMG (iEMG), variance (VAR), standard deviation (STD), simple square integral (SSI), kurtosis and average energy were extracted from the filtered EMG data. MAV is expressed as the moving average of the EMG rectified signal (Zhang et al., 2019). iEMG enables signal recognition but without a pattern and is related to the trigger point of the EMG signal sequence. It is defined as the sum of the absolute values of each EMG sample (Alkan and Günay, 2012). Both the MAV and iEMG are related to the strength of the muscle contraction. VAR is derived from the EMG power while the STD is defined as the square root of the VAR. SSI is the sum of squared values of the EMG signal amplitude (Spiewak et al., 2018). Kurtosis helps to evaluate the effect of changes in VAR on the shape of the EMG distribution. Kurtosis is determined by comparing the peak of the curve inclination data distribution and the normal curve. Average energy is the average power of the EMG signal for a given period of time.

2.3.3 Data classification

To classify rebar subtasks, supervised machine learning classifiers were used to learn patterns from the extracted features. After all the features were extracted, all the algorithms in the MATLAB classier application were trained to find the classification model best suited using all seven features combined. Researchers have used a variety of supervised machine learning classifiers for recognizing activities from EMG data, including Decision tree (DT), Support Vector Machine (SVM), Ensemble, K-nearest neighbor (KNN), Naïve Bayes (NB), Neural Network (NN) and Logistic Regression (Chan et al., 2022). There is evidence that there is no specific best-performing classifier (Murthy, 1998). As such, it would be beneficial to compare the performance of the different types of supervised machine learning classifiers to achieve the best-performing model. This study selected the following classifiers: SVM, KNN, Ensemble, NN, NB, Logistic Regression, DT, Linear Discriminant, and Kernel from the MATLAB Toolbox. Prior to training the classifiers, the extracted feature dataset was split into a training dataset (80%) and a testing dataset (20%). The training dataset was trained with the nine classifiers and thereafter validated using a holdout validation. Generally, with a large dataset holdout validation can save on the computational cost (Wang and Fey, 2018).

2.4 Performance Evaluation

After training the classifiers, the performance of the resulting models needs to be evaluated to understand their efficacy for future applications. Four common performance metrics were used to measure and compare the performance of the classifiers, namely, accuracy, precision, recall, and F1 score. The accuracy of a classification model can be computed by dividing the total number of correctly predicted classes by the total number of class samples as shown in Equation 1. However, the accuracy could be biased towards a class. For example, if the training dataset for both classes are different and the correctly predicted values of the class with a higher training dataset is more, then the accuracy of the model will be biased towards the class with the larger training dataset. Thus, to overcome this bias, it is necessary to employ other metrics such as precision, recall, and F1 score. These metrics were computed for both classes i.e., the placing and tying subtasks. Precision and recall account for the implications of the misclassification. Precision indicates the number of positive class predictions (i.e. True positive) that belong to the positive class (i.e., True positive + False positive) (Equation 2) while the recall signifies the ability of the model to correctly identify the true positive or negative class. That is, the recall is the number of positive class predictions (i.e. True positive) made from the total class samples (i.e., True positive + False negative) (Equation 3). The F1 score is the harmonic mean of the precision and recall (Equation 4). The higher the F1 score, the better the model of a given class performs.

$$\text{Accuracy} = \frac{\text{Total correctly predicted classes}}{\text{Total class samples}} = \frac{\text{TP} + \text{TN}}{\text{TP} + \text{FP} + \text{TN} + \text{FN}} \quad \text{(Equation 1)}$$

$$\text{Precision} = \frac{\text{Correct class predictions}}{\text{Total positive class predictions}} = \frac{\text{TP}}{\text{TP} + \text{FP}} \quad \text{(Equation 2)}$$

$$\text{Recall} = \frac{\text{Correct class predictions}}{\text{Total class sample}} = \frac{\text{TP}}{\text{TP} + \text{FN}} \quad \text{(Equation 3)}$$

$$\text{F1 score} = \frac{2 \times \text{Recall} \times \text{Precision}}{\text{Recall} + \text{Precision}} \quad \text{(Equation 4)}$$

Note. TP = True positive, TN = True negative, FP = False positive, and FN = False negative.

3. RESULTS AND DISCUSSION

This study is focused on understanding the extent to which muscle activity obtained from the erector spinae muscle groups can be used to detect and classify activities performed by construction workers. While performing the rebar task, EMG data was collected from all participants. The data was combined and used to detect and classify rebar subtasks i.e. placing and tying subtasks. In this study, the activities of the erector spinae muscles of all the participants were collected while performing the rebar subtasks with and without a back-support exoskeleton. Considering both conditions in the study is significant given the growing interest in exoskeletons to address WMSDs in the construction industry. The performance of the classifiers was evaluated on 20% of the datasets (i.e. 20% holdout) using the performance metrics described in Section 2.4. The performance evaluation allows for investigating the extent to which construction activities can be detected and classified from new data collected from future instances. The extent to which the activities of the erector spinae muscles can be used to recognize rebar subtasks is discussed by comparing the with and without exoskeleton experimental conditions (i.e. Exo and NoExo conditions) for the best classifier and the top-performing classifiers.

3.1 Performance of the Best Classifier

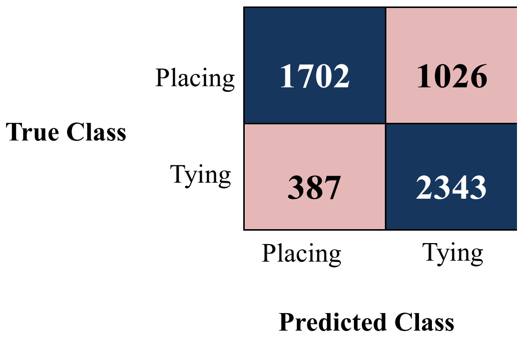
Table 1 shows the accuracy of the classifiers employed in training the datasets for both Exo and NoExo conditions. The confusion matrixes of the classifier with the highest accuracy are presented in Fig. 5. The confusion matrixes illustrate the correctly and wrongly classified classes of the classification model in the form of a matrix. The dark blue diagonal boxes in the confusion matrix represent the correctly predicted classes whereas the pink boxes represent the wrongly predicted class. For both experimental conditions, the SVM algorithm had the highest accuracy in recognizing the actions of construction workers during rebar tasks. This is supported by similar studies (Antwi-Afari et al., 2018) that highlighted the effectiveness of SVM for classifying construction workers' postures.

Table 1: Accuracy of all the trained algorithms for both experimental conditions.

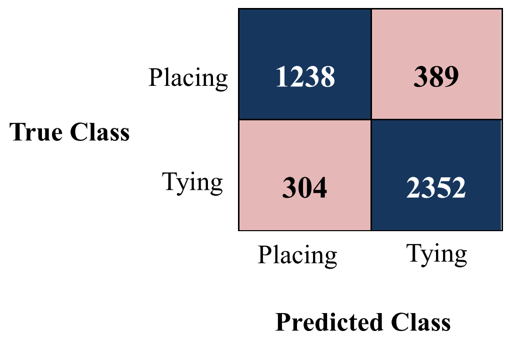
	Decision Tree	**Linear Discriminant**	**Logistic Regression**	**NB**	**SVM**	**KNN**	**Ensemble**	**NN**	**Kernel**
Noexo	73.6%	73.4%	73.5%	73.7%	**74.1%**	69.0%	73.5%	73.7%	72.9%
Exo	81.7%	78.8%	82.4%	82.1%	**83.8%**	78.0%	82.9%	83.7%	82.4%

For the Noexo condition, the holdout validation utilized a total of 545,800 datasets, transposed into 5,458 rows out of which 2,728 and 2,730 rows represented placing and tying subtasks respectively. The classifier with the highest accuracy is the SVM with an accuracy of 74.10% whereas the classifier with the lowest accuracy is KNN with an accuracy of 69%. The confusion matrix for SVM (Fig. 5a) indicates that the model correctly classified 1,702 and 2,343 rows of samples as placing and tying subtasks respectively. The model misclassified 1,026 and 387 rows of data as placing and tying subtasks respectively. The precision signifies that from the total number of placing predictions, only 81.5% are correct, whereas, from the tying predictions, only 69.5% are correct. The recall indicates that the model can accurately identify 62.4% and 85.8% of placing and tying subtasks respectively. Compared with the F1 score of the placing subtask that was 0.707, the F1 score of the tying subtask is 0.768.

The total number of training samples for the Exo condition was 428,300. This was transposed into 4,283 rows comprising of 1,627 and 2,656 rows of placing and tying subtask respectively. SVM also outperformed the other classifiers with an accuracy of 83.80% while KNN had the least accuracy of 78%. Fig. 5b shows the confusion matrix of SVM for the Exo condition. The model accurately predicted 1238 rows of the testing dataset as placing subtask while 2,352 rows were accurately predicted as tying subtask. The recall and precision for the tying subtasks are higher than the placing subtask. This means that the model can predict and identify the tying subtasks than the placing subtasks. This is also reflected in the F1 score, which is higher for the tying subtask (0.872) than the placing subtask (0.781).



(a)



(b)

Fig 5: (a) NoExo Confusion Matrix (SVM); (b) Exo Confusion Matrix (SVM)

Table 2: Performance of the top three classifiers for both the experimental condition.

Experimental Condition	Classifier		Accuracy	Precision	Recall	F1 score
NoExo	Support Vector Machine	Placing	74.10%	0.815	0.624	0.707
		Tying		0.695	0.858	0.768
	Neural Network	Placing	73.70%	0.786	0.651	0.712
		Tying		0.702	0.823	0.758
	Naïve Bayes	Placing	73.70%	0.767	0.679	0.720
		Tying		0.712	0.794	0.751
Exo	Support Vector Machine	Placing	83.80%	0.803	0.761	0.781
		Tying		0.858	0.886	0.872
	Neural Network	Placing	83.70%	0.801	0.758	0.779
		Tying		0.857	0.884	0.870
	Ensemble	Placing	82.90%	0.762	0.801	0.781
		Tying		0.874	0.847	0.860

Compared with the NoExo condition, the classifiers for the Exo condition performed better and yielded a higher accuracy as shown in Table 2. For both conditions, the classifier with the highest accuracy was SVM while the classification algorithm with the least accuracy was the KNN (Table 1). From the total number of placing and tying predictions, the Exo condition had the highest precision (Fig. 6). The ability of the model to correctly identify either subtask (recall) was higher for the Exo condition (Fig. 6). The overall performance of the model, considering the precision and recall (F1 score), was highest for the Exo condition as shown in Fig. 6.

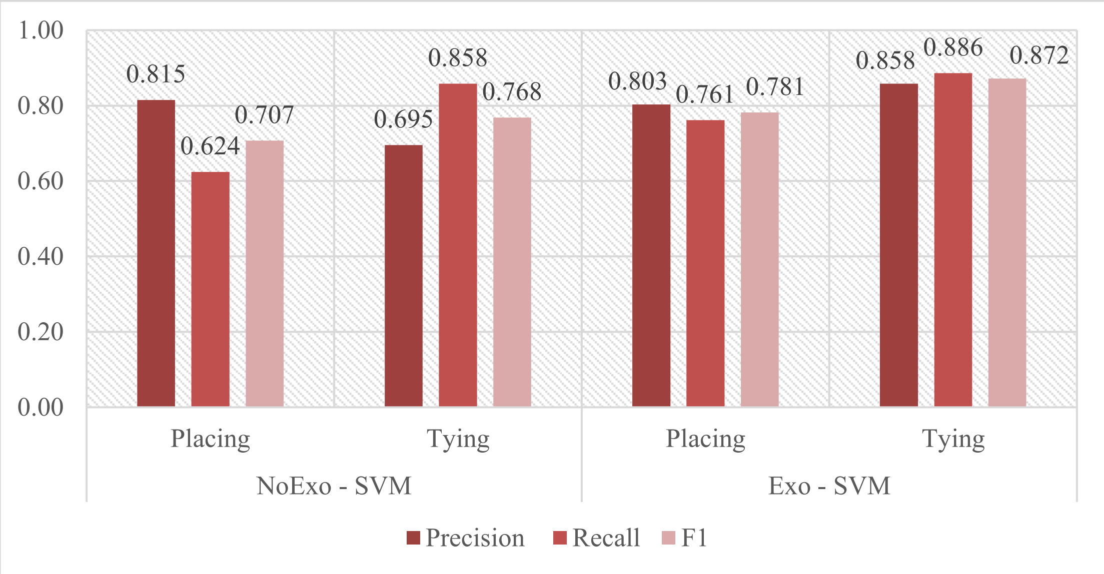


Fig. 6: Comparison between Exo and NoExo condition for SVM.

3.2 Performance of Top Classifiers

Although nine classifiers were employed for classification, only the top three are compared as a convenience sample in this paper. For the comparison, performance metrics described in Section 2.4 were employed.

In the NoExo condition, SVM was the most accurate in predicting placing subtask with a precision of 0.815. NB had the worst precision i.e. 0.767. However, NB outperformed SVM and NN in being able to correctly identify the placing subtask with a recall of 0.679. Similarly, NB was most precise in predicting the tying subtasks with a precision of 0.712. Moreover, SVM can correctly predict the tying subtasks with a recall of 0.858 than NN and NB. SVM had the highest F1 score for predicting tying subtask compared with placing subtask (Fig. 7a).

SVM also performed best in accurately predicting the placing subtasks (0.803) for the Exo condition. The performance of SVM for correctly identifying the placing subtasks was not far behind the highest recall value. The highest recall was registered by Ensemble (0.801) followed by SVM (0.761). During the Exo condition, Ensemble was the most precise in predicting tying subtask (0.874). The potential of the models in correctly predicting the tying subtask (recall) was greatest for SVM (0.886). Similar to the NoExo condition, SVM also outperformed NN and Ensemble in predicting tying subtasks compared with the placing subtask during the Exo condition (Fig. 7b).

Furthermore, considering the precision, recall, and F1 score for the NoExo condition during placing and tying subtasks, the model yielded better results for the tying subtask than the placing subtask. This may imply that there are more movements in the hand during the tying subtask that could trigger more activations in the erector spinae muscles than during the placing subtask. Bangaru et al. (2021) also revealed the efficacy of EMG data for recognizing construction activities involving more muscle activations. Furthermore, this could be attributed to similar postures being assumed by the participants since they were not experienced rebar workers. It is evident that the performance of the Exo classification model is better than that of the NoExo condition. This reveals the potential of the classification model for recognizing rebar tasks during the utilization of wearable robots, which can culminate in improved workers' safety.

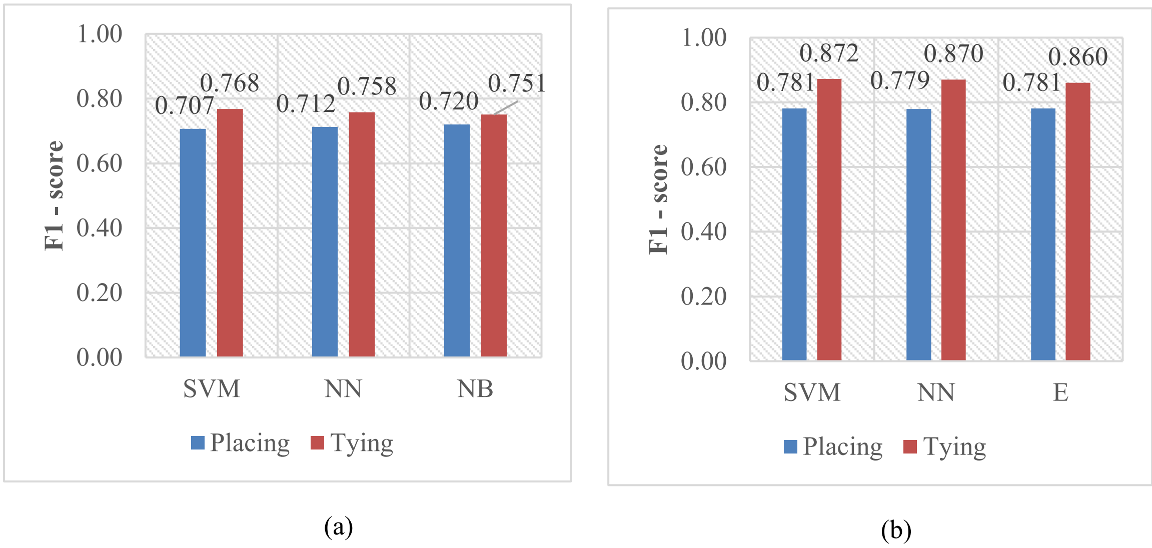


Fig. 7: (a) F1 score graph - Noexo; (b) F1 score graph – Exo.

4. CONCLUSIONS AND FUTURE WORK

This study evaluated the potential of muscle activity acquired from the erector spinae muscles to automatically detect actions of construction workers wearing and not wearing an exoskeleton. A simulated rebar task was performed in a laboratory to examine the feasibility of the approach. The performance of supervised machine learning classifiers was compared in order to select the most suitable. Overall, SVM obtained the highest accuracy of correctly classifying placing and tying subtasks in both experimental conditions (i.e., Exo and NoExo). The performance of the SVM algorithm showcases the efficacy of erector spinae muscle activity for the recognition of workers' tasks. It is expected that the implementation of the classification models will enhance workers' productivity analysis and human resource allocation. Likewise, understanding workers' trunk muscle activity can support ergonomic risk assessments, which can improve decision-making for the adoption of a wearable robot system to mitigate WMSDs in the construction industry. This study also sets precedence for future work that explores real-time models for detecting workers' actions using the erector spinae muscle activity, such as the investigation of smart exoskeletons that are triggered in response to the required muscle activations during construction activities. Also, considering a growing interest in wearable technologies as part of workers' personal protective equipment, this study suggests the efficacy of embedded EMG sensors for real-time detection of workers' muscle activities, which is critical for reducing WMSDs and crew management.

Although the findings of this study reveal the effectiveness of detecting rebar tasks from activations of the erector spinae muscles which can be utilized for improving construction workers' safety, some limitations exist and should be addressed in future studies. Firstly, muscle activations from only ten participants who are students and not construction professionals were employed. Hence, future work will entail a field study with more participants who are actual construction workers to achieve a robust training dataset that is representative of the construction workers' actions. Furthermore, data augmentation methods will be employed to create synthetic datasets for improving the accuracy of the classifiers. Also, the classification algorithm was trained using seven time-domain features, but the impact of each feature on the classification model was not explored in this study. Future work will investigate the models' performance for different sets of data features to understand which combination yields the highest performance. This will inform the choice of the dataset for classification models when limited data is available. Likewise, two separate classification models were trained for both the experimental conditions in this study. Thus, future studies will explore the suitability of recognizing workers' actions during both experimental conditions using the same classifier.

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USING VOICE-ASSISTANT FOR DATA MANAGEMENT IN A BIM MODEL: AI-ASSISTED BIM SOLUTION

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ABSTRACT: *With the growing use of automatic speech recognition-based virtual assistants in various digital platforms, information retrieval and fulfilling user demands on voice commands is becoming more common. In today's information age, where speed, efficiency, and convenience are continually being improved for data-related tasks, voice assistants serve as an artificial intelligence-based interaction medium to enhance productivity and efficiency in various fields. There have been only a few studies in the AECO industry related to the use of automatic speech recognition (ASR) system.*

These ASR-based research lack the study on developing and customising the voice commands for data management in a BIM model. Therefore, this study aims to develop a workable and simpler framework for BIM professionals and developers to use Alexa as a voice assistant for data manipulation in a BIM model and information retrieval from it.

Based on the recent studies on integrating ASR system to BIM and guide to creating Alexa custom skills on Amazon developer console, a framework named VADM is developed to introduce Alexa as a voice assistant into the BIM environment for data management. VADM framework has testified that Alexa could be a valuable and intuitive voice assistant for data manipulation and information retrieval in a BIM model. No research has been conducted on explicitly utilising Amazon's Alexa skills kit for integrating it with a BIM model. The introduction of Alexa voice assistant for data management is a new concept in AECO's research domain.

KEYWORDS**:** *Alexa for BIM, ASR in BIM, AI Data Management, Artificial Intelligence, Retrieving data Verbally.*

1. INTRODUCTION

BIM technology has evolved to address challenges in the building industry and to improve the construction sector's worldwide competitiveness (Ding et al., 2019). Because of BIM technology, the construction industry has become a part of the information technology zone (Zhang and Beetz, 2017) The computational power has risen dramatically in the previous decade, bringing Artificial Intelligence into public sectors. As a result of these advancements in AI developments, artificial intelligence (AI) seems to have a substantial influence on the sectors of AECO and BIM (Elghaish et al., 2021b; Rahimian et al., 2021). Building Information Modelling (BIM) becomes increasingly massive as information from several disciplines continues to integrate across the whole life cycle of an Architecture, Engineering, and Construction (AEC) project (Hardin and McCool, 2015). As a result of the application of BIM and the combination of computation and technology all through the building's life cycle, AI and related technologies such as voice recognition have become increasingly viable to employ within the AECO. (Shin et al., 2020b).

Alotto et al. (2020) state that the future of digital construction requires a necessary collaboration between human intelligence and Artificial Intelligence. On a mobile device with limited room for interaction, this circumstance will make it difficult for consumers to obtain the information they genuinely desire (Lin et al., 2016).

Voice-based information retrieval systems have grown more prevalent in search engines since the introduction of automatic speech recognition (ASR) technology for virtual assistants (Croft, 2019; Wu et al., 2020). Such search engines have recently improved to detect and understand natural human language in addition to accepting keyword-based requests from the human voice (Shin et al., 2020a). Moreover, there are some attempts to implement ASR systems in their domains to improve job efficiency (Ivanov, 2017). For example, An approach to intelligent data retrieval and representation for cloud BIM applications based on natural language processing has been developed to improve the utility of BIM large data (Lin et al., 2016). However, there haven't been many research on these systems in the Architecture, Engineering, Construction and Owner-operated (AECO) field (Akinosho et al., 2020). Therefore, AECO industry falls behind other sectors attempting to implement natural language-based ASR systems (Shin et al., 2020b).

Alexa skills kit is used for creating custom skills (voice commands) which is further used to achieve tasks in BIM model through Alexa devices, and it provides a major platform (interface) to utilise all its services (Shin et al., 2020a). Henceforward, this study introduces Alexa skills kit for creating commands and provides a framework that is designed to combine all workflows in a step-by-step method, allowing a professional to accomplish tasks for data management in a BIM model based on visual programming scripts via voice command in a cohesive manner.

With all the above in mind, this study aims to develop a workable and simpler framework to use Alexa as a voice assistant for data manipulation in a BIM model and information retrieval from it to use by BIM professionals and developers. The aim is achieved through a specific steps as (1) Studying the current methods adopted for data manipulation and information retrieval from a BIM model using voice assistant, (2) Analyzing the use of voice assistants in AECO industry and understanding its implementation in BIM technologies. Further, exploring how voice assistants enhance productivity and prove to be time-consuming for users in their workflows through present researches. (3) Based on the present research and frameworks proposed in the literature, a workable framework for architects and engineers with basic knowledge of Python and Dynamo to be developed. This would include the stepwise methods for data retrieval and modification from a BIM model while introducing Amazon Alexa (Voice assistant).

2. CONCEPTUAL BACKGROUND

2.1 Voice-based Technology and data retrieval with BIM

Voice-based technology, such as Interactive Voice Response (IVR) technology, has been used in construction with limited success (Bhalla, 2018; Motawa, 2017). To improve project progress tracking, Abdel-Monem and Hegazy (2013) combined a cloud-based IVR service with a customised scheduling application. Abudayyeh (1997) has also associated numerous activities with voice-recorded files. Voice-based technology has also been utilised in voice commands to assist in the documenting of bridge inspections (Abdel-Monem and Hegazy, 2013; Sunkpho et al., 2000). Tsai (2009) recorded and updated site-material logs using speech recognition. However, the use of voice-based technology in connection with BIM and Knowledge management (KM) systems has never been tried in the construction industry (Zhoui et al., 2019).

In order to regulate BIM, the sector of building construction has also looked into automated voice recognition systems (Shin et al., 2020b). BIM technology in conjunction with other emerging technologies have arisen in order to solve difficulties in the construction industry and improve the global competitiveness of the construction sector (Elghaish et al., 2021a). The construction business is now a part of the information technology field because to BIM technology (Zhang, 2020). Like, Voice 360 is a Revit API that allows you to use voice recognition to perform Forge Viewer instructions, rather than utilising a keyboard and mouse, the user can utilise a microphone to provide orders. This programme connects effortlessly with an existing interface and may be expanded as needed with more commands (Autodesk, 2021; Chen et al., 2019).A study presented by Motawa et al. (2014) designed a method for capturing the knowledge generated by Energy Managers during the monitoring and maintenance of building performance in order to achieve Energy Efficient Buildings.

As concluded by Preidel et al. (2017), the retrieval of information from digital building models is important to the construction industry's digitalisation. In the context of Building Information Modeling, it is believed visual languages offer a lot of promise for data analysis and processing workflows. The relevance of data retrieval features is anticipated to rise as the usage of BIM in practice increases, resulting in an increase in the number of engineers and architects using this approach (Lin et al., 2016). Furthermore, increased usage will raise the complexity of projects, digital models, and project structures. As a result, there will be greater demand for tools that architects and engineers can utilise to quickly extract relevant data from models. Also, Pauwels et al. (2016) have presented researched techniques to textual-based data retrieval from BIM models.

2.2 Use of Visual Programming Software (Dynamo) in BIM

Autodesk created an open-source visual programming platform called Dynamo. This software is compatible with the visual scripting interface from Revit API and allows you to expand on its parametric capabilities for a variety of life cycle data management applications. By scripting in a visual workspace, Dynamo allows its users to create, modify, aquire, and document data from a Revit file (Dynamo, 2021).

Scripting behaviour, creating both geometric and non-geometric data (e.g., enhancement of the semantic - based levels for model elements in a BIM), and information retrieval and validation of existing models are just some of the applications of such functions (Preidel et al., 2017).

Dynamo's visual programming interface is a key feature, since it enables users with little or no computer programming experience to perform numerous project life-cycle analyses on BIMs (Danhaive and Mueller, 2015).

The Dynamo library contains a number of functions that are organised into distinct categories and can be used to compose an intended information process.Users can further customise Dynamo to meet their own requirements by developing new nodes from existing core nodes and publishing them for future use (Dynamo, 2021; Preidel et al., 2017).

2.3 Relevant studies

Shin et al. (2020b) in their research proposed a framework for developing a speech-oriented interface-based system in BIM that can react to human voice. To connect the key elements, the proposed framework was created in Dynamo. Voice-to-Text (VTT), Query Analysis, and BIM to RDBMS were the three components that made up this architecture.

Smartphones with an ASR function (e.g., iOS's Siri and Android's Google Assistant) would be implemented in the suggested framework at both a software and hardware scale to accept human speech based on natural language. Users may connect to the network environment using 4G or 5G, allowing them to access the BIM model at any time and from any location, even if no computers are available.

The Voice-to-Text module is crucial in converting a human voice inquiry into a text-based question. Natural language processing will take place at the same time, with the goal of better understanding and grasping a human's spoken words. Then, in the Query Analysis Module, a human voice will be converted into a type of text query, which will be examined through the method of mapping with a SQL pattern in order to be changed to the most appropriate SQL grammar. The automatic change and the ability for the system to learn by itself using a machine learning algorithm to increase accuracy are key features here. After this process, this modified information will be processed into the last module, the BIM-to-RDBMS transformation module, to extract information that is matched to what the human voice wants to find. Following that, it will be detailed how these modules are connected to one another and what role they play in the proposed architecture (Shin et al., 2020b).

The links between each module are essential to the validation of this study.As previously stated, three main computer environments will be used to do this: Dynamo, Python, and the Oracle Database. Dynamo not only converts Revit data to a CSV file format which can be imported into a database, but it also applies or updates updated CSV files from the database to the original Revit data.When it comes to integrating Revit and the Oracle Database, the Python environment is crucial.To begin with, Python allows smart devices (such as the iPhone's Siri or Amazon's Alexa) to enter natural language questions into the computer, which are then processed using natural language processing. Then, in Python, the analysed queries can be transformed to SQL, in the database language. These procedures will allow BIM to communicate with end users. Finally, Python is used to enable the Oracle database to accept CSV files extracted by Dynamo and to update the original CSV data in Revit. The Oracle Database communicates using natural language queries to save, alter, and delete data (Shin et al.,2020b).

The other framework was proposed by Alotto et al. (2020). This framework utilises the parametric modeling software Revit by implementing the Dynamo (an open-source visual programming platform for designers) for the automation of procedures and flows. A client-server architecture that employs cloud servers as glue between the data sent by the voice communicator and the data required by Dynamo for the generation of the model on the BIM software is at the intersection of voice assistant technology and BIM Authoring Software. The prototype presented here allowed for the construction of a one-room dwelling with doors and windows. The user activates the tool in the first phase by speaking into it: The assistant will give a quick overview of the tool's features after it has been launched. The wizard now requests user voice input for each essential parameter.Each request is followed by an example of the system's expected input structure.Finally, once all of the required data has been gathered, the wizard will exchange it with the cloud computer and provide feedback to the user on the data's legitimacy.

The information from the voice wizard is delivered to the reference cloud server system as signals (AWS for Amazon Alexa and Google Cloud for Google Home). The sound inputs will be transformed into data using the artificial intelligence techniques for decrypting natural language previously stated. The information is extracted by the cloud server, which then compares it to the predetermined range values. The voice assistant will indicate if the data verification was successful; otherwise, it will prompt the user to repeat the incorrect variable (Alotto et al., 2020).

After all of the information has been obtained and validated for compliance with the ranges, it is sent to the user's computer in the next phase. A bespoke architecture has been constructed to support communication between the local computer and the cloud computer. The private IP of the user's computer has been exposed on another machine with a Public IP, allowing data transfer (forwarding) from one computer to another over a specified communication port.

The information will be sent from the cloud computer to a server with a public IP address, which will then transmit it back to the user machine with a local IP address. This machine will communicate with the outside world via a local port that listens for data and can deliver the data it receives. This port accepts the data payload that was supplied from the cloud computer and changes it from JSON to CSV format. The fact that the dynamo built-in libraries lend themselves to real-time reading of csv files that vary over time necessitates this modification. It will be possible to edit and create the model in real-time by launching the port in listening mode (Alotto et al., 2020).

Table 1: Previous studies for *automatic speech recognition* in BIM

Author(Year)	Focus of Study	Method	Input Type	Limitations
(Shin *et al.*, 2020b)	Develop a framework for ASR-based building information retrieval from BIM software	Introducing BIM to RDBMS module Semantic-based BIM	SQL Query	Relies on Oracle database, not on cloud-based database
(Alotto *et al.*, 2020)	Building modelling with artificial intelligence and Speech recognition for learning purpose	Developed a prototype for automated modelling in BIM using a voice assistant	Natural Language understanding	Focused on parametric modelling using voice assistant
(Motawa, 2017)	Develop a Spoken Dialogue BIM system to capture building operation knowledge	Integrating cloud-based spoken dialogue system and case-based reasoning BIM system.	Natural Language queries	Only IFC protocol based knowledge information retrieval from the BIM model
(Kim *et al.*, 2018)	Information retrieval from BIM and modification for BIM data in Revit	Using the conventional artificial intelligence technology and the Algorithm-based BIM	Keyword-based commands	User requires knowledge of customised commands

3. METHODOLOGY

The literature study is reviewed to understand and analyse the suitable framework to integrate ASR system to BIM for data management in BIM model. This literature study included learnings from the amazon developer website to understand the creation of Alexa custom skills on Alexa skill kit (ASK). A practical framework for architects and engineers with a basic understanding of Python and Dynamo was developed based on the current research and frameworks proposed. This included integrating Amazon Alexa to retrieve and modify data from a BIM model.

Figure 1 shows the flowchart diagram consisting of the methods that has been followed to develop the framework.

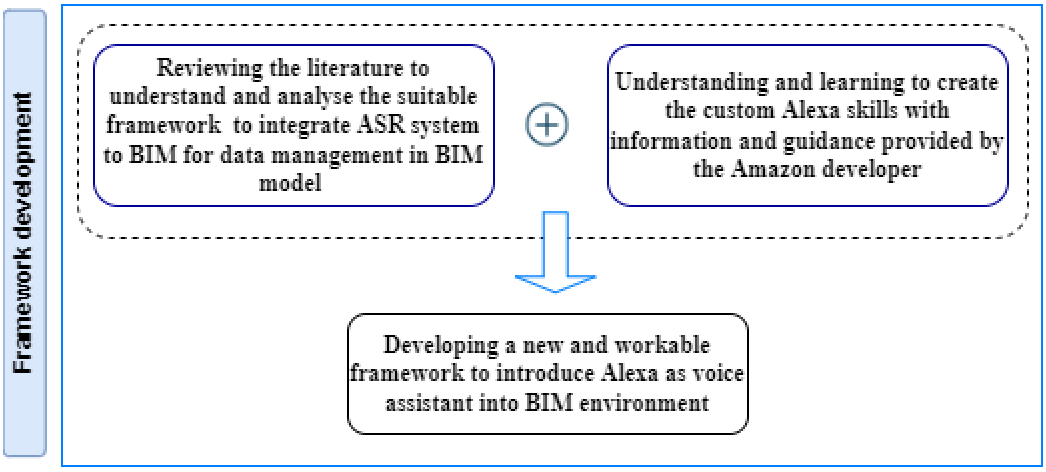

Fig 1: Research design and method

4. VADM FRAMEWORK DEVELOPMENT

Based on the recent studies and existing frameworks for ASR systems, the framework developed is categorised into primary sections, which explain the process to integrate Alexa to BIM model for data management. Starting from creating a developer account on Amazon to designing the visual programming script for the BIM model, it explains how BIM data transmits and can be manipulated through voice commands. This developed framework is designed to integrate all the processes in a stepwise manner so a professional can achieve the aim to customise tasks for data management in BIM model based on visual programming scripts through voice command in a consolidated way. Afterwards, it can be used by any user with whom the developer wants to share the project information stored in BIM data. It is based on the assumption that the data in BIM model/element is already present to be retrieved or changed. In figure 2, the process has been explained in brief, with the flow-through arrows depicted from start to finish of the framework.

This framework can be divided into interconnected stages which are as follows:

Stage 1 - Building Alexa Skills

Stage 2 - Python-based Environment Creation

Stage 3 - BIM model to CSV Data transformation

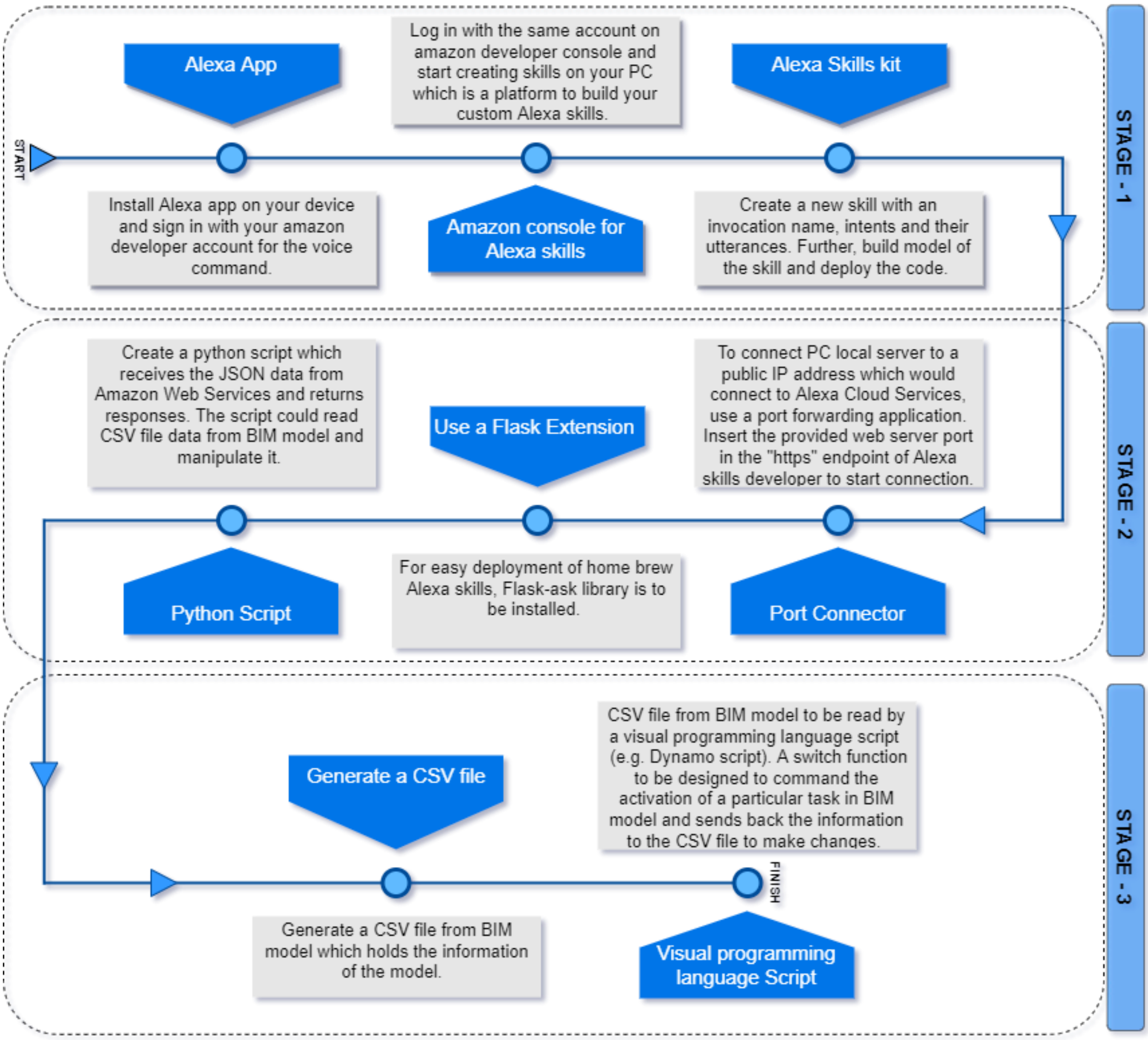

Fig 2: Framework to integrate voice-assistant Alexa to BIM model

4.1 Stage – 1 : Building Alexa skills

Alexa Skills Kit(ASK) has been developed by Amazon, which is a software development framework that is used to create "Skills". Skills are like an app for Alexa which provide a platform to customise your skills within Alexa cloud-based API, skills components and other tools to develop and maintain skills over the course of their lifecycle. Alexa's interactive voice interface allows users to communicate with your skills easily. To accomplish a task or information retrieval from bim model, user can easily develop a skill on ask without any technical or coding knowledge.

4.1.1 Initial set-up for Alexa skills kit

It requires an Amazon developer account to create any kind of Alexa skill. Sign with an existing Amazon account or establish a new Amazon developer account. For a particular skill, by using account linking and permissions options, a user can allow other users to access their custom skills developed. For instance, in BIM environment, a project lead or company can allow permission or access to these skills to its members working on the same project. It would be useful to utilise the customised skills for a project or team for specific workflows.

To build a custom skill, an interaction model is firstly defined by the developer according to the skills set he desires to build. The user's spoken input translates to the requests, or intents, that your skill can handle, according to your particular interaction model. When a user talks to your skill, Alexa determines the underlying intent using your interaction model and passes it to your skill application logic.

4.1.2 Build Interaction model

Amazon provides many ways to start creating a skill. These are custom models or existing built models. Pre-built models are the developed packages of intents and utterances that you can opt for, to create a new skill in the Amazon's developer console. The custom model is the most appropriate model for the method being followed here.

In general, the interaction model refers to a set of intents, sample utterances, slots, and dialogue models. To understand the concept of the interaction model, the meaning of these items is described below.

Intents: User requests by which the skill can be invoked are represented by intents. You define the intents for your skill's specific features and can also use built-in intents for basic actions like stopping, cancelling, and asking for assistance.

Slots: Slots are optional parameters or variables that can be added to intents. Each slot in your interaction model gets a name and a slot type. In order to improve recognition accuracy, the slot type comprises a list of representative values for the slot. For widely used arguments like dates and numbers, you can use a developed slot type or create your own.

Sample Utterances: Users will use a skill with sample utterances, which are spoken phrases. You specify the phrases users will use throughout your skill session and how Alexa can map them to your skill intents when you develop your interaction model.

Explained with an example, if user wants to create a room schedule using Alexa, he/she can utter command like "Alexa, ask project 101 to create a room schedule". Here, word "Alexa" is the wake word to enable the Alexa service, "ask" as the launch or action word, "project 123" is the invocation name, and "to create a room schedule" is a complete utterance consist of a slot "room". Here slot can be "door", or "window", which can be known as variable for a request for the schedule.

Amazon developer console provides an interface to develop and create skills. It comes with a checklist which consists of : "Invocation Name", "Intents, Sample, and Slots", "Build Model" and "Endpoint".

Name a new invocation name that would launch the skill on voice command. This is to start an interaction with a custom skill, custom intent and providing sample utterances which are the phrases used for an action.For example, it can be "name of floor finish on 3rd level", in case user wants to enquire about floor materials. Within these utterances you can provide slots which are variables to define a specific request like in the utterances "name of floor finish on 3rd level", 3rd floor can be put as slots with the option provided in the interface. It can be 2nd or 4th floor. The developer doesn't have to create separate intents for these variables.

4.1.3 Deployment of code, testing and endpoint.

In the developer console, the code is automatically generated which is further deployed to a server to be used. This code is in JSON data format which is forwarded to python script. To deploy, use "deploy" option under code section. Under Test option, test your skill developed by saying your invocation name and utterances. If Alexa replies with the "your skill is triggered", it means the test has been passed. Make sure your all set intents, slots and sample utterances are triggered by Alexa with voice commands.

For the final step, Choose the endpoint for skill as "HTTPS" to deploy your code on the public IP address. When the web server port (public IP address) is provided by port connector, make sure to insert it in this section.

4.2 Stage – 2 : Python-based Environment Creation

4.2.1 Port connection

To connect the PC local server to a public IP address which would connect to Alexa Cloud Services, use a port forwarding application. Insert the provided web server port in the "HTTPS" endpoint of Alexa skills developer to start the connection. It must be able to receive JSON data, process it, and respond with JSON data. For example, Ngrok application provides HTTPS endpoint and serves as a port connection application.

4.2.2 Use Flask-ask extension for python

Flask-ask is a python micro framework used for easy reading, sending the Alexa requests and intent slots to enable functions. Also, It helps to build ask and tell responses. Therefore it is necessary to be installed in advance for using the python script for the process of integrating AWS data to python.

4.2.3 Python Scripting

Python is used by programmers to write code and develop applications. Here, it is used to connect four main platforms- port connector, Flask-ask extension, Alexa input from AWS, and CSV file. A Python script can be written in order to deal with requests, responses and to make changes to CSV file. The script enables the redirecting requests to HTTPS server, which is read by Alexa voice to user.

The script can be divided into five main sections:

- Main Code: This includes CSV import and pandas, initiate flask-ask.
- Start Alexa: It includes connection of flask-ask to Alexa.
- CSV Read: Coding for reading the CSV file.
- Intent-based script: Uses intent from Alexa to manipulate CSV and create a response message.
- Port Connection: To connect local server to public server.

4.3 Stage – 3 : BIM model to CSV Data transformation

4.3.1 Generating CSV file

BIM data from a model can be shared or exported to a CSV file, this data can be further transformed or used for manipulating the data in BIM model data through voice command. Therefore, the CSV file plays an important role as a data base for BIM model information. The CSV file is extracted from BIM model using a visual programming platform for a certain entity or elements. Then the file is used to read data for information retrieval, data manipulation or management from the BIM model file. It acts as a database between Visual programming language script and a python script.

4.3.2 Developing Visual programming language script

The visual programming software like Dynamo can be used in Revit environment to manage data in BIM model through CSV file and it can also manipulate data in model file after the changes are reflected in CSV file. The Visual programming language script can be designed for both ways depending on the task.

A Dynamo script consists of nodes which are designed to read data from CSV file and achieve a certain task. For example, A room schedule in Revit model can be automatically created by using a Dynamo script linked to a CSV file, which occurs if it is triggered by a certain change in the data of CSV file. This change is updated by the Python script in CSV because of the input from Alexa service. This way, Visual programming language script is utilised to make changes in BIM data through the Alexa voice command.

5. DISCUSSION

The present literature studies were reviewed for automatic speech recognition system in BIM industry to understand and analyse the process of introducing a voice assistant in use for data manipulation and information retrieval. Based on these studies, the VADM framework was developed.

There were two significant practical and relevant researches, proposed by Shin et al.(2020) and Alotto et al. (2020). Alotto et al. (2020) proposed a workflow to use voice assistant as tool for parametric modelling for learning purpose. It uses a sound input (voice command) sent to cloud servers (AWS or Google Cloud). Data from cloud servers were forwarded to local server which manipulates the JSON data to CSV format adopting NLU based language. Dynamo libraries were used to trigger task for modelling in real-time. In contrast, Shin et al.(2020) proposed a framework which consisted of three modules, Voice to Text, Query Analysis and BIM to

RDBMS transformation which adopted the Oracle database not cloud database and SQL query language.

Both of these studies provided case studies on their respective frameworks proposed to testify their aims but lack the information on involving a specific voice assistant and creating customised voice commands for their purpose. With the availability of various highly used voice assistants in digital world such as Bixby, Alexa, Cortana or Siri, it is important to include its full fledge use in BIM environment. Moreover, cloud-based services for voice assistants are more suggested for ease of use in their case studies.

The above mentioned research on voice assistant for BIM assisted to build the better and workable proposed VADM framework. VA Alexa was chosen as it provides a cloud-based service and proven to be a more used by common public. The VADM framework was divided into main stages, each of which explains how to link Alexa with a BIM model for data management. It illustrates how BIM data transmits and may be handled with voice commands, from creating an Amazon developer account to constructing the visual programming script for the BIM model. This framework was created to integrate all of the procedures in a step-by-step manner so that a professional can reach the goal of customising jobs for data management in BIM models using visual programming scripts and voice command in a cohesive method. After then, any user with whom the developer wishes to share project information saved in BIM data can use it. It was based on the assumption that the data in the BIM model/element was already present and may be retrieved or modified.

In the VADM framework, three stages have been used to incorporate VA Alexa: Stage 1: Building Alexa Skills, Stage 2: Python-based Environment Creation, and Stage 3: BIM model to CSV Data Transformation.

6. CONCLUSION

The aim of this study was to develop a workable and simpler framework for BIM professionals and developers to use Alexa as a voice assistant for data manipulation in a BIM model and information retrieval from it. To achieve this aim, 1) the literature study is reviewed to understand and analyse the suitable framework to integrate ASR system to BIM for data management in BIM model 2) A practical framework for architects and engineers with a basic understanding of Python and Dynamo was developed based on the current research and frameworks proposed. This included integrating Amazon Alexa skills kit, a platform to customise Alexa voice commands interface provided by Amazon.

The framework developed was limited to utilise by the professionals who acquire basic knowledge of python language coding and Dynamo. But the end-user can be anyone related to project who desires to use Alexa for BIM workflows. Framework developed are based on literature study and guidance to build custom voice commands on Alexa skills kit on amazon developer. Other voice assistants for users are also available which can be introduced to BIM, but this study is limited to use of Alexa and Alexa skills kit in a BIM model.

Reviewing the literature based on ASR system, it was found that no study has been conducted on explicitly utilising Amazon's Alexa skills kit for integrating with a BIM model. Thus, the introduction of Alexa voice assistant for data management is a new concept in AECO's research domain.

Alexa skills kit provided a user-friendly interface, developed by Amazon, to create interaction model and custom skills easily with all Alexa features. These skills can be easily deployed and utilised. Using Flask and port forwarding is limiting to a single computer setup. This is applicable for testing, but probably not robust for a long term deployment.

Analysing the findings of this study, it can be concluded that using voice assistant Alexa is a reliable and usefull intelligent voice assistant which holds the potential to revolutionise BIM industry in Big data. The VADM framework can be applied in real projects as a practical approach and any BIM professional with basic knowledge of Python scripting and Dynamo, can create custom successful data management tasks for the end user using VADM framework considering the limitations and challenges.

It is recommended for the VADM framework to implicate it into real projects for check the feasibilty. BIM managers and other users can automate their workflows by using their mobile using Alexa app. They can search and retrieve information about the projects by voice commands in few seconds and achieve efficiency and productivity in terms of BIM workflows. The future for this framework proposed would be how it can be utilised on the cloud services. Since all database for projects are moving to cloud technology and applications are being developed for cloud services. It may open the BIM industry towards new possibilities for information management.

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BIOMIMETIC INNOVATION IN THE UK CONSTRUCTION INDUSTRY: AN ASSESSMENT OF ADOPTION READINESS

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ABSTRACT: *There is an urgent need for radical innovations to tackle the climate crisis, especially in the construction and property sectors given their significant contribution to carbon and other harmful emissions. The adoption of biomimetics – reimagining man-made products and systems by emulating natural principles - is one such innovation by which these problems may be addressed, though it would require systemic change to the sector's traditional workflows and business models including some commitment to the principles of a 'circular economy'. In this study we consider the industry's readiness for such transformative technologies and business models. Following a review of the relevant literature, the results of 100 participant interviews evaluated overall enthusiasm for biomimetic innovation and the barriers and drivers for its adoption; including current business models and procurement arrangements. The attitude of Construction clients and perceptions of the general public were seen as having a major influence. A further perceived issue was the impact of product certification, insurance, and accreditation on the adoption of innovative technologies. Technological barriers, often cited in the literature as the major barrier to innovation, was ranked least problematic by the respondents in this study. The results demonstrate the willingness of the Architecture, Engineering and Construction (AEC) industry in the UK to embrace a biomimetic circular economy, but that significant barriers exist in the form of institutional, rather than technological conservatism. The barriers and drivers identified in this study and confirmed by past studies, were examined through the lens of complexity theory to provide a more systemic perspective of the industry and demonstrate the potential to induce a deliberate butterfly effect giving way for a gradual industry-wide biorevolution to organically emerge.*

KEYWORDS: *Climate crisis, biomimetic innovation, bioeconomy, circular economy, stakeholder interviews, readiness assessment, complexity theory.*

1. INTRODUCTION

The need for innovation that can tackle climate change is not a new phenomenon; scientists have warned about the impact industry is having on ecosystems since the 1980s. In 2006, scientists suggested that there is a decade-long window to alter the trajectory of climate change or face irreversible changes caused by cyclical feedback loops (IPCC, 2018). Today, humanity is entering into a world of unpredictable climatic conditions, otherwise known as the Anthropocene - the result of anthropogenic action altering planetary conditions and disturbing a 10,000-year pattern of relatively stable climate, otherwise known as the Holocene. In 2015, the World Meteorological Organisation announced that planetary temperatures have risen 1°C higher than the pre-industrial revolution period. This explains the extreme shifts in climate and catastrophic weather events being experienced by cities and forests around the globe. The longer industries delay action against the, currently declared by scientific consensus (Tol, 2014), human-induced climate crisis, the more complex and costly the situation becomes. Intergovernmental action, such as the Paris Agreement, global and European carbon and energy targets, highlights the global acknowledgement of the current climate emergency with, unfortunately non-binding, commitments to urgent action that will keep global temperatures from increasing beyond 1.5°C from pre-industrial levels. Contemporary life is currently setting humans on a trajectory to raise global temperatures by 3-5°C and breach the 1.5°C target sooner than anticipated (IPCC, 2018). The 2021 IPCC (Intergovernmental Panel on Climate Change) report on ‘The Physical Science Basis’ further emphasises how our economies our fueling the climate crisis and urges governments and organisations to take radical action to reduce greenhouse gases and reliance on fossil fuels (IPCC, 2021). The 26th UN Climate Change Conference of the Parties (COP26) took place in November 2021 resulting in promising commitments including world leaders representing over 85% of the world’s forests committing to halt and reverse deforestation and land degradation by 2030, a Climate Finance Delivery Plan to mobilise $100 billion per year in climate finance to support developing economies and a drive to decarbonise every sector of the economy (UK Government Cabinet Office, 2021a and 2021b; UK Government Prime Minister's Office, 2021).

The Architecture, Engineering and Construction (AEC) industry creates a built environment in which inhabitants can flourish, whereas optimal ecosystems and environments have been evolving for over 4 billion years in the natural world, making them ideal sources of inspiration. Understanding nature’s principles and applying them to create solutions is known as biomimetics. It is the abstraction of formations, structures, functions and processes in biological systems to synthesise man-made solutions (John et al., 2005), resulting in advances in bio- based technologies and industries, placing the bioeconomy at the forefront of government agendas for addressing the UN’s Sustainable Development Goals (Colglazier, 2015). The resulting concept of the ‘bioeconomy’ is often juxtaposed with that of the ‘circular economy’; defined by the Ellen MacArthur Foundation (2013) as an industrial system that is restorative by intent.

However, the development of flourishing circular bioeconomies will require investment in research, digital and physical infrastructure, changes in laws and regulations, supply chain and procurement reforms and a balanced market and social demand. Although the barriers and drivers of the circular bioeconomy have been identified and discussed in extant research, particularly in relation to the construction industry (e.g., by López Ruiz et al., 2019 and Sayed, 2019), further research is needed to assess the industry’s readiness for such transformative technologies and business models, particularly in countries demonstrating lower levels of innovation and R&D expenditure in mainstream construction. (Farooque et al., 2019; Rosa et al., 2019; Aguilar et al., 2018; Adams et al. 2017).

Modern methods of construction, including off-site manufacturing can enable the circular economy as they often integrate ‘design-for-deconstruction’ principles for end-of-life waste management or recycling. However, their uptake in the UK - forecasted by Taylor (2010) as 6-7% of the construction market by 2013 – compares poorly with countries such as Japan, Malaysia and Australia (Goulding and Arif, 2013) with the exception of conventional off-site timber-frame technologies and volumetric concrete-slab modules (Hampson and Brandon, 2004). This confirms the image of the UK’s construction industry as one that is more rigid and conservative than those of other prominent economies (Kulatunga et al., 2009 and 2007; Fairclough, 2002).

Assessing the readiness of the UK’s AEC professionals for biomimetic innovation may shed light on the major challenges associated with implementing a circular bioeconomy within a conservative and risk-averse construction industry. This scoping study, therefore, examines the UK construction industry’s readiness for biomimetic innovation through interviews carried out with industry professionals representing a variety of organisations of different sizes at major industry events.

2. METHODOLOGY

Past literature has offered various perspectives on the industry's readiness and the factors, actors, barriers and drivers at play (Sayed, 2019; Kirchherr, 2018; Adams et al. 2017). A related literature review was carried out using various relevant databases including those of the British Library, the Building Research Establishment (BRE), The International Council for Research and Innovation in Building and Construction (CIB) and the UK Green Building Council.

For the primary data collection, it was important to access a wide variety of the UK construction industry's professionals. The target population was, therefore, organisations of varying sizes from the private sector, public sector and academia that represent industry professionals in the UK's construction sector of the AEC industry. Information on biomimetic innovation was presented to the interviewees prior to the interview and this enabled respondents to address the interview questions more effectively and helped ensure more informed and accurate responses. Basic statistical analysis was performed and is presented in the following section.

Given the sample size, generalisations must be made with caution, however, the purpose of this study is to gather insights into general perspectives on the bioeconomy and the industry's readiness for biomimetic innovation. Consequently, the chosen approach was deemed adequate and appropriate. This study will also help confirm or challenge the conclusions of extant literature on the subject as well as inform more in-depth research on the implementation of biomimetic innovation.

3. RESULTS

In order to further define the barriers and drivers in relation to organisation size, the 100 participants that took part in the study were divided into the following organisation groups and sub-groups:

- Micro-enterprise - less than 10 employed
- Small-enterprise - 10-49 employed (local and international sub-groups)
- Medium-enterprise - 50-249 employed (local and international sub-groups)
- Large-enterprise - more than 250 employed (local and international sub-groups)

A total of 31 participants representing large enterprises (17 international), 26 representing medium enterprises (2 international), 23 representing small enterprises (4 international) and 20 representing micro-enterprises took part in the study. Levels of seniority ranged from director (51%), through senior (25%), to junior (24%).

The majority of participants (84%) were from the private sector with a much smaller number from the public sector (7%) and academia (9%). In the first question, interviewees were presented with a series of barriers to the bioeconomy (derived from a review of the literature) and asked to rank them by their impact and difficulty to overcome. The results are shown in Table 1.

Table 1: Answer to Question 1. Barriers to the bioeconomy in construction ranked by impact and difficulty (N=100)

Barrier	Impact					Difficulty to Overcome				
	5	4	3	2	1	5	4	3	2	1
Upper management perceptions and influence	89%	11%	0%	0%	0%	11%	26%	63%	0%	0%
Clients and general public perceptions and demand	82%	16%	3%	0%	0%	0%	66%	34%	0%	0%
Cross-sectorial collaboration	76%	20%	0%	4%	0%	2%	8%	36%	41%	14%
Construction industry's perception of new technologies	72%	10%	0%	0%	18%	0%	39%	0%	61%	0%
Product Certification, Insurance and Accreditation	70%	25%	5%	0%	0%	0%	24%	21%	32%	22%
Building regulations	62%	30%	8%	0%	0%	80%	10%	11%	0%	0%

Government subsidies and support	50%	56%	3%	0%	0%	9%	45%	47%	0%	0%
Collaboration within the construction industry	47%	39%	6%	2%	7%	37%	59%	4%	0%	0%
Conventional Procurement Process	39%	30%	0%	0%	31%	8%	36%	50%	6%	0%
Building standards and Certification	27%	66%	7%	0%	0%	58%	51%	0%	0%	0%
Internal R&D spend within construction companies	27%	42%	17%	11%	3%	74%	21%	5%	0%	0%
Conventional Business Models	14%	42%	41%	0%	4%	16%	29%	55%	0%	0%
Laws and Legislation	13%	23%	45%	12%	8%	89%	5%	6%	0%	0%
Technology readiness	0%	37%	55%	8%	0%	0%	9%	84%	7%	0%

Upper management perceptions and influence and *product certification, insurance and accreditation* were amongst the barriers with the highest impact but could be overcome over the long-term. *Laws and legislation* was perceived as one of the barriers that are most difficult to overcome but may or may not impact the bioeconomy. The results also indicate that the barrier that should be addressed with the lowest priority is *technology readiness* followed by the construction industry's *perception of new technologies* and *cross-sectorial collaboration*.

Question 2 directly asked participants whether or not they would be willing to use biomimetic innovations and 95% responded 'yes'. The 'small enterprise' respondent-group produced the highest number of negative responses to this question at 13% (3 out of 23). On the other hand, all the respondents who operated internationally (24) were willing to embrace biomimetics, whilst 9% (7 out of 79) of those only operating within the UK were disinclined to do so.

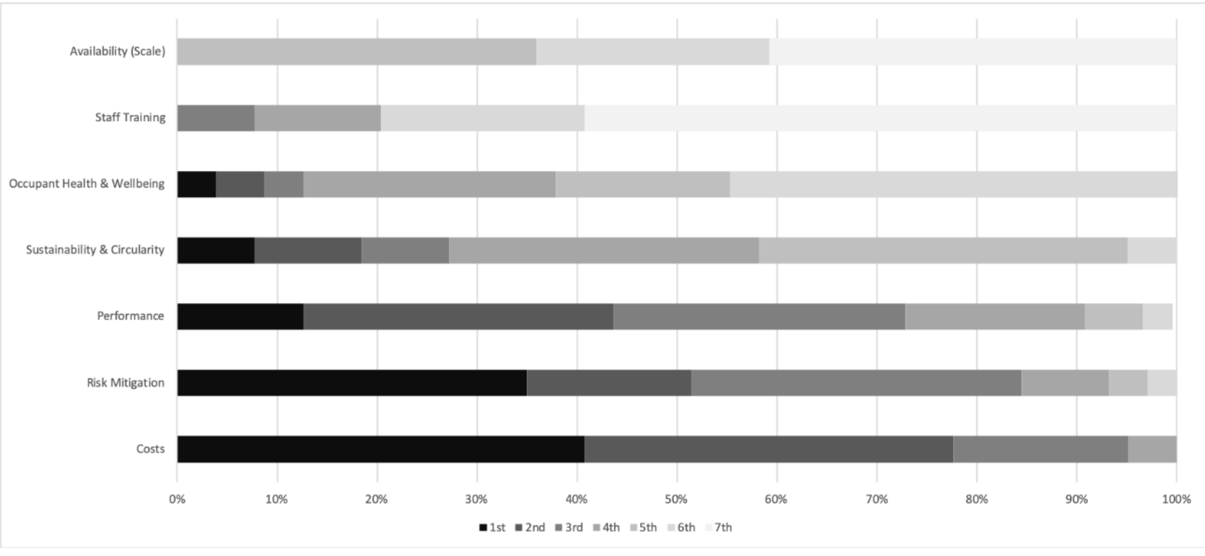

Fig 1: Answer to Question 3. Please rank what, in your opinion, are the main aspects associated with the uptake of new innovative materials and construction systems. In order of highest to lowest importance. (N=100)

In Question 3 respondents were presented with 7 factors, again derived from the literature, that might influence their uptake of innovative materials and construction systems (see figure 1). Over 40% stated that *costs* are the number one factor and just under 40% chose *risk mitigation*. The *performance of biomimetic innovations* in relation to industry standards was the next most important factor (13%) followed by *sustainability and circularity* and *occupant health and wellbeing*. The remaining factors (*staff training* and *accessibility at scale*) were lowest ranked. *Costs* was the only factor that all participants ranked in their top 4 and *availability at scale* was the only factor consistently in the bottom 3.

Question 4 asked respondents whether their organisation's current business model encouraged the integration and adoption of the bioeconomy. A clear majority of organisations (78% of large enterprises and all six SMEs) operating internationally believed that their current business model did indeed support the bioeconomy; a view shared by 50% of large organisations and 72% of SMEs who only operate nationally. Of the micro-enterprises, there was an expected lack of business model suitability for most, however in marked contrast, all 9 respondents engaged in Architecture and three of the four sustainability consultants felt that their business models encouraged the adoption of such innovations.

The final question asked the interviewees for their opinion on whether or not conventional procurement methods are conducive to the bioeconomy and almost 70% (68%) of the responses were negative (see Figure 6). Architecture firms formed 27% of the participants who believe the current procurement methods are indeed conducive followed by contractors, construction system developers and housebuilders respectively.

4. DISCUSSION

As we enter the epoch of the Anthropocene, it is clear that transformation needs to take place in all major industries. As one of the largest contributors, the AEC industry presents ample opportunity for systemic change to reduce carbon emissions and invest in carbon sequestration and renewable technologies and resources. Although the bioeconomy, and particularly the circular economy, is now widely discussed across all sectors and industries, there has been little progress in its implementation. Whilst much of the literature reviewed suggests that this is due to technological barriers, the respondents of this study ranked *technology readiness* as the barrier of lowest priority. This result corresponds with a ‘large-N-study' on circular economy barriers recently carried out in the EU, where no technological barriers were ranked among the most pressing (Kirchherr et al., 2018). This may be due to most construction-related technologies used within a circular bioeconomy being driven by pre-established biological and agricultural processes and digital technologies that have been implemented in other industries for decades.

The findings of the large-N-study also correspond with other results of this scoping study by highlighting that cultural barriers, such as lack of interest from client, awareness, company culture and lack of symbiotic governmental intervention are considered, by businesses and policy-makers, to be the main blockers for the transition. It is clear that collaborative action from industry, government, community and academia needs to become commonplace in the AEC industry in order for a sustainable transition to take place. The alignment between the results of this scoping study and other recent qualitative and quantitative studies in literature with larger samples, provides further reassurance when using these results to cast generalisations on the AEC industry, at least in Europe.

As extant literature suggests, this scoping study confirmed that costs and risk mitigation are the most important factors when considering the uptake of biomimetic innovation in the UK’s construction industry. This was expected in an industry with such risk-averse culture and slim profit margins, which is why the next most important factor is the performance of biomimetic innovations in relation to industry standards. Ensuring the safety, reliability and suitability of materials and technologies used in buildings is justifiably of highest priority for industry professionals as the impact of the risks associated with any errors made could be catastrophic.

Industries deploy standardisation and regulations in order to enforce best-practice and mitigate against failure. However, conventional approaches to standardisation and regulation can also form a challenging barrier to innovation (Garcia et al., 2020). Today’s fast-paced advances in science mean that we are able to venture beyond the requirements of building regulations and standards in a much more agile manner. Conventional, paper-based and static standards and regulations are not capable of maintaining their relevance with rapidly developing products that allow us to achieve performance and efficiencies spanning beyond minimal requirements. Building regulations were selected by the study’s participants as the most difficult barrier to overcome and the one with the highest impact. They also find building standards and certificates to be a barrier of significantly high impact and also difficult to overcome. This means that the public and private sector need to prioritise changes in building regulations, standards and certification in order to maintain their relevance and allow for a biomimetic transition, whilst maintaining their primary purpose of ensuring a safe and secure built environment. Recent advances in regulatory compliance research demonstrate digital data-driven approaches that provide a promising approach to dynamically and responsively assess and ensure compliance (Hwang et al., 2022).

Current linear business models that heavily rely on a competitive advantage and, thereby, prioritising cost and time reductions often at the expense of environmental, social and economic inequity are simply not suitable for biomimetic innovation. The results of this scoping study supports this assessment with almost a third of all participants revealing that their current business model does not encourage the adoption of the bioeconomy. This was particularly the case with contractors, construction system developers and house-builders. Such business models discourage upper management from considering environmental, social and wider economic costs when making decisions. It is only the immediate short-term economic cost that appears to be the driving factor for both short and long-term decisions. Therefore, when a sustainable product is used within a conventional business model, it becomes economically unviable - ethical labour, local sourcing, local manufacturing, effective waste management and renewable energy, for example, add relatively significant production costs in today's developed economies.

The industry's conventional approach to procurement is one of the major obstacles for SMEs and innovation, with almost 70% of this study's participants in agreement. Although it may be surprising, 90% of the remaining participants (27%), who believed that current conventional procurement methods encourage the integration and adoption of the bioeconomy, were architecture firms. Generally, architects' involvement with the procurement process tends to be high-level and for limited periods of the process. Mainstream construction projects, such as residential social housing developments in the UK, rarely use architects in projects in an attempt to save time and costs. Therefore, architects are much more likely to be involved in larger commercial and higher-end residential projects which provide budgets that enable the integration of new technologies and the use of innovative and exemplary procurement methods.

It seems that a bottom-up approach, where different individual parties in the industry collaborate to implement change and inspire others, is necessary to instill more innovative procurement approaches (Adams et al., 2017). Perceiving the industry through the lens of complexity theory, which describes the world as a collection of complex systems that are endlessly interacting and influencing one another (Waldrop, 1993), may help demonstrate the impact of bottom-up collaborative and aligned action within an industry. As a complex system, the industry is subject to 'Phase Transitions' resulting from the actions of its elements or stakeholders, which may eventually influence widespread changes in the system or industry as a whole. Fundamental concepts of complexity theory and its analytical capabilities, can inspire and help create intelligent procurement models that utilise digital technology to gradually change perceptions and, in turn, legislation within the industry. If we were to break down the construction industry into complex systems with various elements that interact with one another and explore how these interactions affect the whole, it would become much easier to identify where change needs to occur to address the challenges identified. Complexity Theory can be used as an analytical tool to offer great insights into the way the industry operates. Any system can be perceived as a set of parts known as elements, that are ordered or unordered, and the connections between them are known as relations. All systems can be observed on multiple levels as the elements themselves can also be perceived as sub-systems with their own elements. If one was to observe a system from a higher level, the system will appear to interact with other systems, giving way to a new level of organisation and there is almost no limit to the number of levels from which a system can be observed (Plsek and Wilson, 2001).

When analysing a system from the appropriate level, a global pattern of organisation that functions as a coherent whole surfaces. A phenomenon known as emergence. The elements within the system are distributed without centralised control. However, the local interactions between the elements allow them to self-organise. As each element contains a certain degree of autonomy relating to its capacity to adapt to its local environment, the elements can synchronise their behaviour locally or co-operate with one another enabling the emergence of patterns of organisation from the bottom upwards. Such autonomy and adaptation result in a variety of responses by each element for any given stimulus or phenomenon. Much like in the natural world, complex systems observed on the macro scale develop through an evolutionary process where elements are subject to a selection process guided by their ability to successfully adapt. Those who have developed to be better-suited to their ecosystem are selected and multiplied whilst others fade. This results in the entire system gradually adapting to its environment without centralised coordination (Wright, 2004; Waldrop, 1993).

This demonstrates how complex systems are multidimensional as they are composed of various elements on various levels, all of which affect one another. It is perceived to be short-sighted to isolate one element or even a system and reduce it down to a single level without considering the holistic, pervasive and highly interdependent interactions and relations at play. Such interdependence results in nonlinearity or circularity. Nonlinear systems are able to grow or diminish at an exponential rate. A process of rapid change known as a 'Phase Transition', allowing systems to shift into entirely new regimes in short periods of time. This process is the result of feedback loops, which occur through the exchange of information and sequential cascading changes in the relations between the elements, allowing the insignificant actions of one element to cause significant changes to the entire system.

This is only appreciated when considering the system as a whole (the big picture). It is a concept which explores how a small local change can result in large global changes through feedback loops and is more widely known as the Butterfly Effect within Chaos Theory (Tunc and Turan, 2013).

Virtually, every aspect within the AEC industry could be perceived and modelled as a complex system. From material production and construction methods to organisations, projects and the industry as a whole. As explained, the number of levels of observation for any given system are limitless, but boundaries must be defined to allow for the appropriate prediction, evaluation and manipulation of the system (Plsek and Wilson, 2001).

biomimetic approaches to procurement and business model development are best described through the lens of complexity theory. Applying this intelligent nature-inspired approach to developing solutions may enable the industry to holistically and systemically initiate long-term change. By introducing the bioeconomy, we may be able take fundamental steps towards decarbonizing the industry. Therefore, if we model the industry as a complex system and observe it from the appropriate level, we would be able to identify clear emergent patterns that can be studied to unveil the roots of these issues. Collectively and collaboratively, the industry's stakeholders may be able to induce a deliberate butterfly effect in the form of various incremental nudges as well as step-changes, depending on their influence and reach, giving way for a gradual industry-wide biorevolution to organically emerge.

5. CONCLUSIONS

The bioeconomy may be the next human frontier and industry may certainly be undergoing a biorevolution of sorts, but both are near-impossible to implement with conventional business models, linear economic and industrial systems and one-dimensional (reductionist) thinking.

The results of this study clearly demonstrate that the AEC industry in the UK is very much willing to embrace the bioeconomy. However, major barriers, such as outdated and static building regulations, standards and certification processes, company culture, public perception, appreciation of R&D investment and fragmented linear procurement and supply chain models, prevent implementation. Therefore, further research as well as deliberate collaborative action is needed to address the barriers and challenges that this study highlights. Particularly, further work is needed on understanding how large international or national enterprises who, according to the results, appear to be the most prepared for the bioeconomy can actively lead and drive the transition in collaboration with smaller enterprises, communities, academia and government.

The bioeconomy appears to present a variety of environmental, social and economic benefits. Further work is required to measure and quantify the extent and impact of these benefits to present a solid case for an industry-wide transition. Although various case studies that demonstrate how biomimicry can be applied to tangible products and systems exist in various sectors, examples of biomimicry in intangible systems and frameworks tend to be limited to the field of Information Technology and, in particular, Artificial Intelligence. Therefore, there is a clear need for the development of biomimetic frameworks, business models and problem-solving methodologies to demonstrate the full potential of biomimicry and its wide-ranging impact across sectors. In simple terms, biomimicry enables us to have a more systemic, nuanced and dynamic understanding of the world around us, revealing the complexities of the various systems at play. With the ever-increasing drive for urgent climate action, biomimicry presents a significant opportunity to develop multifaceted and holistic long-term solutions that systemically address the climate crisis, further emphasizing the need to demonstrate its potential and impact.

The dynamics of our economies, cities and natural world are ever-changing and are predicted to change drastically within the near future. Scientists predict that humanity along with all of our economic, governance, industrial and academic system are on the verge of collapse or major reform. Contrary to what is currently being observed in the world's major economies, governments and large multinationals should own a large proportion of the responsibility of the impact that we have had on the planet and adopt a collective, regenerative and truly equitable approach to all of their operations in order to survive during such a transitional moment in humanity's history.

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STRATEGIES FOR IMPLEMENTING BIG DATA CONCEPT IN THE CONSTRUCTION INDUSTRY OF THE DOMINICAN REPUBLIC

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ABSTRACT: *The Big Data (BD) boom has increased exponentially in recent years, reaching even the most traditional industries. In construction, this technology has come to be considered as the possible solution to the challenges that the industry has been facing in recent years, with some authors even naming this technology as the future of the construction industry. However, despite this reception, studies that explain in detail the factors that favour the adoption of Big Data are scarce and non-existent in some cases. Understanding these influencing factors is a key element in ensuring future technology adoption across the industry. Such is the case of the strategies which make up an action plan for companies that seek to adopt Big Data in the future. Therefore, the objective of this study is to identify the strategies that would allow the adoption of Big Data in the construction industry of the Dominican Republic. To identify these strategies, qualitative research was carried out due to the scarcity of sources that address the subject. In the data collection process, a total of 21 interviews were conducted representing companies with undoubted presence in the construction market of the Dominican Republic. As a result of the data analysis, four main strategies were identified which include the promotion of standardization and popularization of the BD concept and its benefits, investment in training and development of staff skills, support for the development of current technologies as well as the inclusion of technology in the education curriculum of present and future professionals. These strategies identified in the study will help companies that plan to implement Big Data in the future to carry out an action plan and identify the steps to follow to achieve a successful adoption of the technology. Also, this study contributes to the body of knowledge of research professionals who focus on the elements for Big Data adoption as well as possible future professionals in the area.*

KEYWORDS: *Big Data, Construction, Dominican Republic, Strategies, Technology.*

1. INTRODUCTION

Construction industry has remained the same during the last decades, construction methods have varied or little or nothing during this time despite the great technological advances presented by other industries, the resistance to change of this industry implies that the small changes that have occurred such as the adoption of BIM, IoT and smart devices have occurred gradually and many years after similar advances have occurred in other areas (Silverio Fernandez et al., 2019). Nevertheless, there are more and more technological advances that arise aimed at the construction industry (Bello, 2021; Nik-Bakht et. al., 2021and Naoui et. al., 2021), the increased awareness of the limited resource availability and the impact of the construction practices in the environment and the future generations have led the industry to adopt tools aimed at mitigating if not eliminating these impacts (CLC, 2021)

Big Data (BD) is a technology which has emerged as a response to the need to manage the increasing volumes of data that are currently generated and transmitted (Sayah et al., 2021 and Tamiminia et al., 2020). This technology is characterized by providing the tools for efficient decision-making through the identification of trends and patterns that help to improve production processes (Tabesh et al., 2019). Industries such as retail, banking and healthcare have been taking advantage of the benefits provided by technology for years, but in other cases industries such as manufacturing, and construction are just beginning to explore their potential (Tabesh et. al., 2019 and Chen et. al., 2020). However, the successful adoption of this technology depends in large part of the industry's ability to integrate new technologies which represents a disadvantage for the construction industry which tends to adhere to traditional practices (Silverio Fernandez et al., 2019).

On the other hand, the effects of BD in the sustainable development of the industry are evidenced in applications aimed at the efficient use of energy and resources, as well as the elimination of waste during the construction processes to mention a few (Lu, 2019; Xu et. al., 2020; and Lu et al., 2021), so the integration of this technology in the construction processes would imply an advance for the industry and a chance to meet the future requirements of the world.

2. **A determining factor in the adoption of new initiatives is the need for well-based strategies, companies have to establish clear objectives as well as responsibilities. In order to implement any new initiative companies, require well-based strategies where the aim and responsibilities are clearly expressed (Wattanajantra, 2020). Because of this the aim of this study is to explore the strategies for implementing BD in the construction industry based on the expertise of Dominican decision makers. Since the construction industry is only beginning to acknowledge BD and its impacts in the industry, an extensive literature review showed that some information can be found regarding some new implementation cases but there is no concrete information on the strategies necessary to achieve such adoption so this topic will be explored through qualitative research which is explained in the methodology section of this paper. Prior to it, the theoretical background of the research is presented.THEORETICAL BACKGROUND**

Big Data can be considered as any dataset that because of its size or complexity requires nontraditional tools for its management and analysis (Miloslavskaya & Tolstoy, 2016 and Liu, 2015). This heterogeneous dataset possesses four main characteristics that ideally should always be present. These characteristics are Volume, Velocity, Variety and Value, better known as the 4V's of BD (Tabesh et al., 2019). Global BD adoption grows exponentially with each passing day, for 2021 the BD market is expected to reach around 99 billion dollars Kulkarni (2021). According to Davenport and Bean (2019). 97.2% of companies are already investing in BD and AI. This mainly because the benefits of BD adoption have been proven over and over during recent years throughout most industries (Chen et al., 2020; Rabhi et al., 2019; Tabesh et al., 2019), benefits such as improved decision making, and increased revenue (Bange et. al., 2015) are some effects of implementing BD in businesses.

2.1.Early Stages of Big Data in Construction

The construction industry currently faces many challenges that cost the world economy about $ 1.6 trillion a year, lack of efficiency, low productivity and safety issues are some of the problems that arise in the industry and what projects must face on a daily basis (Yousif et. al., 2021). Meanwhile, the amount of data generated by construction projects keeps increasing (Chen et al., 2020 and Caesarius and Hohenthal, 2018).

The overall benefits of BD implementation offer a direct solution to the problems faced by the industry which is evidenced by the rising amount of BD adoption by construction companies around the world (Hwang et al., 2021). Nowadays, BD is being applied in every stage of the project lifecycle providing improved decision-making and benefiting all stakeholders (BIGRENTZ, 2021). Authors Wong (2020) and Morrison (2021), list some of the most important impacts produced by the adoption of BD in construction, these impacts are presented in the following figure (Figure 1).

Efficient Management

- BD can make more accurate time estimations with stronger algorithms to reduce wasted time and improve project efficiency.

Accurate budget stimates

- The more data that becomes available, the better predictions can be made for future budget estimates.

Lower Project Risk

- More in-depth insights and better data.

Increases Building Efficiency

- Data analytics technology works to reduce construction time and material-related costs by presenting clear, digestible data and identifying potential structural errors before they happen.

Reduces Environmental Impact

- Construction data from past projects can be integrated into BIM technology to more accurately predict the materials and energy needed for a future project.

Improves Working Conditions

- Technology like smart construction wearables and safety management software is quickly gaining traction in the industry.

Sustainability

- BD can help reduce waste, which will improve the industry's environmental footprint. Similarly, as crews work faster, they'll run fossil-fuel-powered machinery for less time, decreasing emissions.

Figure 1: Impacts of BD implementation in Construction Projects.

Source: Adapted from Wong (2020) and Morrison (2021)

Many sources such as Burger (2019) and Wong (2020) agree in the increasing value of BD in daily life as well as in the construction industry where the added value received in the form of better decision making and improved project efficiency makes this technology to be considered by many as the future of construction. However, both authors also agree that to benefit from BD a high level of skills is necessary, since, by themselves, large volumes of data do not represent great benefits, while with the right knowledge and tools it is possible to take advantage of all the advantages that technology offers.

2.2.Strategies for implementing new technologies in Construction

According to Wattanajantra (2020), the development of a well based strategy is a key element in the adoption of new initiatives, technologies like BD are not the exception. Even though every day more studies are emerging focused on the implementation of BD in construction, there is still no clear path that indicates the steps to follow for a successful adoption, elements such as critical success factors and strategies have not been the focus of these new studies. Therefore, due to the lack of sources that identify the particular case of strategies for the implementation of BD in the construction industry, this study will use as a basis the strategies identified for the implementation of new technologies in general. Hwang et. al. (2021), makes a compilation of these strategies which have been summarised in two main areas government-oriented strategies and organization-oriented strategies and are presented in the table below (Table 1).

Table 1: Strategies to promote adoption of smart technologies

Government Oriented Strategies	**Organization Oriented Strategies**

Training of skilled workforce	Communication and change management
Government incentives	Partnership
Establish standards	Top-down leadership
Showcase of successful case study	Clear organization structure
Promoting knowledge management for smart technologies	Staff training and development

Source: Adapted from Hwang et. al., 2021.

These strategies identified in the aforementioned study (Hwang et. al., 2021), will serve as a point of comparison for the primary data collected during this investigation.

2.3.Dominican Republic as a Focus Point

The construction industry plays an important role in the economy of many countries, such is the case of the Dominican Republic where it contributed around 12% of its GDP in 2019 (Central Bank of the Dominican Republic, 2020), and a contribution of around 57% to the nation's economic growth after the effects of the COIVD-19 pandemic (Valdez Albizu, 2021). Moreover, DR’s economy is considered by The World Bank (2021) as one of the most important in the region. Also, the DR has been ranked in multiple occasions by the Economic Commission for Latin America and the Caribbean (CEPAL), as the highest economic growth of the region (UN, 2019), which indicates that the results of this research could be representative of other industries in the region with similar characteristics.

Within its national development strategy (NDS) which seeks to provide the guidelines to achieve the sustainable development goals (SDGs) the Dominican Republic developed objectives such as improvement of quality of life that are directly related to the construction industry through the provision of infrastructure, low-cos housing and basic need services to mention a few (MEPYD, 2017). These SDGs approved by the member states of the UN in the agenda 2030 of 2015 (UN, 2015) highlighted the importance of sustainable construction practices (Yousif, et. al., 2021) and therefore, the adoption of technologies such as BD that could help the country's industry could help with its achievement.

Moreover, in the country there is evidence of studies that explore the implementation of BIM (Silverio Rodriguez, 2020) and the use of Smart Devices (Silverio-Fernandez et. al., 2019) in the industry, where both serve as a basis for a future implementation of BD since their adoption implies the existence of a data generation and transmission structure and according to Tamiminia et. al. (2020) is one of the very reasons the technology emerged in the first place.

Finally, this study as a part of a bigger exploration of the Implementation of BD in the construction industry of the DR could help identify the strategies for implementing this and other similar technologies that would benefit an industry in need of modernization.

2.4.Research Scope and Gap

Big Data has been identified as a possible solution to the needs of the construction industry, this data driven technology provides benefits that would ensure the much-needed sustainable development of the industry as well as its modernization (Vellante, 2021). However, the proven resistance to change and the technological drive required by the technology makes its adoption not a safe bet, this combined with the lack of clear guidelines on adoption makes the implementation of BD and uphill battle (Ngo et al., 2020).

Despite becoming the aim of a great number of studies such as Mourtzis et. al., (2016); Wu et. a., (2017); Raguseo, (2018); Caesarius and Hohental, (2018); Silva et. al., (2019); Salleh and Janczewski, (2019); Baig et. al., (2019); Knowles, (2020); Balti et. al., (2020); Bag et. al., (2021); and Aversa et. al., (2021), to mention a few, none directly addresses the key factors for implementation, particularly no studies were found that explore the strategies implemented in the adoption of the technology, nor is there detailed documentation of implementation cases outside of North America and Asia.

Also, the construction industry's adherence to traditional practices makes the process of adopting new technologies inefficient and requires in-depth knowledge of them (Silverio-Fernandez et. al., 2019). Therefore, the main objective is to explore the understanding of BD technology and the elements that would enable am industry wide adoption, with this study focussing on this last part by exploring the strategies that industry decision makers understand are essential for implementation.

By identifying the strategies for implementing technologies such as BD in the construction industry of the Dominican Republic this paper provides possible guidelines for adopting this and other technologies and that could also be replicated in other environments.

3. RESEARCH METHODOLOGY

This section details the methodology used to carry out this research, the results of which will be presented in the following section. Even as the number of cases of big data implementation in construction continues to increase, sources detailing the basics on how to achieve this adoption are scarce (Creswell, 2017). This fact directs the research towards the qualitative approach which facilitates a deep exploration of an issue that otherwise could not be addressed with another type of methodology (Busetto et. al., 2020). This phenomenon is better known as the principle of data availability (Kumar, 2014).

The information on which this study is based was collected through the performance of 21 semi-structured interviews in the construction industry of the Dominican Republic between the months of October 2019 and March 2020. These interviews were performed to decision-making representatives of medium and large companies with undoubted presence in the Dominican Republic market, this in order to ensure that they have both the knowledge and the possibility of adopting the technology in the future. The following figure (Figure 2) summarizes the research design process carried out in this study.

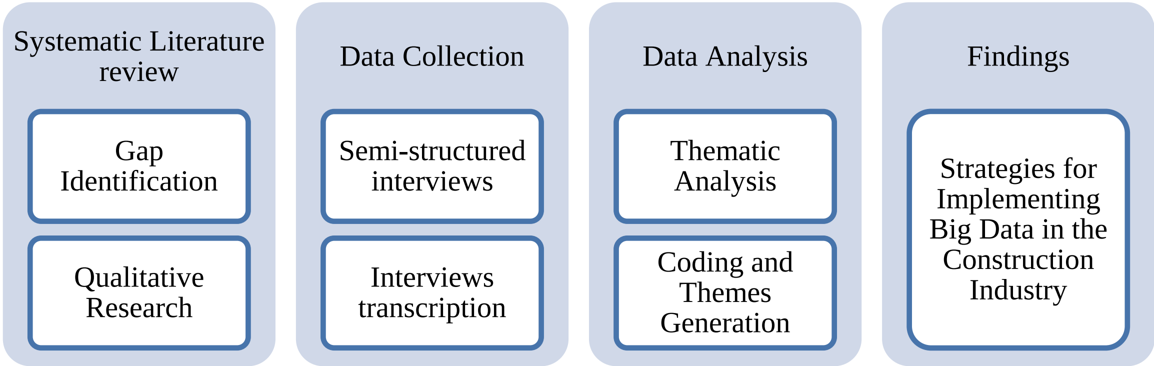

Figure 2: Research Design

3.1.Design of the interviews

The interview used to collect the information was aimed firstly at exploring the level of knowledge of the participants about Big Data and then exploring the different factors that could influence its implementation. one of these factors is the focus of this study which explores the strategies that according to the professionals of the area are necessary for the future industry-wide implementation of the technology.

The need to collect consistent data that would allow in-depth exploration of the topic suggested the adoption of semi-structured interviews as a capture method (Cohen and Crabtree, 2006), in addition to the fact that this method is characterized by capturing the participants' point of view which is one of the objectives of this study (DeJonckheere and Vaughn 2019).

In the section of the interview addressed in this study the participants were asked to describe the strategies that could allow the adoption of technologies such as Big Data in construction at both organisational and industrial level, to determine if the difference exist between the strategies for implementing the technology in the two levels.

3.2.Sampling and data collection

Two defining factors were identified during the literature review, which would directly affect the study sample. In first place, the size of the company was determined as a key element for the adoption of new technologies, indicating that this occurs mainly in large companies (Ngo, et. al., 2020 and Maroufkhani et. al, 2020), and in second place the input from decision makers it is vital not only to provide the required information but also to promote the adoption of the technology in the future. The consideration of these factors in the selection of the sample makes the method used non-probabilistic, which, according to McCombes (2019) is characterized in the use of some criteria for the selection of the sample.

To pinpoint the participating companies the “General Law of Commercial Companies and Individual Limited Liability Companies” (Congreso Nacional de la Republica Dominicana, 2008) was consulted where the official classification system for companies in the Dominican Republic is detailed. This system classifies the companies in four categories: Micro, Small, Medium, and Large companies, according to their size, number of employees, active capital and revenue.

At the end, to participate in the study, medium and large-sized companies from the construction industry of the Dominican Republic were contacted, while the selection of participants was made according to the position they occupy in the company, making sure the participants were construction professionals with experience and within the areas of management and decision-making of their respective companies.

The interviews were performed in Santo Domingo, D.R., between October 2019 and March 2020. The interviews were captured using voice recordings and lasted between 9 and 22 minutes approximately. Lastly the size of the sample was determined by using the saturation method, which indicates that the number of interviews is sufficient when new information is no longer perceived, and only information similar to that which is possessed is being obtained (Hitchings and Latham, 2020). The literature indicates that in semi-structured interviews saturation is usually reached between 15 and 20 interviews (Crouch and McKenzie, 2006), in this studio it was reached around 19 interviews were reached and two more were carried out as a safety factor.

3.3.Data Analysis

For the analysis of the information collected, the thematic analysis method was used, which consists of the identification of patterns and themes within the analyzed data through a six-step systematic method (Figure 3) (Caufield, 2019).

First, to prepare the data for the analysis Creswell's method for interviews for analysis was partially applied, which consists in the transcriptions of the audio interviews, followed by the preparation and iterative review of transcripts (Creswell, 2013). Also, in this study it was necessary to add another step of translating the interviews from the original Spanish language in which they were perform.

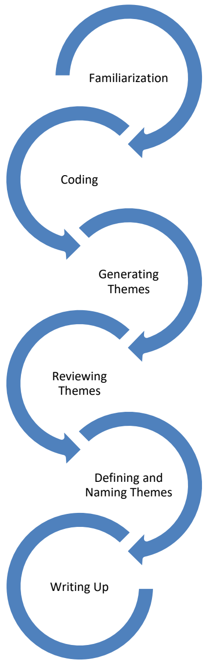

Figure 3: Thematic analysis process. *Source: Adapted from Braun et. al., (2019).*

According to Caufield (2019), the selected thematic analysis is especially applicable to interview transcripts, since the iteration of the six stages allows the generation of themes that are representative of all the relevant information contained in the data (Braun et. al., 2019). Also, the use of software like NVivo which are specially designed for qualitative data analysis (McNiff, 2016), facilitates this process for which it was used in this study to streamline the process.

Finally, the understanding of relevant themes contained in the data through the review of interviews-codes relationship the objective of the analysis was reached (Martinez, et. al., 2021), by identifying the different strategies that according to the expertise and experience of the construction professionals of the Dominican Republic, are necessary for a future implementation of BD in the country's industry.

4. STRATEGIES FOR IMPLEMENTING BIG DATA IN CONSTRUCTION

In this section, the four main strategies identified in this study will be presented. the identification of these strategies for the implementation of BD in the construction industry of the Dominican Republic will serve as a guide or action plan for professionals who understand the impact this could have in their projects and those who wish to implement the technology in the future.

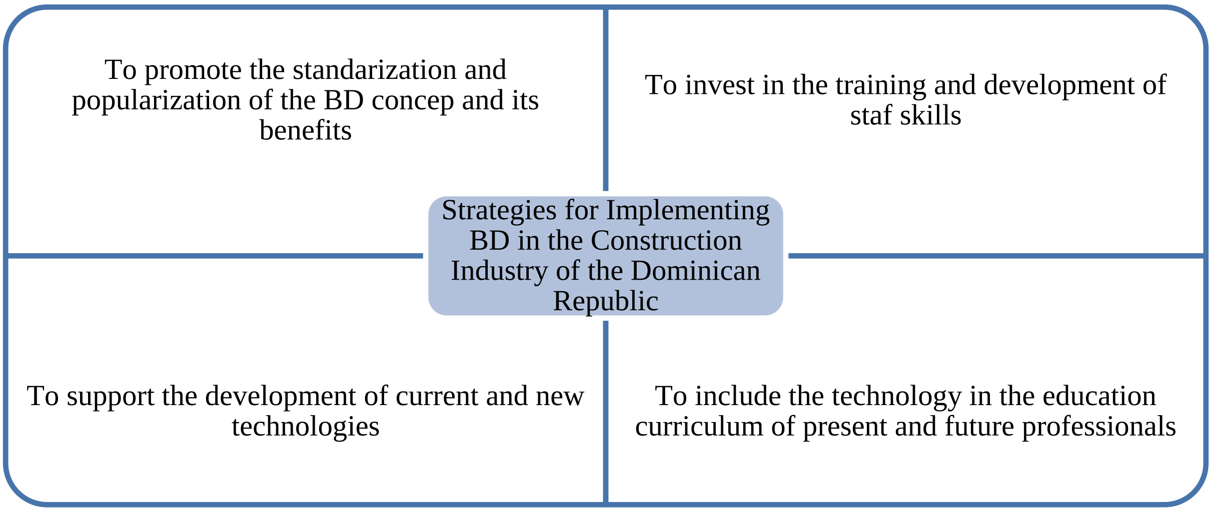

Figure 4: Key Strategies Identified in the Data Analysis

In this case, all the strategies identified by the participants were from the point of view of the organization and the industry, thus generating the first major difference with the literature review where the governmental approach was identified.

4.1. To promote the standardization and popularization of the concept and technology benefits

All throughout the development of this research, including previous studies, the importance of an in-depth knowledge of the BD concept and its benefits has been highlighted, this is based on the low level of understanding that the industry has about the technology in presented in Reyes-Veras et. al., 2021a, as well as the identification of "Lack of awareness" as a key challenge in Reyes-Veras et. al., 2021b. Subsequently, it is consistent for participants to identify the popularization and standardization of the concept of BD and its benefits as a key strategy for the adoption of the technology in the industry. In this regard, interviewee I7 expressed the following:

> "[…] dissemination of concept and at the same time, benefits of its implementation".

The need for a consolidated concept in the industry is a key element for adoption (Reyes-Veras et al., 202[a]), as the knowledge of the benefits helps more companies risk investing in the technology. Furthermore, Participant I13 also expressed:

> "To implement BD, I believe that the main strategy would be to standardize the concepts and to make sure that everyone knows of the benefits of its implementation, to provide proof of the positive results of its applications and to emphasize which areas of the project process would benefit with its adoption".

Coinciding with the previous comments, interviewee I18 expressed the following:

> "[…] that people get to know the concept and its benefit better, a strategy could be popularising the term […]".

With the above statements, the participants expressed that one way to counteract the basic levels of knowledge that the industry has about BD is through the standardization and popularization of the term. This strategy will allow, above all, to understand the benefits of the adoption of the technology as well as the impact that it could have on construction projects.

4.2. To invest in the Training and Development of Staff Skills

Another key challenge facing the adoption of new technologies is the lack of technological expertise (Reyes-Veras et. al., 2021[b]), which is especially true for emerging technologies, as professionals are in the early stages of the learning curve (Chehri et al., 2021). For the adoption of some technologies, companies must decide between bringing personnel from other areas and training them in the area of interest i.e., management of construction projects, or train company personnel in the use of the new tool.

The adoption of new initiatives in a company requires many cases to invest in staff training, such is the case of BD implementation, participants identified this strategy based on their experience with previous technology implementation and as a main step they believe will be necessary for a future adoption of the technology, as can be seen in what was expressed by interviewee I17, who stated the following:

> "[…] we don't have any strategy other than personal training; we have workshops to learn new techniques and we get encouraged by the company to continue our education with workshops, courses, MBAs, etcetera."

Interviewee I20, also agreed by expressing the following:

> "[…] the ongoing capacitation of workers and management personal". I20

In both cases, the participants identified staff training as a recurring process in their companies, and which can be adapted according to the present and future needs of the business, thus confirming the effectiveness of the strategy and the development of staff skills as a key element in the adoption in the advancement of the company.

4.3. To support the development of current and new technologies

There are many technologies that could serve as a stepping point for a future adoption of BD, in the case of the Dominican Republic, technologies such as BIM (Silverio Rodriguez, 2020) and the adoption of Smart Devices and drones (Silverio Fernandez, 2019 and Reynoso Vanderhorst et. al., 2019) in the construction industry serve this purpose through the generation and transmission of data as well as the general digitization of processes that is achieved with the implementation of BIM. Therefore, the investment in the development of current technologies is closely related to the development of emerging technologies, as expressed by the interviewee I2.

> “[…] the implementation of the Drones and to advance more in the technology part for topography (Land Surveying), because is something that we manage daily, and for example, we have projects that they require it, they require that we become more technological, more developed in that area, for instance bridges, eh, roads, everything that is infrastructure […] to develop that part in the technology in the topography area, those three are like the main axis [Project Management, BIM and Implementation of Drones] right now of [this company] five years from now”. I2

The recognition that BD currently receives makes companies include investment in the development of areas that allow the adoption of technology in the short or long term within their future development strategies, with what I11 agrees by expressing the following:

> “[…] to invest in tools that can use that storage data so we can create a process that will upgrade our decision-making process based on the previous experience”. I11

The investment in tools that companies can take advantage of today as well as serve as a basis for the adoption of future technologies is an attractive strategy that companies could be motivated to implement, since they would not only be investing to receive benefits to future but, that at present they would be incorporating tools that can be applied to current projects.

4.4. To include the technology in the education curriculum of present future construction professionals

As well as the investment in the development of the skills of professionals in the area (4.2), the education of future professionals also plays an important role in the implementation of new technologies (XXX). This is because future professionals would be familiar with the technology to be implemented. An example of this is expressed by interviewee I18 in the following statement:

> “[…] start teaching about it in the last modules of university, that way the people that will start their work carrier already know about this and have a better understanding that, that they can contribute to their workplaces”. I18

The inclusion of BD within the educational curriculum of future construction professionals would result in a positive impact for a future adoption of the same, since these professionals would possess the basic knowledge required about the concept and the benefits, which would translate into less resistance. at the time of implementation.

5. DISCUSSION

The need to manage today’s sustainable development needs as well as in the role of construction in the achievement of the goals that have been set plays an important role in the modernization of the industry and the search for tools that allow managing and meeting these expectations. On the other hand, many sources highlight the ability of BD to generate change in the industry that allows meeting these needs, based on the positive results of its BD in other disciplines (Tamiminia et al., 2020; Caesarius and Hohenthal, 2018; Pigni et al., 2016; The Economist, 2012; Raguseo, 2017), whereas limited sources exist about the factors that enable the BD adoption within the construction industry indicating the presence of a gap.

The identification of strategies that allow the adoption of new technologies such as BD in the construction industry allows both the industry and the companies to develop an action plan whose objective is to adopt technology as part of the project delivery process Wattanajantra (2020). In comparison with the strategies identified in the literature (Hwang et. al., 2021), the strategies identified by this study adhere more to the basic effects of technology implementation such as knowledge of it and investment except for the approach to the development of staff skills, which is found in both areas.

In the first place, the need for in-depth knowledge of BD technology as well as a homogeneous concept has been repeated in the different areas of this research (Reyes-Veras et. al., 2021[a] and Reyes-Veras et. al., 2021[b]), as well as in literature. As an acknowledgment of this and based on their experience, the participants of this study have expressed the need for a strategy that addresses this demand. The promotion and standardization of the BD concept and its benefits seeks to improve the general knowledge of the industry about BD, thus facing challenges such as lack of awareness and contributing to the decrease of the resistance to change identified previously (Reyes-Veras et. al., 2021[b]) since familiarization with the concept reduces the chances of its rejection.

Likewise, staff training was identified as a recurrent element within some participants companies (4.2), which is reflected in the choice of staff training as a strategy that would benefit the implementation of BD in the industry, in any case, the development of staff skills is an element considered in most cases within the investment of new technologies, but in this particular case, the impact of providing early BD training for the construction professionals would benefit not only the future adoption of the technology but also the overall digitalization and efficiency of the company processes, and since some cases construction companies already offer ongoing training to its workers it would be a matter only to focus on the development of skills relevant to BD.

This strategy is also supported by the literature, were Hwang et. al. (2021), identifies it as a key element both from the governmental and the organizations point of view, confirming that the implementation of this strategy could represent the difference between a successful adoption of BD in the construction industry and a failed attempt of improving processes and decision-making.

Moreover, another key strategy identified by participants is the development of current technologies that will enable the adoption of BD in the future (4.3). initiatives that companies are currently applying such as BIM, Smart Devices and Drone implementation (Silverio Rodriguez et. al., 2020; Silverio Fernandez et. al., 2019 and Reynoso Vanderhost et. al., 2019), will serve as the basis for the future adoption of BD, both in the adaptation of the data generation and transmission systems necessary for the technology to be implemented and in the familiarization of companies with the digital environment.

Finally, the strategy of including the key elements of technology within the curriculum of future professionals in the industry ensures that they are familiar with it at the time of starting their working life thus minimizing any resistance they may present to the adoption of Big Data in the future (4.4). The low level of knowledge that the industry has about the concept of Big Data and its benefits represents one of the greatest challenges for implementation.

In summary, the key strategies presented above reflect the current state of BD technology in the construction industry of the Dominican Republic. And therefore, they focus on the basic elements such as improving awareness, promoting investment in tools that benefit both the current projects of companies and the future adoption of technology, developing the capacities of the person to adopt this and other technologies, as well as the expansion of the concept towards the area of education in charge of training future professionals in the industry.

6. CONCLUSION

Change is inevitable and the challenges faced by the construction industry become more difficult due to the low productivity and efficiency that have characterized the industry in recent years. The possible solution that Big Data offers to these problems as well as the improvement of construction processes in general is what makes this technology to be identified by various sources as the future of the industry. The attachment of the construction industry to its traditional practices makes difficult the leap to digitization needed both to overcome these challenges and to meet the requirements of an evolving society.

The demonstrated ability of improving decision-making and efficiency are some of the aspects that make BD a key tool for the future of the industry, so the exploration of the elements such as strategies that reveal a path to a successful adoption plays a key role in the implementation of the technology, thus improving the odds of being successful as well as speeding the implementation process.

The identification of BD adoption strategies will help construction companies to plan their implementation process by taking actions today that can smooth the process once they are ready for the technology. This study highlights the need for the industry to join in the efforts to standardize and popularize the concept of BD in order to overcome the challenges faced by the industry. in-depth knowledge of this technology and its characteristics will ensure that it is adopted at all levels of organizations as well as industry thus reducing the intrinsic resistance to change of the construction, also, the popularization of technology ensures affordability. Moreover, the investment in technologies that companies can take advantage of in their current projects as well as serve as a basis for the implementation of BD as well as the development of workers' skills, it will ensure that when implementing the technology, companies have the necessary tools. Finally, the strategy of including BD related content in the education stage of future professionals will create familiarity between the professionals and the technology which reduces resistance to change and makes adoption smoother.

This study is limited to the identification of strategies for the implementation of new technologies such as Big Data. The impact of this strategies exists within the framework of the construction industry of the Dominican Republic, but with the prospect that they may be useful for the overall adoption of technology.

Ultimately, this study and the wider research to which it belongs, will serve as a contribution to the body of knowledge of BD technology aimed at researchers, professionals, and students alike. The specific case of these strategies will serve so that both the industry and construction companies can create an adequate action plan that paves the way for future adoption of technology.

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THE POTENTIAL FOR INTELLIGENT PASSIVE ROOM ACOUSTIC TECHNOLOGY IN CLASSROOMS: A BIM-BASED SIMULATION

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ABSTRACT. *A BIM-based acoustic simulation is conducted for the first time using the novel intelligent passive room acoustic technology (IPRAT) in classrooms. IPRAT achieves real-time room acoustic improvement by integrating passive variable acoustic technology (PVAT) and acoustic scene classification (ASC). 20 classroom environments are accounted for and virtually configured for the study, multiplying 5 classrooms with 4 aural situations typical to New Zealand classrooms. I-Simpa acoustic software is used to perform the simulations, in which the acoustic parameters reverberation time (RT), sound clarity (C50) and sound strength (G) are analysed. The RT, C50 and G ranges achieved with IPRAT are presented, and to analyse the improvements offered by IPRAT, 'optimized' RT's were calculated for each aural situation, by manipulating C50 and G. A comparison of 'current,' 'achievable' and 'optimized' acoustic parameters reveals the potential benefits of IPRAT. As the first original research attempting to quantify the effect of IPRAT, this paper makes significant contributions to acoustic technology advancement, acoustic quality improvement, and smart acoustic control in buildings.*

KEYWORDS: *acoustic simulation, classroom acoustics, acoustic optimisation, intelligent acoustics, room acoustics, acoustic technology*

1.0 INTRODUCTION

Recently, intelligent passive room acoustic technology (IPRAT) has been conceptualized, achieving real-time room acoustic improvement (see figure 1). This achievement is realized through the integration of passive variable acoustic technology (PVAT) and acoustic scene classification (ASC) (Burfoot *et al.*, 2021). Functionally, ASC intelligently identifies changing aural situations, and PVAT physically varies the reverberation time (RT) using dynamic wall panels. The RT (time taken for a 60dB sound level decrease after a noise has stopped) is changed by altering the average sound absorption coefficient of the space. The wall panels achieve this varying sound absorption coefficient by using reflective and absorptive materials, and alter this parameter in real-time as they respond to the dynamic aural state of a space.

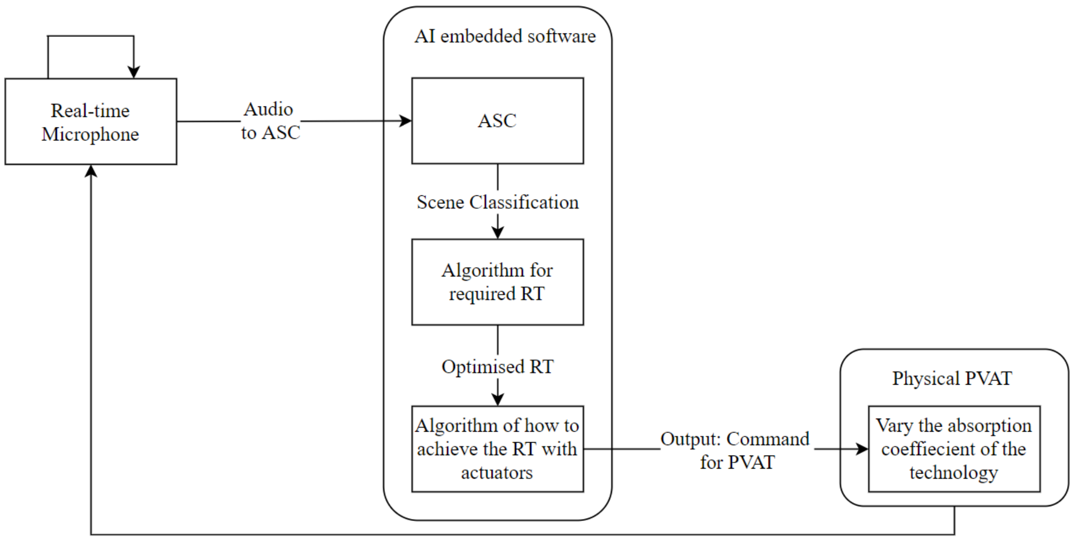


Figure 1. IPRAT functionality (Burfoot *et al.*, 2021)

The inventors of IPRAT have proposed classrooms as an appropriate architectural space to improve RT, as better acoustic quality in classrooms correlates with higher academic performance (Benka-Coker *et al.*, 2021). Additionally, background noise and/or long RT's contribute to poor listening conditions, impairing memory and learning (Ljung *et al.*, 2009). In lecture or instruction situations, long RTs are needed to project and enhance the teacher's voice and reduce vocal strain. Alternatively, in a group or individual study situations, short RTs are needed to absorb noise and increase voice clarity. IPRAT can detect these changing aural situations, and vary the RT accordingly to improve room acoustics. Thus, the benefits are realised as reductions in teacher vocal disease and increases in student comprehension and cognition.

With the novel IPRAT, classrooms receive improved RTs for any aural situation happening in the space. But what is the ideal RT for each situation? When RT is varied, the sound clarity (C50) and strength are also affected. C50 is used to measure the clarity of speech objectively; how well you can understand speech due to sound arriving at different times and intensities to the ear canal. As sound strength (G)[dB] increases, C50 decreases. Additionally, a longer RT results in a larger G, and a lower C50. So, we must consider which values of RT, C50 and G will create the most favourable acoustic environment for each aural situation, accounting for the interdependencies between these parameters. A literature review of classroom acoustic parameters reveals better learning performance with RT values within the interval 0.4-0.9s, but most favourably at 0.6-0.7s (Minelli *et al.*, 2021). This, however, doesn't allow for changing RT's within the space. Unfortunately, the concept of optimising RT in real-time is in its infancy; there is no current literature outlining optimal values. In section 4, RT values are defined, which strategically maximise C50 or G for each classroom and aural situation, and a database for these values is created. By achieving appropriate acoustic parameters for changing aural situations, room acoustic quality is improved. In this sense, RT can be used to describe the behaviour of IPRAT, and C50 and G can be used to quantify the acoustic improvements.

IPRAT is a novel, emerging technology, and there is a need to quantify its effect on room acoustics. It is imperative to continually analyse and re-define the built environments effect on occupant wellbeing (Ghaffarianhoseini *et al.*, 2018), and this shouldn't neglect acoustic quality consideration (Ganesh *et al.*, 2021). Thus, this research aims to discover the potential for IPRAT. Objectively, an acoustic simulation experiment is conducted and presented to measure the effect of IPRAT. 20 virtual environments have been considered in this research to test the IPRAT, by combining 5 classrooms with varying characteristics and 4 aural situations. The study focuses on values assumed by the acoustic parameters RT, C50 and G. These parameters allow the understanding of acoustic improvements for both teacher vocal relief and student comprehension. The IPRAT is assumed to vary RT and is represented in the simulation by 6 different absorption coefficient spectrums. For the purpose of this simulation, the panels achieve varying RT by rotating sound reflecting louvers in front of porous sound absorption panels. Thus, the 6 absorption coefficients are expressed as louver 'rotations' from 0-100% open. A comparison of 'current', 'achievable' and 'optimized' acoustic parameters reveals the benefits of IPRAT.

2.0 BACKGROUND

2.1 Indoor environmental quality and acoustic comfort

When looking at spaces intended for cognitive functions, noise is one of the most studied Indoor Environmental Quality (IEQ) factors in relation to effects on occupants (Wang *et al.*, 2021). Studies reveal acoustics as the majority factor for IEQ acceptance in university classrooms (Lee *et al.*, 2012) and primary school classrooms (Zhang *et al.*, 2019) (Bluyssen *et al.*, 2020). Although great strides have been made in recent literature to improve the IEQ elements of indoor air quality, thermal and light comfort (Berquist *et al.*, 2019) (Kallio *et al.*, 2020) (Korsavi and Montazami, 2019) (Korsavi *et al.*, 2020) (Zhang *et al.*, 2022), acoustic comfort research is trailing behind. Acoustic comfort is acknowledged in IEQ research, yet it is often neglected in the data collection and analysis stages or given less attention than other IEQ's. Furthermore, a space's 'Acoustical Quality' index considers room acoustics, vocal effort, acoustic satisfaction, and consequences of bad acoustics (Minelli *et al.*, 2021). Many of the IEQ studies which do not neglect acoustics, do neglect the RT measurement in their assessment of acoustic comfort. Some choose to solely focus on outdoor noise pollution (Zuhaib *et al.*, 2018) (Barrett *et al.*, 2015) or indoor sound level (Parkinson *et al.*, 2019) (Wong *et al.*, 2018) (Mydlarz *et al.*, 2013) (Yang and Moon, 2019) (Wu *et al.*, 2020). Agreeably, Larsen *et al.* (2020) present an interesting criterion to assess the acoustic comfort in dwellings, made up by 'noise from surroundings 35%', 'noise from neighbouring dwellings 35%', 'noise from within the dwelling 25%' (of which 60% weighting is given to sound level and 40% to RT) and 'occupants possibilities' to adjust the acoustic IEQ 5%'. Although acoustic comfort encompasses all noise experienced in classrooms, IPRAT does not reduce noise pollution from outside the classroom, this should be considered in the envelope design. Nevertheless, in the case of classrooms using IPRAT, the RT can be optimised, and the occupants may adjust the acoustics to their preference.

2.2 BIM-based simulation for intelligent technology optimization

Another rising trend in the built environment is the use of BIM for building design and optimisation. Apart from the more commonly understood applications, BIM can simulate the performance of smart building technology, which literature proves should be incorporated into our built environment to maximise IEQ (Ghaffarianhoseini *et al.*, 2019) (GhaffarianHoseini, 2013). For example, simulation optimization techniques have been used to improve the performance of Internet-of-Things networks (Kumar *et al.*, 2020). The integration of BIM and smart building systems has also been used to maximize unique occupant thermal comfort (Birgonul, 2021), so, the same can be done for acoustic comfort. The time-savings associated with BIM adoption for technology optimisation have also been emphasized in literature (Doan *et al.*, 2020), especially when utilised as a building element visualization and optimisation tool (Ghaffarianhoseini *et al.*, 2017b). Furthermore, simulations are especially appropriate now that lockdowns around the globe due to Covid-19 are hindering manufacturing progress and on-site research. There is a strong need to intelligently vary acoustic conditions in our modern, dynamic classroom spaces. Features of IPRAT such as sensors, real-time data monitoring and user control contribute to increasing the intelligence of a classroom (Ghansah *et al.*, 2020). In this study, a BIM-based simulation is used for design optimisation of the smart building element IPRAT. So, the BIM software I-Simpa is used to explore the relationship between IPRAT, room acoustics and IEQ.

2.3 I-Simpa simulation software

It is often beneficial to simulate the performance of the technology before developing a working prototype. In this case, we can see approximately how IPRAT will perform without having to build and train an acoustic scene classifier. The applied simulation tool for this study is I-Simpa, selected for its capabilities: custom design of various room layouts and geometries, custom aural situation simulation, surface absorption coefficient adjustments, building component modelling, and accurate measurement of RT, C50 and G. In a simulation study, it is challenging to verify experimental results without simultaneously conducting a real-life study of similar nature. Thus, it is beneficial to implement model verification and validation throughout the entire life cycle of a simulation study. Verification involves building the model right. However, validation involves building the right model (Hensen and Lamberts, 2019). In recent literature, three acoustic modelling software were assessed by comparing modelled and measured RT data (Raymond, 2019). I-Simpa achieved modelled RTs lower than measured values in both of the simulations. However, the nature of this study involves a pre/post condition analysis, so inaccuracies experienced 'pre' treatment will equally exist 'post' treatment. Thus, I-Simpa software can still provide us with reliable comparative data as it is presented in a relative context. It cannot however be compared with relevant industry standards, as this would require the simulation values to be properly validated against measured data. The simulation method and process are outlined in Section 3.

3. METHOD

The benefits of IPRAT are realised when RT is uniquely improved for each classroom (1-5) and aural situation (A-D) combination. Thus, in each of the 20 virtual environment configurations, RT, C50 and G are measured firstly in the classrooms' current state and secondly when IPRAT is being used. I-Simpa acoustic software is used to conduct the simulations. However, the validation and verification of this software falls outside of the scope of research. To simulate the behaviour, performance, and benefits of IPRAT, a virtual representation of the technology is created and tested in the 20 virtual classroom environments. In this section, details on the simulation environment and processes are provided.

3.1 Classroom geometry and surface properties

The classroom profiles used in this study were originally received as detailed models from Burfoot *et al.* (2020). These virtual environments were created based upon various physical environments described in existing New Zealand (NZ) studies, validated by comparison with international classroom profile studies. I-Simpa software prefers simplified geometries combined with precise absorption and diffusion coefficients for each surface. Thus, the detailed classroom models were simplified into basic shapes; a rectangular box within a larger classroom space (see figure 2). The walls are of negligible thickness, as I-Simpa only requires you to model the interior of a room. The small inside box represents the furniture and occupants (1m high, 2.5m from the front wall, 1m from all other perimeter walls).

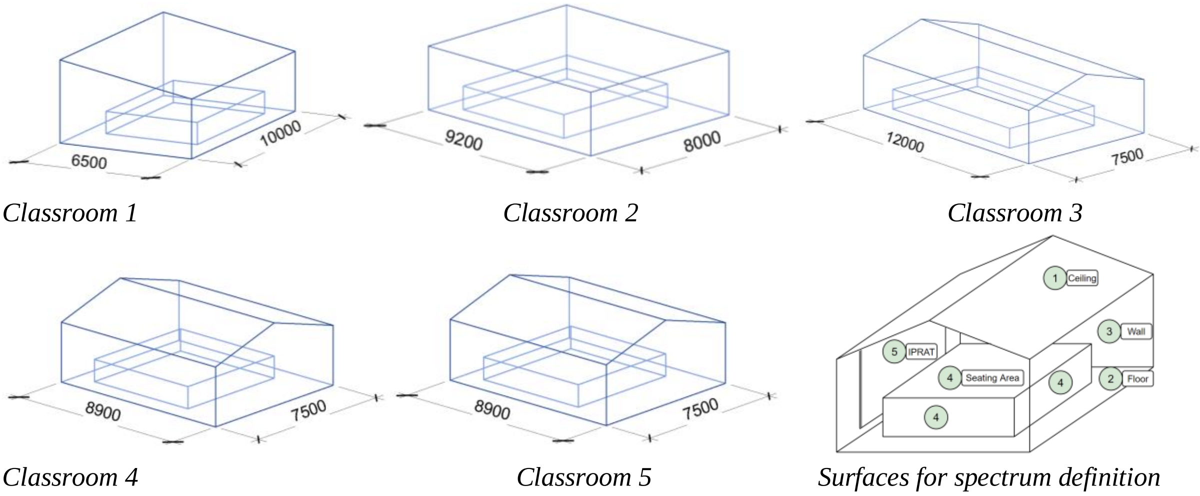


Figure 2. Simplified classroom geometries and surfaces

Through interpolation, the coefficient spectrums were obtained and applied to each simplified surface to accurately represent the unique distribution of objects and materials on that surface (see table 1). Also shown on this table are the surface characteristics for each classroom, based on the data from Burfoot *et al.* (2020).

Table 1. Interpolated absorption and diffusion coefficient spectrums for each surface option

Surface	Spectrum Interpolation Requirements	Classroom characterised with this surface type	Interpolated Absorption Coefficient Spectrum (125, 250, 500, 1000, 2000, 4000, 8000Hz)	Interpolated Diffusion Coefficient Spectrum (125, 250, 500, 1000, 2000, 4000, 8000Hz)
1 - Ceiling	Acoustic Pinex Ceiling – no interpolation	2, 4	(0.27, 0.28, 0.36, 0.43, 0.39, 0.39, 0.45)	(0.06, 0.07, 0.1, 0.15, 0.15, 0.2)
	Gib ceiling - no interpolation	1, 3, 5	(0.12, 0.09, 0.09, 0.09, 0.08, 0.09, 0.13)	(0.03, 0.03, 0.02, 0.01, 0.01, 0.01)
2 - Floor	Thin carpet on concrete - no interpolation	1	(0.05, 0.1, 0.25, 0.3, 0.35, 0.4, -)	(0.06, 0.07, 0.1, 0.15, 0.15, 0.2)
	Thin carpet on timber - no interpolation	2, 3, 4, 5	(0.14, 0.19, 0.21, 0.24, 0.29, 0.33, 0.49)	(0.06, 0.07, 0.1, 0.15, 0.15, 0.2)
3 - Wall	Wall - Large Glazing - 63% Gib, 35% Glazing, 2% Wood	1, 3, 4	(0.201, 0.146, 0.121, 0.100, 0.076, 0.072)	(0.066, 0.045, 0.03, 0.028, 0.023, 0.023)
	Wall - Some Glazing - 73% Gib, 25% Glazing, 2% Wood	5	(0.178, 0.130, 0.113, 0.1, 0.077, 0.077)	(0.059, 0.043, 0.031, 0.025, 0.021, 0.021)
	Wall - Some/Little Glazing - 88% Gib, 10% Glazing, 2% Wood	2	(0.144, 0.106, 0.1, 0.093, 0.079, 0.084)	(0.048, 0.04, 0.028, 0.02, 0.012, 0.018)
4 – Seating Area	Seating Area – Concrete - 20% occupants, 45% furniture, 35% Thin carpet on concrete	1	(0.071, 0.099, 0.16, 0.172, 0.195, 0.222)	(0.415, 0.371, 0.339, 0.384, 0.358, 0.375)
	Seating Area – Timber - 20% occupants, 45% furniture, 35% Thin carpet on timber	2, 3, 4, 5	(0.10, 0.13, 0.14, 0.151, 0.174, 0.2)	(0.415, 0.371, 0.339, 0.384, 0.358, 0.375)
5 – IPRAT	Closed - 100% Wood		(0.15, 0.11, 0.09, 0.07, 0.06, 0.06)	(0.6, 0.45, 0.32, 0.38, 0.3, 0.3)
	20% Open		(0.18, 0.24, 0.3, 0.28, 0.26, 0.25)	(0.6, 0.45, 0.32, 0.38, 0.3, 0.3)
	40% Open		(0.21, 0.37, 0.49, 0.48, 0.46, 0.44)	(0.6, 0.45, 0.32, 0.38, 0.3, 0.3)
	60% Open		(0.24, 0.49, 0.7, 0.69, 0.65, 0.62)	(0.6, 0.45, 0.32, 0.38, 0.3, 0.3)
	80% Open		(0.27, 0.62, 0.9, 0.89, 0.85, 0.8)	(0.6, 0.45, 0.32, 0.38, 0.3, 0.3)
	Open - 99% Autex Quietspace		(0.3, 0.75, 1.1, 1.1, 1.05, 1)	(0.6, 0.45, 0.32, 0.38, 0.3, 0.3)

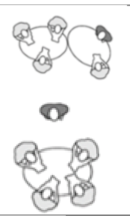
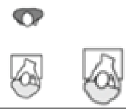
3.2 Representing the IPRAT

When IPRAT is not in use, all 4 walls for each classroom are considered as ‘Surface 3 – Wall’. When IPRAT is in use, 2 walls for each classroom are applied with ‘Surface 5 – IPRAT’ (the back wall and right hand wall), and the remaining 2 walls stay as 'Surface 3 – Wall'. For these simulations, the PVAT component of IPRAT is conceptualized as hard reflective louvers which rotate open and closed to cover or reveal a porous sound absorption material behind. When the louvers are rotated closed, the sounds waves reflect off the hard surface to increase RT. When the louvers are rotated open, the sound passes through and is absorbed by the panel behind, to decrease RT. The IPRAT is represented by spectrum coefficient interpolated in increments of 20% from closed (spectrum for 'wood' used) and open (spectrum for 'Autex 50mm Quietspace Panel' used). For the diffusion coefficient, the spectrum for 'furniture' is used for all rotations. Inaccuracies from this constant diffusion coefficient are minimized because, as the IPRAT rotates from 'closed' to 'open,' more surface is acting as an absorber, and sound that is absorbed is not diffused. The simulations assume that when the louvers are rotated open, 99% of the sound waves pass through to the absorption panel. In reality, the actual percentage would depend on the width and thickness of the louvers, and should be scientifically tested.

3.3 I-Simpa acoustic simulation

To streamline the simulation process, a blank template project was set up in I-Simpa, which included all surface materials, sound sources, and receivers. This template was then adjusted and used for each simulation, by 'enabling' the Aural Situation applicable once the 3D model was imported into the template. The surface materials were grouped into specific categories for easy application. The 4 aural situations were sourced from Burfoot *et al.* (2020) (see table 2), which are based on teaching styles typical to NZ, identified by Bradbeer *et al.* (2017). Within the template, the aural situations contained the number of speakers and at what sound level, but not their position in space.

Table 2. Aural situations used in the simulation

Aural Situation	NZ Teaching Approach	Representation	People speaking	Voice intensity	dB	I-Simpa Approach
A	-Teacher speaking to all children -Teacher facilitating large group discussion		1-2	Classroom Voice	65	1 omni-directional speaker source, grid of punctual receivers
B	-Teacher facilitating small group discussion -Collaborative/shared learning supported by teacher when needed		4-6	Conversational Voice	59	4 omni-directional speaker sources, plane receiver at 1m height
C	-One-on-one instruction in low voice -Individual learning		0-1	Conversational Voice	59	1 omni-directional speaker source, plane receiver at 1m height
D	-Informal use of the space		6+	Conversational Voice	59	8 omni-directional speaker sources, grid of punctual receivers

For this study, 5 receivers have been used in 4 aural situations, so 20 combinations have been used per classroom, allowing for accurate sound measurements (Arvidsson *et al.*, 2020). Several additional steps were taken before the calculation; the type of spectrum for sound sources was defined as bluit blanc (white noise - background noise type). The 'animation – meshing' tool was used to create a geometrical mesh, the particle theory property was changed to 'energetic,' and the calculation theory was changed to SSPS which involved defining the spectrums used in the simulation under the SPSS calculation properties. From the simulations, numerical data was extracted for each of the 20 configurations; global RT30, global C50 and global G. Global values were extracted, as acoustic parameters can be inaccurate at extremes of the room, and can be compared against other studies and standards which use global values. Lastly, 'calculate for each frequency spectrum' was unchecked to cut down calculation time. The simulation was then executed by a separate command to the software *(Enable SPSS calculation theory: Double click 'SPSS' under calculation and define the spectrums* *used. Right click 'calculation,' select 'run calculation.' Right click 'global sound levels,' select 'calculate acoustic parameters'. Double click 'acoustic parameters' for the results).* This brings up a spreadsheet with the parameter values at each frequency band, global and average, which can be exported to an analysis software.

4. RESULTS AND DISCUSSION

4.1 Current acoustic state of classrooms and acoustic parameter range possible with IPRAT

Following are the descriptive results of the acoustic parameters RT, C50 and G achieved with and without IPRAT for the twenty experimental conditions. This section firstly illustrates the current acoustic state of each classroom whilst not using IPRAT (figure 3), and secondly, the acoustic range achieved when using IPRAT for all rotation states from 'open' to closed' (figure 4). The range achieved for each classroom using IPRAT is calculated, and mean range values are derived for each acoustic parameter. This range is then directly graphed alongside the current acoustic state to demonstrate the possibilities of IPRAT (figure 5).

Figure 3 shows the mean simulation results for RT, C50 and G for the 20 virtual environment configurations in their current state whilst not using IPRAT. Classroom 4 has the highest RT in its current state, and classroom 5 has the lowest. Classrooms 2 and 4 achieve the highest C50, and accordingly, the lowest G values. This could be explained by these being the two classrooms with acoustic ceiling tiles for Surface Type 1. This figure also reveals that C50 is lowest during aural situation A for all classrooms. However, the G does not vary significantly between the aural situations.

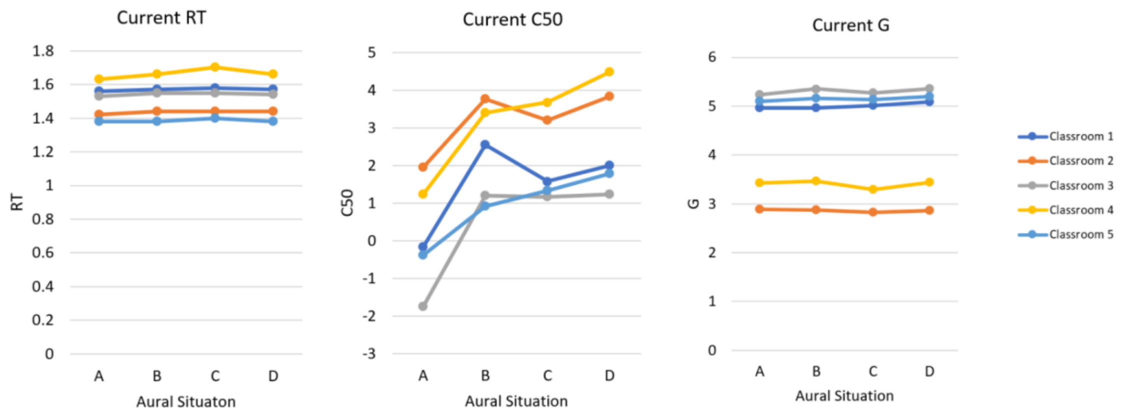


Figure 3. Current acoustic state of classrooms (not using IPRAT)

Figure 4 illustrates the RT range achievable whilst using IPRAT at various settings from 'Open' to 'Closed,' based on the simulation outputs in each classroom. Derived from these graphs, a summary of the ranges achievable for each classroom using IPRAT is provided in table 3. The range was calculated by finding the difference between the value achieved when IPRAT is 'open,' and when IPRAT is 'closed.' For example, classroom 2 achieves a maximum RT of 0.80s when IPRAT is 'closed', and a minimum RT of 0.43s when IPRAT is 'open.' Thus, the RT range for classroom 2 is 0.80s – 0.43s = 0.37s.

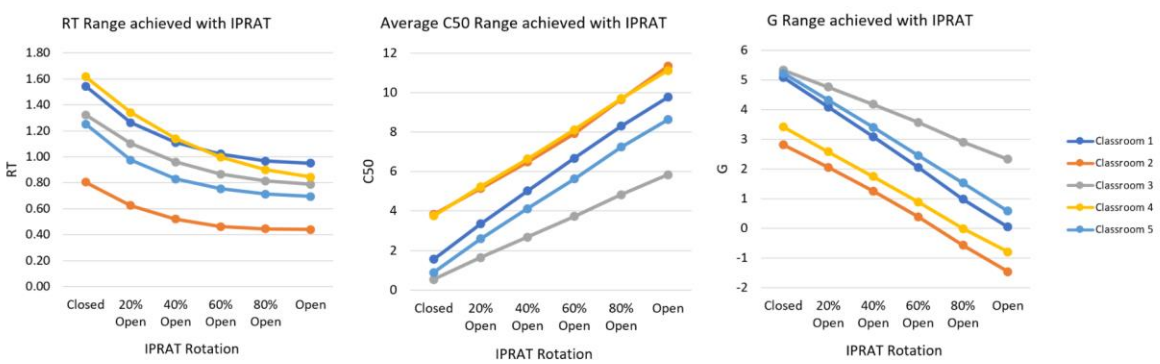


Figure 4. Acoustic parameter range achieved when using IPRAT

Table 3. Acoustic parameter mean ranges achieved when using IPRAT, derived from figure 4

Classroom	Mean RT range (s)	Mean C50 Range (dB)	Mean G Range (dB)
1	0.60	8.21	5.04
2	0.37	7.50	4.29
3	0.54	5.31	3.01
4	0.77	7.36	4.22
5	0.56	7.74	4.66
Mean	**0.57**	**7.22**	**4.24**

The mean can be used to segregate the sorted samples into statistically significant and statistically insignificant (if any) groups (Mbachu *et al.*, 2017). Classroom 4 achieves the most extensive RT range at 0.77s, whilst classroom 2 achieved the smallest RT range at 0.37s. Classroom 4 had the highest current RT, which could explain why it achieved the largest potential improvement. Classroom 2 was the only subject with a flat roof, and had the lowest sound strength in its current state. The largest C50 and G ranges are achieved by classroom 1, which could be due to the carpet-covered concrete floor characteristic or the smallest dimensions. The smallest C50 and G ranges were achieved by classroom 3, which had the longest dimensions of the rooms. All classrooms could further increase these ranges by having more extensive IPRAT wall coverage. Likewise, the achievable ranges would be decreased by reducing the IPRAT coverage.

Thirdly, in figure 5 the range achieved with IPRAT (from figure 4) and the current mean parameter values (from figure 3) are indicated for each classroom. This demonstrates the existing acoustic state against the potential acoustic states attainable with IPRAT. This figure shows the potential improvements in RT, C50 and G whilst using IPRAT. In the next section, the optimal IPRAT rotation is calculated based on these achievable ranges.

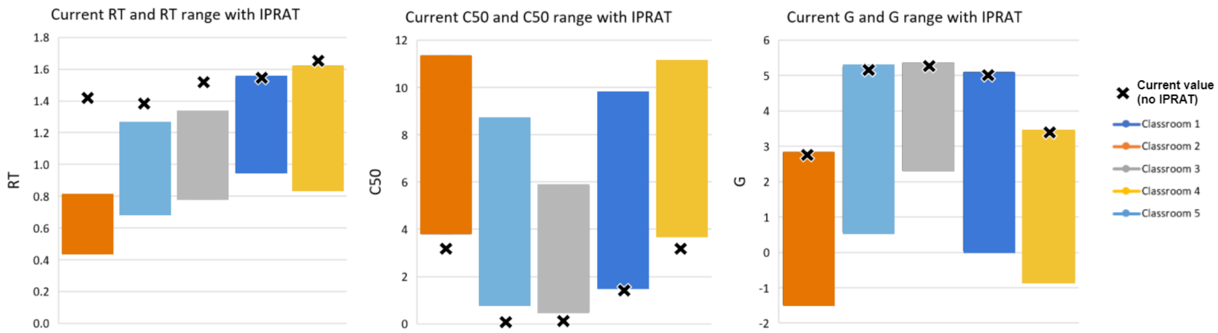


Figure 5. The current mean acoustic state of classrooms (not using IPRAT) indicated against acoustic parameter range attainable when using IPRAT

4.2 Optimal IPRAT rotation (and acoustic parameters) for each aural situation

The acoustic quality in an educational or highly cognitive space can be determined by how clearly the occupants understand the speech that is meant for them. Thus, a certain RT is defined for each virtual configuration, which optimises C50 and G within the ranges achieved with IPRAT. In quiet study situations - aural situation C and D - C50 is important, so we should minimise G (to do this, we minimise RT by rotating IPRAT 'open'). In lecture situations - aural situation A - G should be maximised to offer vocal relief to teachers (to do this, we maximise RT by rotating IPRAT 'closed'). In group working situations - aural situation B - both C50 and G are important in varying amounts; each teacher and class type will have their preferences. For these improvements, IPRAT should be rotated to some state between 'open' and 'closed.' First, the relationship between RT, C50 and G was derived from the trendlines in figure 4 for each classroom. Table 4 shows these relationship equations. The relationships are expressed as equations in x, where the x-axis represents the IPRAT rotation.

Table 4. Relationship equations for Aural Situation B, where optimal IPRAT rotation = x

Classroom	C50 (dB)	G (dB)	RT (s)
1	$C50 = 1.67x + 1.04$	$G = 6.07 - 1.01x$	$RT = 0.03x^2 - 0.32x + 1.83$

2	*C50 = 1.56x + 2.64*	*G = 3.80 – 0.89x*	*RT = 0.02x² – 0.22x + 0.99*
3	*C50 = 1.09x + 0.22*	*G = 6.02 – 0.60x*	*RT = 0.03x² - 0.32x + 1.83*
4	*C50 = 1.5x + 2.32*	*G = 4.31 – 0.85x*	*RT = 0.02x² – 0.32x + 1.89*
5	*C50 = 1.58x – 1.43*	*G = 6.21 – 0.95x*	*RT = 0.03x² – 0.33x + 1.53*

Note: Aural situation A optimal rotation = 'closed'. Aural situation C and D optimal rotation = 'open'.

Next, a simplified method was adopted where C50 was optimised at 5.0dB, x was calculated, and with this x value, the corresponding G and RT could be determined. The equations were derived from trendlines between exact data points on Microsoft excel software with an accuracy (R^2) of 0.99 or above. Figure 6 reveals these optimised RT, C50 and G values achieved with IPRAT for each aural situation.

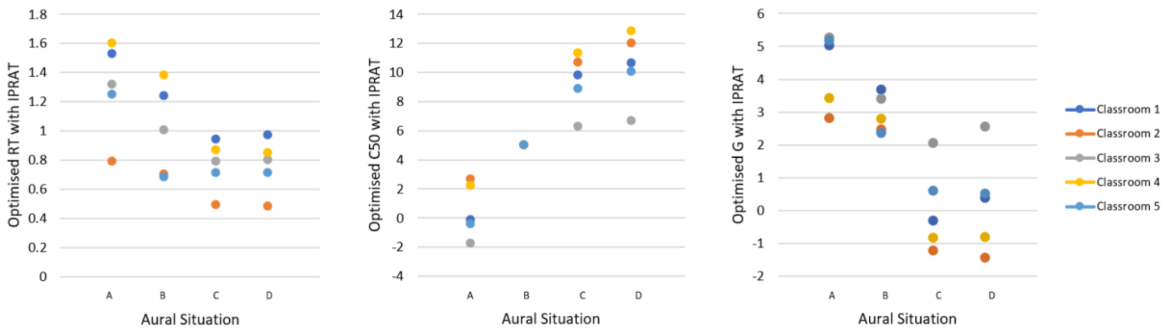


Figure 6. Optimised acoustic parameters for each classroom and aural situation combination

It is recognised that if the technology were deployed in a live classroom, each teacher and class type would have individual preferences to trial with between 'open' and 'closed' for group working situations. Thus, this is not an exact science, but values have been selected here to demonstrate the options available for these virtual configurations. It is also acknowledged that there will be aural situations that fit between the 4 situations described in this study in a live classroom. For any of these 'in between' states, teachers and students can again experiment with a rotation that works best for them.

It is widely believed that model calibration can improve the validity of simulation results. Unfortunately, it is difficult to calibrate models to correctly account for input parameter uncertainty or inaccuracy (Hong *et al.*, 2018), and I-Simpa relies upon numerous input parameters. Model calibration can be done manually or automatically, but I-Simpa does not have a function for automated calibration. Furthermore, manually calibrating the models in our simulations cannot be done due to the scarcity of I-Simpa simulation data previously compared to real acoustic measurements. Thus, it is not beneficial or advisable to attempt model calibration at this early stage in I-Simpa literature. This study, however, has the potential to provide future research simulations with a base for model calibration.

4.3 The potential for IPRAT

The mean difference for each acoustic parameter from current to optimised state is shown in table 5, for each classroom variable and each aural situation variable. Figure 7 illustrates these current acoustic parameters for each classroom, compared with optimised values, demonstrating the improvements achieved with IPRAT for each aural situation. Visually, we can see the reductions in RT and G achieved with IPRAT, and the increase in C50. Aural situation A maximised RT to optimise the acoustic state, which meant these values are the closest to the current acoustic states of the classrooms without IPRAT.

Table 5. Mean improvements achieved with IPRAT (difference between 'current' and 'optimized' values)

	Mean Difference						
Classroom	**RT**	**C50**	**G**	**Aural Situation**	**RT**	**C50**	**G**
1	-0.40	4.85	-2.81	**A**	-0.21	0.34	0.01
2	-0.82	4.40	-2.22	**B**	-0.52	2.64	-1.43
3	-0.56	3.58	-1.99	**C**	-0.77	7.20	-4.25
4	-0.49	4.64	-2.27	**D**	-0.76	7.77	-4.16

5	-0.55	4.97	-2.99
Overall Mean Difference	**-0.56**	**4.49**	**-2.46**

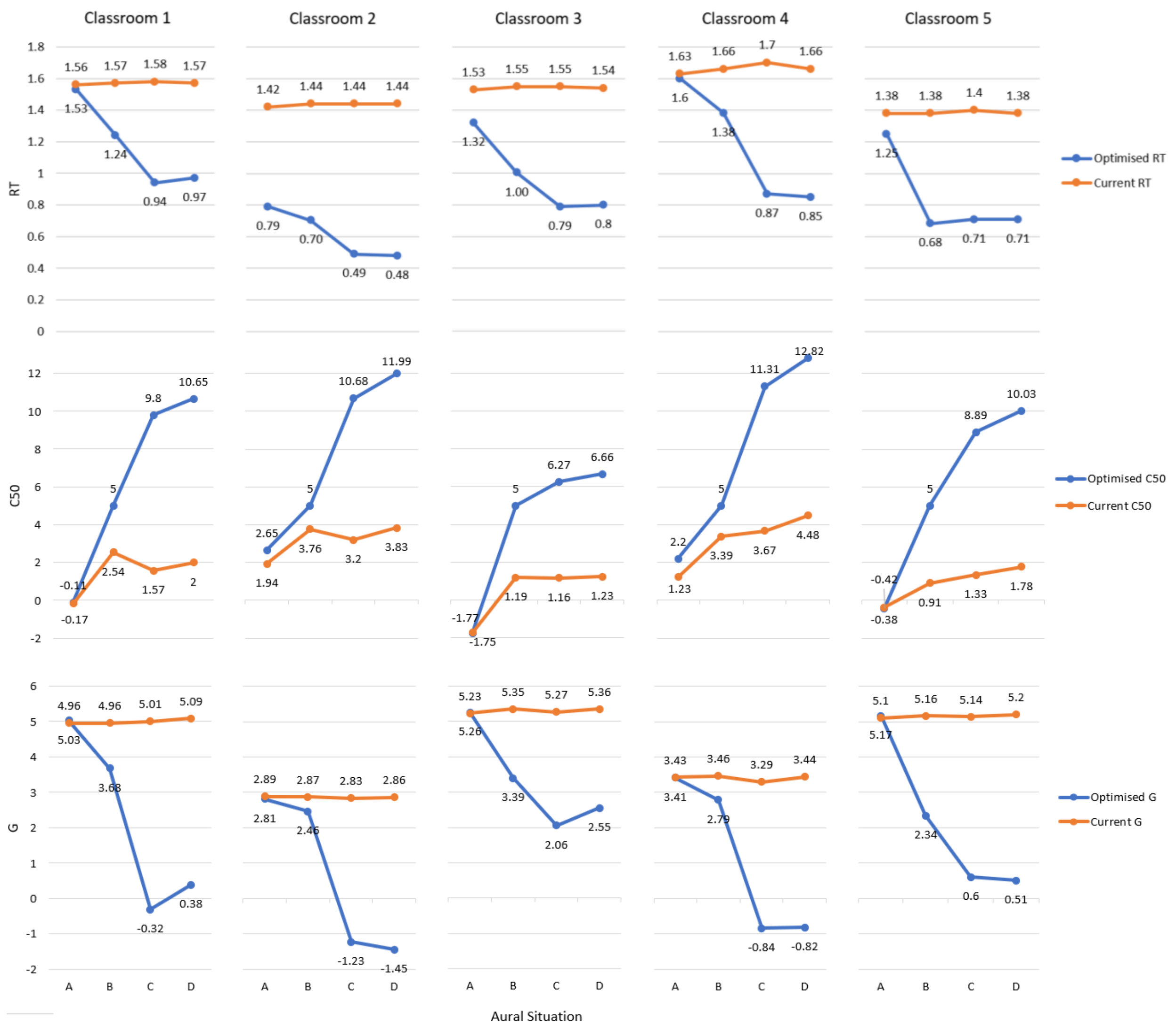


Figure 7. Current (no IPRAT) vs. optimised (with IPRAT). *Top: RT. Middle: C50. Bottom: G.*

The data were analysed using IBM SPSS software (version 27; SPSS Inc., New York, NY). Using the Shapiro-Wilk method, the data sets for RT (p=.11 before and p=.16 after) and C50 (p=.53 before and p=.28 after) were found to be normally distributed. Thus, a pairs sample t-test was conducted to evaluate the impact of IPRAT on RT and C50. The results showed a significant decrease in RT before (M=1.52, SD = 0.10) to after (M = 0.96, SD = 0.33), t(19) = 8.65, p<.001 (two-tailed). The mean decrease in RT was 0.56 seconds with a 95% confidence interval ranging from 0.43 to 0.70. The Cohen's d statistic (1.94) indicated a very large effect size (Cohen, 2013). Secondly, the results showed a significant increase in C50 before (M=1.85, SD = 1.58) to after (M = 6.33, SD = 4.36), t(19) = 5.98, p<.001 (two-tailed). The mean increase in C50 was 4.49dB with a 95% confidence interval ranging from -6.06 to -2.92. The Cohen's d statistic (-1.34) indicated a very large effect size. The data for G (p=.00 before and p=.20 after) was not found to be normally distributed. Thus, a related-samples Wilcoxon signed-rank test was conducted to evaluate the impact of IPRAT on G. The results showed a significant decrease in G before (M = 4.35, SD = 1.04) to after (M = 1.89, SD = 2.16), Z = -3.58, p<.001. The mean decrease in G was 2.46dB.

5.0 CONCLUSION

In this research, the improvements achieved by IPRAT are obtained by comparing current, achievable and optimal values for each acoustic parameter RT, C50 and G. Results highlight that acoustic improvements using IPRAT in classrooms is promising. For example, when using IPRAT, in group discussions and quiet study where the sound should be absorbed, the RT can be reduced to as low as 0.49 seconds. In the same classroom, the RT can be increased to as high as 0.79 seconds for a lecture where a teacher needs to project their voice. This range of 0.3 seconds allows for improved acoustic conditions in the same classroom space, for changing aural situations. The most extensive RT range achieved using IPRAT was 0.75 seconds – which could significantly increase student comprehension while reducing teacher vocal strain.

When comparing the current (no IPRAT) versus optimal (using IPRAT) acoustic values, the following improvements are attained: a mean RT reduction of 0.56 seconds, a mean C50 increase of 4.49dB and a mean G decrease of 2.46dB. This is based on the assumption that the PVAT can achieve a varying absorption coefficient, and that the ASC can correctly categorise each aural situation in a classroom. The nature of this data involves a pre/post condition comparison, so inaccuracies experienced from the BIM-based software have little effect on the relative comparative results. As an extended contribution of this paper, a detailed account of the BIM-based acoustic simulation method using I-Simpa is provided. I-Simpa is an open-source software with a shortage of precedents, detailed methods and software validation in literature. Thus, the method can be used by academics looking to perform similar acoustic simulations involving classroom spaces, aural situations, or initial technology validation.

This study is the first of its kind to explore the potential for IPRAT. To further advance the literature, a physical prototype should be developed and tested in a chamber or closed room. The behaviour of PVAT should be evaluated by measuring various acoustic parameters in a space. Furthermore, research for this novel technology should not be limited to classroom spaces. Benefits will be realised in any flexible, dynamic or multi-use architectural space in the built environment, especially in smart environments where human comfort is prioritized (Ghaffarianhoseini *et al.*, 2017a). Lastly, although the study considers classroom environments typical to New Zealand, the contributions can be helpful for professionals in other parts of the world, also looking to improve classroom acoustics using smart technology. Additionally, the BIM method explained for this research can be followed regardless of geographical considerations. This stands true as long as the appropriate alterations have been made to the classroom characteristics and aural situations, as the effect of IPRAT is unique for each classroom geometry and aural situation.

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