University of Southern Queensland
Faculty of Health, Engineering and Sciences
ENG4111/ENG4112 Research Project

# LEVERAGING DIGITAL TWIN TECHNOLOGIES FOR SUSTAINABLE DEVELOPMENT: AN EXPLORATION OF OPPORTUNITIES AND CHALLENGES

A dissertation submitted by

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In fulfilment of the requirements of Course ENG4111/4112 – Research Project

Towards the degree of

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## ABSTRACT

### METHODOLOGY & AIM

The research will begin by exploring the existing research, scholarly articles, books, and relevant sources to gain a comprehensive understanding of the current knowledge in the field. This review will help identify gaps or areas that have not been adequately addressed.

Four research questions have been developed that specifically address the knowledge gaps identified in the literature review.  The research question aligns with the overall objective of the study.

A combination of quantitative and qualitative approaches for collecting data will be use. For example, quantitative data will be collected through peer research, surveys, questionnaires, or existing datasets. Qualitative data will be gathered through interviews, observations, and case studies. Appropriate sampling methods will be used to ensure data representativeness and reliability.

By following this methodology, the research aims to address the research questions by leveraging management theories and approaches related to construction, validating the theoretical basis through data analysis, and assessing the opportunities and challenges of Digital Twin technology.

**OUTCOMES**

The key outcomes of this paper can be summarized as follows:

Digital Twin Technology for Sustainable Development: The paper explores the use of Digital Twin technology to enhance sustainability practices, reduce project delays and costs, and lower life cycle costs in construction projects, ultimately contributing to a sustainable future.

The research highlights that the potential of Digital Twin technology is limitless, depending on the user's understanding and expertise. Furthermore, The paper emphasizes the role of sensors and IoT technology in supporting Digital Twin applications, particularly during the operational phases of a construction project.

The study identifies numerous barriers to the implementation of Digital Twins, including high initial costs, lack of awareness, resistance to change, interoperability issues, and more. In addition to this, the significance of the findings is multifaceted, with an emphasis on their contribution to knowledge, applicability, worth, and real-world impact in the construction industry.

The research also identifies opportunities and challenges associated with Digital Twin technology, particularly in terms of collaboration, communication, and data security. Practical approaches include utilizing Digital Twins in complex structural design analysis, addressing the lack of accurate as-built information, and integrating with Building Information Modeling (BIM) for more efficient construction processes.

Real-world case studies, such as the NTU EcoCampus and Project SCENe, demonstrate the significant impact of Digital Twin technology on reducing the carbon footprint in the built environment. The paper also acknowledges a knowledge gap related to the potential applications of artificial intelligence (AI) in the AEC industry and suggests further exploration in this area.

Recommendations include comprehensive training and resources, development of standards and guidelines, data security measures, addressing interoperability, and promoting a collaborative mindset in the industry.

The author's personal reflection highlights the value of digital modelling and optimization technologies in the construction industry and their role in promoting sustainability and efficiency.

The paper concludes by emphasizing the growing importance of digital modelling and optimization technologies, such as Digital Twins and BIM, in achieving sustainability and efficiency in building design, construction, and operation. These outcomes collectively underscore the potential of Digital Twin technology to revolutionize the construction industry, enhance sustainability practices, and improve the overall efficiency of building projects.

*Keywords: Digital Twin, Sustainability, Opportunities, Challenges.*

***Glossary:***

*BIM – Building Information Modelling*

*AEC – Architecture, Engineering, Construction*

*IP – Intellectual Property*

*IoT – Internet of Things*

*IES – Integrated environment solutions*

*PLM – Product Life Cycle Management*

*TPO – Team Production Organization*

*IES – Integrated Environmental Solutions*

*NTU - Nanyang Technological University*

*iCIM – Campus Information Model*

*VE – Virtual Environment*

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## DISCLAIMER PAGE

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## CANDIDATES CERTIFICATION

I certify that the ideas, designs and experimental work, results, analysis, and conclusions set out in this dissertation are entirely my own efforts, except where otherwise indicated and acknowledged.

I further that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

**Zack Davis**

**Student Number**: [redacted]

[redacted]

**Date:** 15/10/23

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Special thanks needs to be given to the various participants and mentors across the AEC industry of which have participated in surveys and interviews when requested.

Finally, I would also like to thank my colleagues, friends and family for the support and space I've dedicated the time creating this dissertation report. I would not have been able to accomplish this without the people around me supporting me.

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# 1. CHAPTER 1 – INTRODUCTION

## 1.1. Introduction

The utilization of Digital Twin technologies in the AEC industry has been extensively explored in the literature. Building Information Modelling (BIM) emerges as one of the predominant digital modelling technologies in this field. BIM involves the creation and management of digital building models, fostering collaboration and communication among stakeholders throughout the design and construction process. A review of the literature reveals that BIM has demonstrated improvements in the efficiency and accuracy of building design, error reduction, and enhanced communication among project stakeholders. Moreover, BIM has been instrumental in optimizing building performance, particularly in energy efficiency, through the utilization of advanced simulation and analysis tools.

The literature review also sheds light on the challenges associated with the adoption and implementation of digital modelling and optimization technologies in the building services industry. These challenges encompass technical issues such as data management, interoperability, and compatibility, as well as organizational and cultural factors including resistance to change and a lack of collaboration. Additionally, the absence of BIM and energy modelling standards, along with cost and resource constraints, present further obstacles.

Through an examination of the literature, this review underscores both the potential opportunities, benefits and challenges, and limitations of digital modelling and optimization technologies in building design and operation. Furthermore, it reveals the challenges inherent in their adoption and implementation. These aspects will be reviewed in the subsequent sections of this dissertation.

### 1.2. The Problem

Digital Twins has witnessed significant growth, garnering extensive research and attention within the AEC industry's knowledge base. An investigation on the current body of literature relating to Digital Twins revealed a substantial volume of research on this subject. However, the research identified a missing link on Digital Twin technology and sustainable development in the design stages of commercial construction.

Hence, the purpose of this dissertation is to provide a comprehensive understanding of how Digital Twin concept can be used within the context of construction projects. Furthermore, the study seeks to assess the opinions of construction practitioners regarding the opportunities of Digital Twin technology for sustainable development. To achieve these objectives, the research investigates the various applications, capabilities, and challenges associated with Digital Twin implementation. To establish a practical foundation for this study, two case studies will be included, showcasing a real-world example of Digital Twins in practice. The research endeavors to address four critical research gaps by addressing the following key research questions:

- How can Digital Twin Technology be used in the operation, design, and construction phases of a construction project?

- What are the opportunities of Digital Twin Technology in the operation, design, and construction phases of a construction project.

- What are the perceived challenges of the implementation of Digital Twins for in the operation, design, and construction stages of a construction project?

- What are the practical approaches and applications for implementing Digital Twins in the design & construction phases of construction projects?

By exploring these research questions, the objective is to contribute to filling the knowledge gaps in the field of Digital Twin and sustainable development, fostering a deeper understanding of the opportunities and challenges for achieving sustainable outcomes through the application of digital twin technologies. The methodology employed to address each of the research gap and its corresponding research question can be found in Figure 1.0.

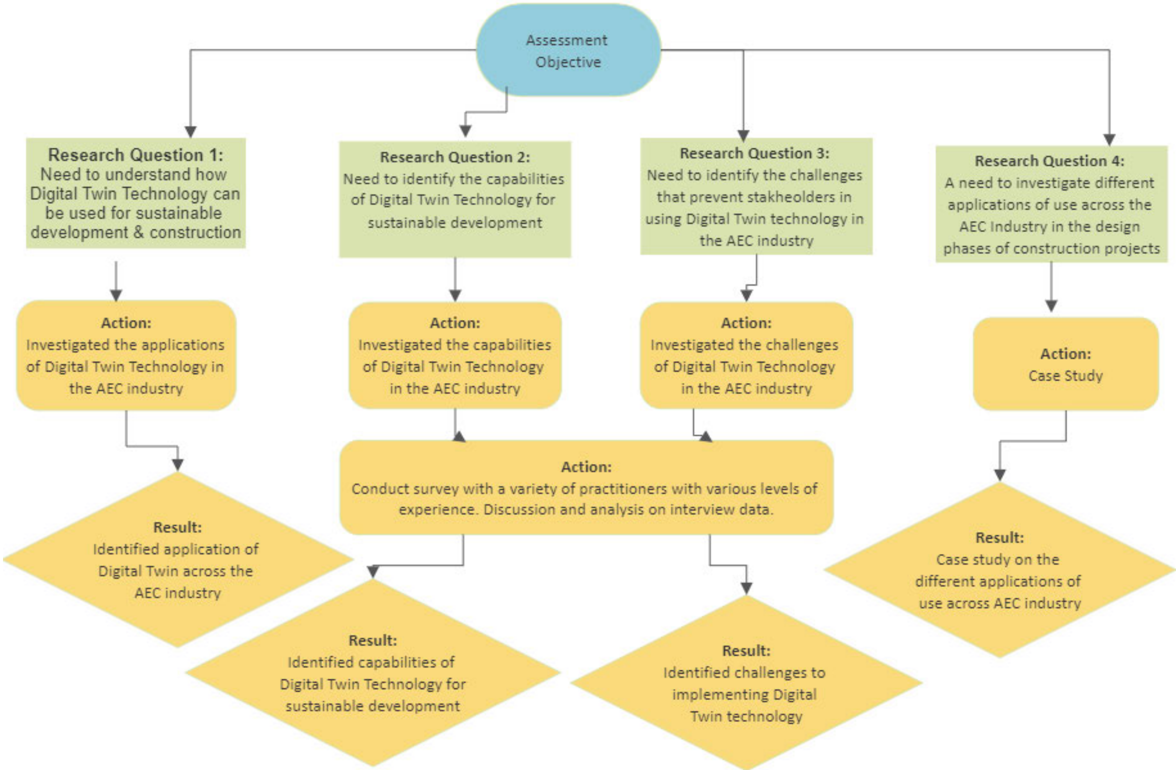


**Figure 1 - Methodology Overview**

### 1.3. Research Question 1:

- *How can Digital Twin Technology be used for in the operation, design, and construction phases of a construction project?*

In this dissertation, the primary objective of research question 1 is to investigate how Digital Twin technology is utilized within the Architecture, Engineering, and Construction (AEC) Industry. To achieve this objective, an extensive literature review has been conducted, encompassing a wide range of studies, articles, and reports that pertain to the adoption and application of Digital Twins in the AEC sector.

By examining this body of literature, we aim to gain a comprehensive understanding of how Digital Twins are being effectively integrated into construction practices. The review will shed light on the diverse range of projects in which Digital Twins are applied, highlighting their specific areas of impact and benefits. Additionally, the literature review will explore the various technologies and tools that are leveraged to implement Digital Twin solutions within the AEC domain.

Through this examination of existing research and industry literature, we aspire to offer valuable insights into the current state of Digital Twin adoption in construction and its implications for enhancing project delivery, collaboration, and overall performance within the AEC Industry.

### 1.4. Research Question 2:

- *What are the opportunities of Digital Twin Technology in the operation, design, and construction phases of a construction project.*

In this research paper, research question 2 focuses on exploring the potential and capacities of Digital Twin Technology in contributing to construction projects during the operation, design, and construction phases of a construction project. The primary focus of this research question is to comprehensively evaluate the various opportunities that arise from the integration of Digital Twins in the design, operation, and construction phases of construction projects.

To accomplish this, the researcher has developed a survey-based approach, targeting a diverse group of practitioners with varying levels of experience. By engaging with professionals from different careers, the study aims to obtain a well-rounded perspective on the subject, capturing insights and opinions from those actively involved in the AEC industry.

The survey will delve into key aspects, including but not limited to how Digital Twins can be used during the operation, design and construction phases of a construction project, their role in optimizing resource utilization, enhancing energy efficiency, and improving overall project sustainability performance. By analyzing the survey data, the study seeks to uncover the capabilities and advantages of Digital Twin technology during the operation, design, and construction phases of a construction project.

Ultimately, this investigation will contribute to the existing body of knowledge, fostering a deeper understanding of how Digital Twins can serve as an enabler for Digital Twin technology within the construction industry. The findings have the potential to inform decision-makers, project managers, and stakeholders about the opportunities available through the adoption of Digital Twins, thereby promoting sustainable practices within the AEC industry.

### 1.5. Research Question 3:

- *What are the perceived challenges of the implementation of Digital Twins for in the operation, design, and construction stages of a construction project?*

In this dissertation, research question 3 focuses on investigating the barriers and obstacles that hinder the successful implementation of Digital Twin Technology in the context of operation, design, and construction phases of construction Projects. The primary aim is to discern the perceived challenges and complexities associated with the adoption and integration of Digital Twins within the construction industry.

To address this research question, a survey has been carefully designed by the researcher. The survey has been developed to capture insights and perspectives from a diverse group of experts with varying levels of experience in the field. By gathering data from this diverse range of professionals, the studies goal is to gain a multifaceted understanding of the challenges faced during the implementation of Digital Twin technology.

The survey will delve into critical areas, such as technological limitations, data interoperability issues, organizational readiness, and potential resistance to change within the AEC sector. By analyzing the responses obtained from the survey participants, the study seeks to identify common themes and patterns, shedding light on the most prevalent and significant challenges hindering the broader adoption of Digital Twin technology during the operation, construction, and design of construction projects.

Through this examination of the perceived challenges, the research aims to contribute valuable insights to the academic and practical realms. The findings have the potential to inform industry stakeholders, policymakers, and researchers, helping them to devise effective strategies and solutions to overcome these barriers and maximize the potential of Digital Twin technology within the AEC industry. By addressing these challenges head-on, the construction industry can move closer to achieving its sustainability objectives while harnessing the transformative power of Digital Twins in project planning, execution, and lifecycle management.

### 1.6. Research Question 4:

- *What are the practical approaches and applications for implementing Digital Twins in the design & construction phases of construction projects?*

In this dissertation, research question 4 represents a pivotal phase wherein two explorative case studies are conducted to address the research inquiry effectively. The primary objective of this question is to investigate and delineate the diverse practical approaches and real-world applications of Digital Twin technology within the Architecture, Engineering, and Construction (AEC) industry.

These case studies serve as valuable instruments for gaining insights into the practical utilization of Digital Twin technology. Through analysis and examination of the real-life implementations, the research aims to identify and understand the tangible challenges that practitioners encounter while integrating Digital Twin technology to promote sustainability in construction projects.

In addition to the case studies, the researcher has planned a comprehensive interview phase, engaging a diverse group of practitioners from different professional backgrounds and varying levels of experience. By conducting these interviews, the study seeks to dig deeper into the firsthand experiences and perspectives of industry experts, gaining an understanding of the perceived challenges surrounding the successful application of Digital Twins for Sustainable Development within the AEC domain.

The interviews will focus on various aspects, such as the complexities faced during implementation, lessons learned, best practices, and the potential areas for improvement. By analyzing the data gathered from the case studies and interviews, through a thematic analysis, the research aims to reveal critical insights into the barriers and obstacles that impact the practical deployment of Digital Twin technology for advancing sustainability in construction.

Through this examination of real-world scenarios and expert perspectives, the dissertation endeavors to contribute to the existing body of knowledge, providing valuable information to practitioners, decision-makers, and stakeholders. The findings have the potential to enrich the discourse on Digital Twin technology's practical applications, enabling industry professionals to navigate challenges effectively and leverage this transformative technology to promote sustainable development within the AEC industry.

### 1.7. Research Objectives

The development of the literature review and in preparing the dissertation, the following project aims and objectives have been identified. In complex development contexts, continuous improvement and the deployment of cutting-edge technology are often required to achieve sustainable development.

Overall, the research objectives collectively aim to provide a comprehensive understanding of the role and potential of Digital Twins in construction project management and commercial construction projects. They serve as the foundation for the research design, data collection, analysis, and discussion, guiding the researcher toward addressing the research questions and contributing to the advancement of knowledge in the field.

Furthermore, the objective of the research is to answer the research questions. By conducting research and collecting the relevant data, the researcher seeks to gather evidence and analyze findings to provide an answer or response to the research questions.

### 1.8. Conclusion

This dissertation aims to add further value to existing research, evaluating research gaps, and offer suggestions for research priorities within Australia to solve knowledge gaps for this topic. The outcomes from this project will be immediately applicable to future research, and contribute to sustainable projects, problem-solving, and creating a better future for society.

Overall, this research is expected to contribute to the emerging field of Digital Twin technology in construction management and sustainable construction projects, providing insights into the opportunities and challenges of leveraging this technology to achieve a more sustainable future. The outcomes of this study will be used for the design and development of sustainable buildings.

# 2. CHAPTER 2 – LITERATURE REVIEW

### 2.1. Introduction

A Digital Twin is the concept of using a digital copy of a physical system to accomplish real-time optimization. (Schellenberger et al., 2020) Digital twin is shaping the planet, and is one of the most useful, insightful tools to drive innovation and value. In Digital Twin technology, physical data, processes, systems, and digital reality simulations are used in simulations which have a wide range of potential applications. A Digital Twin is a simulated model which is created by combining data with state-of-the-art technology such as artificial intelligence, machine learning, and software analytics. This model can be updated simultaneously with or instead of a real counterpart. The digital twin user can investigate possibilities for examining the product and its cost lifecycle, optimizing production procedures, enhancing product development, and prototyping. Furthermore, digital twin can provide a visual representation of a problem, make it easier to solve problems, and design and test solutions in computer software rather than in the real world.

Digital Twin technology is being utilized in engineering and construction to help in the design, construction, and ongoing maintenance of structures and infrastructure. A digital twin can help with the production of a conceptual model during the planning phase, as well as the design process, building, and continuing maintenance.

The Digital Twin has the potential to raise project productivity and client satisfaction in engineering and construction. Owners, designers, contractors, clients, managers, and builders can use Digital Twin to boost design evaluation, project delivery effectiveness, conflict resolution, and teamwork. The technology, which is still in its early stages, has the potential to advance in the next 5-10 years. (Grieves and Vickers, 2017) and Svoreň (2022).

### 2.2. Literature Review

NASA adopted the notion of a Digital Twin for safety and reliability enhancements in (Söderberg et al., 2017). The use of "twins" dates to NASA's Apollo program, when two identical space vehicles were developed to allow mirroring of the space vehicle's circumstances during the mission. (Semeraro et al., 2021). In 2003, Professor Grieves of the University of Michigan introduced the concept of a "Digital Twin" in Product Life Cycle Management (PLM) courses. Michael Grieves (2014), whose expertise in product design initially ground the notion in production engineering, invented the term "Digital Twin" in the early 2000s.

According to (Batty, 2018) a digital twin is a digital depiction of a physical process that, like the physical process, runs in real time. Other definitions include the necessity of communication and data transmission between IoT, sensor, data, and model spaces. Svoreň (2022). (Rasheed et al., 2020) and (IBM, 2020) define a digital twin as a virtual replica of a physical asset that may be used for real-time prediction, optimization, monitoring, controlling, and improved decision-making using data and simulators. (Rasheed et al., 2020) The use of Digital Twin's data-driven analytics to enrich lives has been made possible since the infrastructure for storing and processing large amounts of data has advanced significantly improved over the previous few decades. (Farsi et al., 2020)

The development and integration of sensors, cloud services, data, machine learning, and IoT into a digital twin can be used to uncover flaws in cost assessment and visualization of engineering development projects. In addition to this, it can offer information during the design and construction stages which can be used as a starting point for continuous cost, scheduling, and facility management to help forecast when maintenance is needed.

Pal, 2022 believe the digital twin will become the most powerful and intelligent consultants in the industry. They believe it has the potential become powerful because it has the capacity to function on real-time data received from ongoing operations or systems, and forecast performance or failures, if any, using its elements, physics-based simulation, and data-driven models. As a result, the continuing operation and quality will be completely transparent. Furthermore, if a fault or inaccuracy is detected, digital twin will recommend correction actions in real-time. With this knowledge, the expense of on-site inspections will be reduced, and machine downtime will be avoided. With constant access to sensory data and analytics, the digital twin is predicted to become the most powerful and intelligent consultant. (Bilberg and Malik, 2019)

### 2.3. Overview of existing technologies

#### 2.3.1. BIM

Building Information Modelling (BIM) represents a transformative digital modelling and information management technology that holds immense potential for the construction industry. By utilizing BIM software, designers, engineers, and contractors can create and manage accurate digital representations of buildings and their respective systems. This integrated approach allows for the seamless integration of diverse building systems and services into a unified model, thereby facilitating simulations to optimize the design and operation of these systems.

One of the primary advantages of BIM lies in its ability to foster effective collaboration among stakeholders throughout the entire building lifecycle. From the initial design phase to construction and ongoing maintenance, BIM serves as a platform for enhanced communication and coordination among project participants. By working on a shared digital model, errors can be minimized, leading to improved design quality. Additionally, BIM empowers stakeholders to generate more accurate cost estimates and project schedules, enhancing overall project efficiency.

To better comprehend the BIM process and its applications, Figure 1 & 2 below offers a comprehensive depiction of the BIM lifecycle and showcases the diverse range of uses it encompasses.

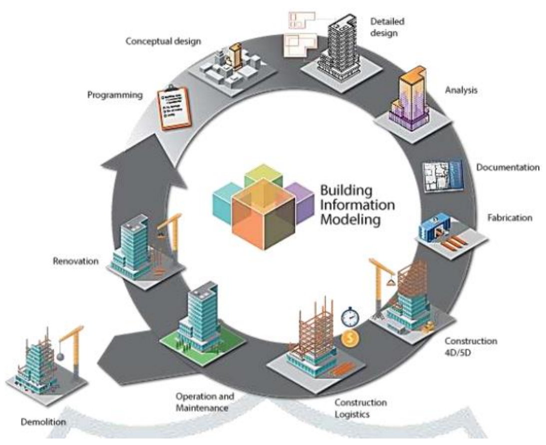


Figure 2 – Applications and uses of BIM

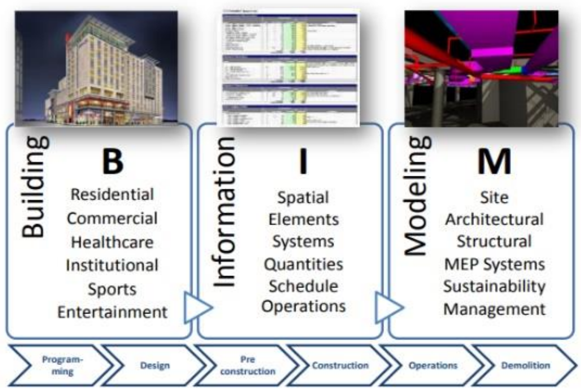


Figure 3 – BIM life cycle (Google, 2023)

#### 2.3.2. Digital Twin

The utilization of Digital Twin technology in engineering and construction holds significant promise for enhancing project productivity and client satisfaction. This transformative technology empowers owners, designers, contractors, clients, managers, and builders to leverage the Digital Twin concept to elevate design evaluation, improve project delivery effectiveness, resolve conflicts, and foster collaborative teamwork.

To provide a comprehensive understanding of the Digital Twin concept, Figure 4.0 below presents a visual representation illustrating the key aspects of this technology.

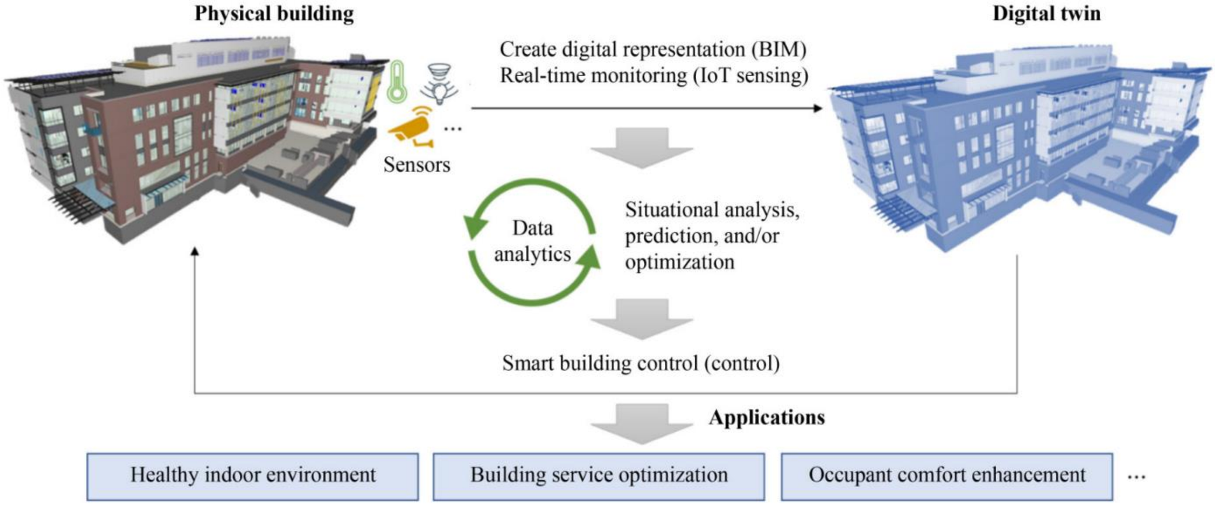


**Figure 4 – Establishment of digital twin and its applications in indoor environment. (Jiannann, 2023)**

### 2.3.3. IoT – Internet of Things

The advent of the Internet of Things (IoT) has brought about a transformative impact on the relationship between individuals and technology, facilitating the interconnection of everyday devices through internet connectivity. This shift has led to numerous potential advantages, particularly within the architecture, engineering, and construction (AEC) industry and the built environment. Extensive research by Lee et al. (2019), Marques and Piatra (2019), and Mujan et al. (2019) has substantiated the far-reaching benefits associated with IoT integration in these domains, including increased efficiency and convenience.

In the area of energy consumption optimization, IoT technology offers substantial potential. By leveraging smart sensors and energy management systems, it becomes possible to monitor and optimize energy usage in buildings, thereby supporting energy efficiency. This entails the placement of sensors and the implementation of energy management systems throughout buildings, enabling real-time tracking of energy consumption. Through this continuous monitoring process, building managers gain valuable insights that facilitate the identification of areas where energy can be conserved, ultimately leading to enhanced occupational thermal comfort.

Notably, the literature by Salamone et al. (2018) and Zahid et al. (2021) has underscored the role of IoT technology in driving energy efficiency and optimizing energy consumption in buildings. The integration of smart sensors and energy management systems empowers building managers with the ability to make data-driven decisions, leveraging real-time energy usage information to implement targeted energy-saving measures. This comprehensive approach aligns with the overarching goal of ensuring occupational thermal comfort while concurrently reducing energy consumption.

## 2.4. Application in AEC Industry

### 2.4.1. Building Design Phase

The utilization of Digital Twin technology during the design phase offers substantial advantages in terms of detailed and precise 3D representations of buildings and structures. This enhanced visualization capability surpasses traditional 2D drawings and physical models, leading to improved communication and comprehension of the design by stakeholders. The integration of BIM also fosters collaboration among architects, engineers, service consultants, contractors, and other project participants, as they can collectively work on a shared digital model in real-time. This simultaneous involvement minimizes communication errors and enhances coordination, resulting in more efficient and effective design outcomes. Furthermore, BIM facilitates the automation of repetitive tasks like quantity take-offs, clash detection, and material schedules, thereby reducing time requirements and errors, ultimately leading to cost-effective designs.

Digital design modeling tools further empower designers to conduct accurate and sophisticated analyses of building performance, including energy consumption, lighting, and thermal behavior. This enables designers to optimize the design for energy efficiency and sustainability, yielding long-term cost savings and environmental benefits. The application of BIM is particularly valuable throughout various stages of the project design, encompassing schematic design (SD), detailed design (DD), and construction detailing (CD) (Salman, 2012).

**Table 1 – BIM Applications and benefits in project design phase. (Salman, 2022).**

| Schematic Design | Detailed Design | Construction Detailing |
|---|---|---|
| • Options Analysis (to compare multiple design options)<br>• Photo Montage (to integrate photo realistic images of project within its existing conditions) | • 3D exterior and interior models<br>• Walk-through and fly-through animations<br>• Building performance analysis (e.g. energy modelling)<br>• Structural analysis and design | • 4D phasing and scheduling.<br>• Building systems and analysis (e.g. clash detections)<br>• Shop or fabrication drawings |

### 2.4.2. Building Operation Phase

Optimization techniques offer valuable tools for improving building energy performance by identifying and addressing inefficiencies in building systems. One critical area where Digital Twin technologies can be applied is in enhancing the performance of Heating, Ventilation, and Air Conditioning (HVAC) systems (Burfoot, 2022). By utilizing digital tools to model and simulate the HVAC systems' performance, designers can pinpoint areas of potential inefficiency and employ optimization techniques to enhance their performance.

IoT devices play a pivotal role in building services operations by providing real-time data on building performance. This data enables building managers to optimize building services for maximum efficiency. By monitoring energy usage patterns, IoT devices offer insights into areas where energy can be saved (Abraham, 2018). Building managers can leverage this data to make informed adjustments to HVAC and lighting systems, thereby reducing energy consumption. The figure on the right provides a framework for smart building control that can guide facility managers in their efforts to minimize energy consumption (ARCOM, 2016).

For instance, the implementation of IoT-enabled HVAC systems allows for dynamic adjustments of temperature and ventilation based on occupancy levels, resulting in reduced energy consumption when rooms are unoccupied (Burfoot, 2022). Smart lighting systems can also be integrated, which adapt lighting levels in response to natural light availability and occupancy, further minimizing energy usage. The remote controllability of these systems empowers building and operation managers to adapt settings in real-time to meet evolving needs. The accompanying figure below illustrates the application of the Internet of Things in the built environment (Jiangnan CAI et al., 2023).

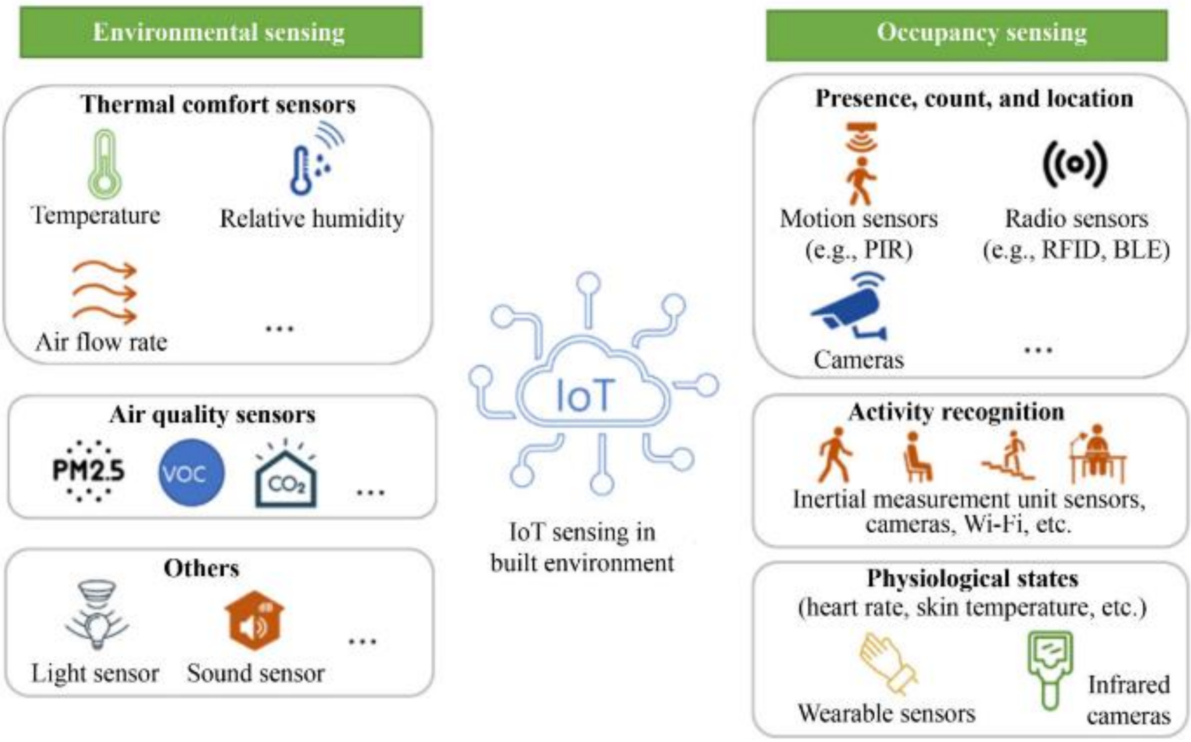


**Figure 5 – Applications of Internet of Things sensing in built environment - Jiangnan CAI et al (2023).**

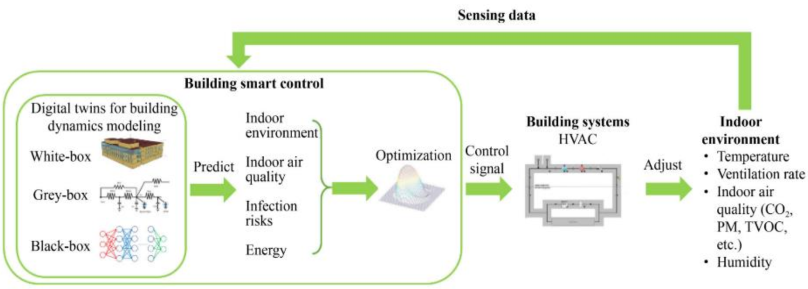


**Figure 6 - Framework for smart building control in Operations management - Jiannan CAI et al (2023)**

Figure 6 presents a depiction of an optimal Digital Twin framework designed to effectively manage the indoor environment within a building (Riker et al., 2021). In this framework, the utilization of Internet of Things (IoT) techniques, such as wireless sensor networks, enables the seamless and real-time collection of precise indoor environmental data without any time delays. This real-time data is essential for ensuring accurate and up-to-date information about indoor conditions and occupant comfort.

To integrate and predict real-time indoor conditions and occupant comfort, it is crucial to ensure the consistency of the collected data. This consistency allows for the seamless integration and analysis of the data, serving as the foundation for accurate simulations and predictions. Key aspects of this framework include building energy performance evaluation, Computational Fluid Dynamics (CFD) simulations for thermal flow prediction, and occupant comfort prediction. These components collectively provide a comprehensive understanding of the building's performance, aiding in effective decision-making for building management.

An integral aspect of this framework is the extraction of information from the Building Information Modeling (BIM) model. The BIM model serves as a valuable source of geometric and semantic data, minimizing the loss of crucial information during simulations and predictions. By leveraging the data within the BIM model, the accuracy and reliability of the simulations and predictions can be significantly enhanced. Riker et al (2021).

To minimize human involvement and optimize system control, the control system should incorporate decision-making capabilities and strategies. These strategies enable the formulation of specific commands that can be transmitted to automated systems such as Heating, Ventilation, and Air Conditioning (HVAC) and lighting systems. By automating these systems based on real-time data and predictive insights, the indoor environment can be efficiently maintained, leading to improved energy efficiency and occupant comfort.

Real-time Digital Twin visualization platforms (ie graphic user interface) based on BIM models play a vital role in enhancing the effectiveness of system control, facility management, and maintenance. These platforms provide real-time insights into the building's status, allowing stakeholders to monitor and analyze various parameters related to the indoor environment. By leveraging these visualizations, facility managers can make informed decisions and take proactive measures to optimize system performance and conduct timely maintenance activities. Ruikar et al (2021).

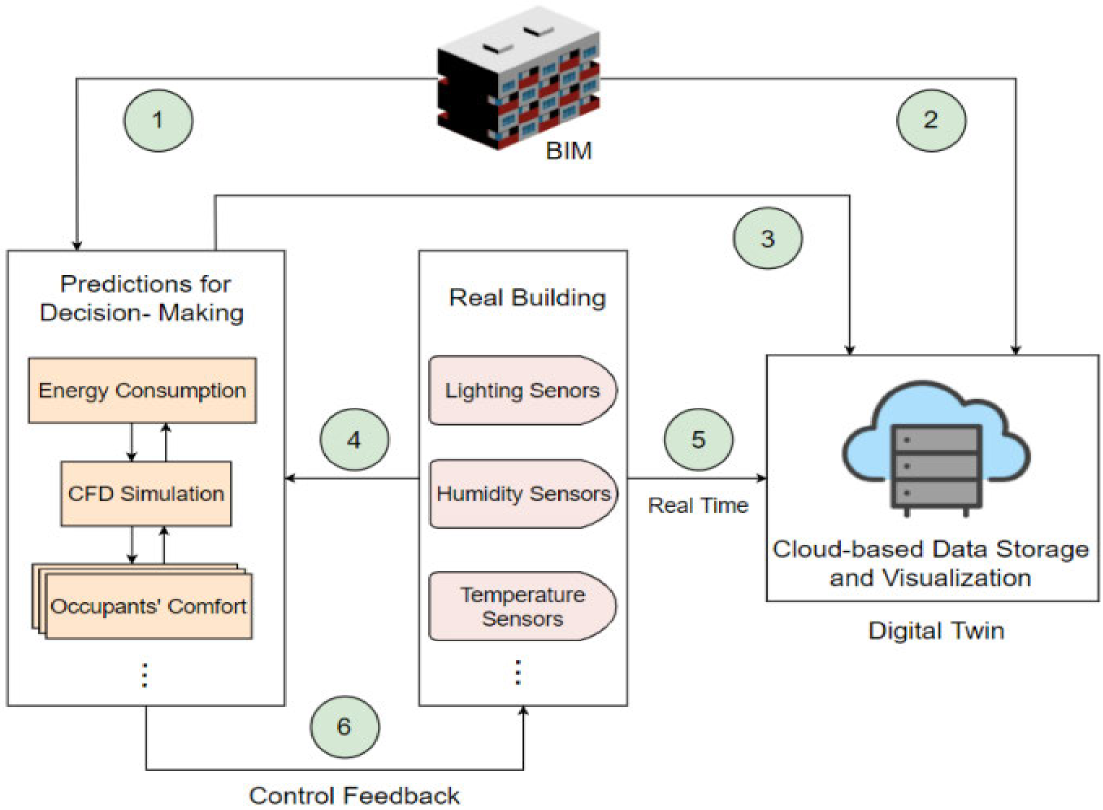


**Figure 7 - Application of Digital Twin for managing operations of a building. Ruikar et al (2021).**

### 2.4.3. Effective operational cost

The operational phase of buildings represents the highest national expenditure within the context of the building life cycle. While the initial cost of constructing the facility itself is relatively small, the expenses associated with operations and the value of activities conducted within the building far surpass it (Smith & Tardif, 2009). Research from the US National Institute of Science and Technology (NIST) highlights those inefficiencies during the operational phases result in the loss of two-thirds of estimated costs in the United States (Arayici, Onyenobi, & Egbu, 2012; Azhar et al., 2012). It is during the operation phase that the largest fraction of expenses in the building life cycle is incurred (Akcamete et al., 2010). Figure 9 provides a graphical representation of the level of influence on costs compared to time. (Grobler, 2005 & Aziz et al., 2016).

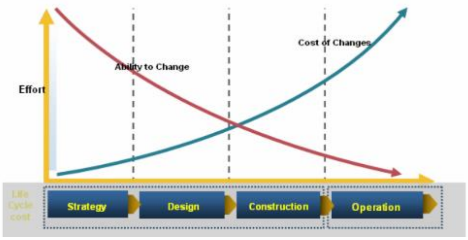


**Figure 9 - Level of Influence on Costs as Compared to time. (Grobler, 2005)**

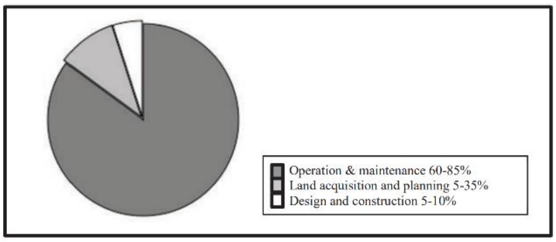


**Figure 8 - Pie chart reflecting each of the costs of the building life cycle. (Aziz et al., 2016)**

The research has found incorporating digital twin technology during the design phases can significantly improve the predictability of operating and maintenance costs for facilities (Aziz et al., 2016; Kans, 2008; Smith & Tardif, 2009). Failure to effectively manage the building during the operational phase can lead to substantial overspending beyond the allocated budget for operations (Myeda & Pitt, 2014). Digital Twin technology facilitates the integration of environmental considerations and life cycle operating and maintenance costs into the design process, allowing for more cost-effective decision-making (Smith & Tardif, 2009). Furthermore, Digital Twin technology enables the systematic consideration of workplace productivity factors based on reliable statistical workplace performance data. By leveraging Digital Twin technology in the operational phase of building management, significant reductions in energy loss can be achieved (Azhar et al., 2012). This iterative process empowers the continual reduction of future operating costs.

#### 2.4.4. Optimization Technologies & Software

Optimization technologies are tools that use algorithms and computational methods to improve the efficiency and performance of building systems. Optimization technologies can help designers optimize building systems such as HVAC, lighting, and ventilation for maximum energy efficiency. By using advanced algorithms and data analysis, these technologies can identify inefficiencies and suggest solutions to reduce energy consumption and lower operating costs. In addition to this optimization technologies can help designers identify the most cost-effective solutions for building systems, materials, and construction methods. By using data analysis and simulation, these technologies can identify areas where costs can be reduced without sacrificing performance or quality. Furthermore, optimization technologies can speed up the design process by automating many repetitive tasks and simulations. This enables quicker design cycles and more effective decision-making by enabling designers to test and assess various design possibilities quickly. Optimization technologies can help designers optimize building systems for sustainability. Such as:

- Reducing carbon emissions,
- minimizing waste, and
- using renewable energy sources.

There is a variety of optimization technology software which allows designers to evaluate the performance of building under different conditions. Some software allows designers to automatically generate and evaluate multiple design options, enabling faster design iterations and better design outcomes.

Sophisticated software tools like IES Virtual Environment and Autodesk Revit have revolutionized the design process by enabling designers to simulate and model the intricate interactions among various building systems. These tools offer the capability to explore the interplay between HVAC, lighting, and envelope systems, as well as variable air volume or underfloor air distribution, across diverse operational scenarios. Through these simulations, designers can evaluate the implications of different design options on energy consumption, occupant comfort, and indoor air quality.

By utilizing these advanced tools, designers can adopt a holistic and integrated approach to building design. They can assess the interdependencies between different building systems and their collective impact on overall building performance. Consequently, designers can strive for optimized designs that not only minimize energy consumption but also ensure occupant thermal comfort.

This shift in design methodology, empowered by tools like IES Virtual Environment and Autodesk Revit, holds potential for enhancing building performance and energy efficiency. By embracing a comprehensive perspective that considers the dynamic interactions between building systems, designers can achieve optimal outcomes that align with sustainability goals and occupant well-being (Abraham, 2018).

Optimization technologies, including genetic algorithms and artificial neural networks, have emerged as valuable tools in the field of building services for enhancing building performance and minimizing energy consumption. These advanced methodologies have proven instrumental in optimizing various building systems, such as heating, ventilation, and air conditioning (HVAC) systems (Abraham, 2018). By leveraging these optimization technologies, maximum efficiency and occupant comfort can be achieved, leading to tangible benefits in terms of reduced energy consumption and operating costs within buildings (Omrany et al., 2023). These findings highlight the significant potential of optimization technologies in enhancing building sustainability and efficiency, making them a key area of research and application in the field of building services.

Another innovative solution, which has just recently come to light is the use of machine learning and artificial intelligence (AI) to optimize the operation of building services systems in real-time. For example, systems such as Honeywell Forge or Schneider Electric EcoStruxure use AI algorithms to analyze data from sensors and other sources, and to predict and optimize the performance of HVAC, lighting, and other building services systems. This can lead to improved energy efficiency, comfort, and indoor air quality, as well as reduced maintenance and operational costs. Some further examples of

Optimization Technology Software are:

- EnergyPlus
- Grasshopper
- IESVE
- eQuest

#### 2.4.5. Computational Fluid Dynamics (CFD)

The design and operation of building services heavily rely on achieving optimal thermal conditions, comfort, and indoor air quality. Factors such as temperature, humidity, and air velocity significantly influence occupants' thermal comfort, while indoor air quality is affected by elements like ventilation, filtration, and humidity control. To assess and enhance the performance of thermal conditions, comfort, and indoor air quality, optimization technologies such as Computational Fluid Dynamics (CFD) can be used.

CFD, a simulation technology employing numerical methods to solve fluid flow and heat transfer problems, plays a crucial role in evaluating and optimizing various building systems, including HVAC systems, fire protection systems, and other building services. By leveraging CFD, designers can simulate the performance of these systems and services, identify potential energy savings, and optimize their design and operation. Consequently, energy consumption and operational costs can be reduced.

CFD technology offers several benefits in improving the efficiency and effectiveness of building systems and services. It enables the identification of areas where airflow or temperature distribution can be improved, allowing for enhanced system performance. Additionally, by simulating different design options, CFD aids in making informed decisions to achieve optimal system performance. Furthermore, CFD helps mitigate the risk of equipment failure and enhances the safety of building occupants (Abraham, 2018). Examples of Computational Fluid Dynamics software commonly used in the AEC industry include:

- AutoDesk CFD

- Ansys Fluent

#### 2.4.6. Solar Analysis Software

Energy modelling software plays a crucial role in simulating and assessing the energy performance of buildings and their systems. It offers valuable insights for optimizing design and operation, leading to reduced energy consumption, greenhouse gas emissions, and enhanced occupant thermal comfort (Abraham, 2018). By utilizing energy modelling, areas of potential energy savings can be identified, such as through the optimization of HVAC systems, lighting systems, and building envelopes. Moreover, it aids in identifying the most cost-effective energy-saving measures and provides more accurate estimates of energy savings and payback periods.

An example of such software is Revit's Insight Solar Analysis, which enables the determination of photovoltaic feasibility and prediction of energy production and savings for a given project. With Insight Solar Analysis, users can create custom analysis types by specifying dates, time ranges, surface selection, result types, and visualization styles (AutoDesk, 2022). The accuracy of results from Insight Solar Analysis has been validated by NREL, with findings indicating differences of less than 1% for surfaces oriented horizontally, east-facing vertically, and south-facing with the latitude tilt angle.

Overall, energy modelling software and tools like Revit's Insight Solar Analysis offer indispensable capabilities for optimizing building performance, promoting energy efficiency, and facilitating informed decision-making in sustainable design and operation.

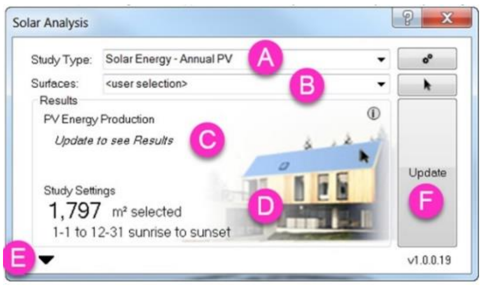


**Figure 10 - Autodesk Solar Analysis Software**

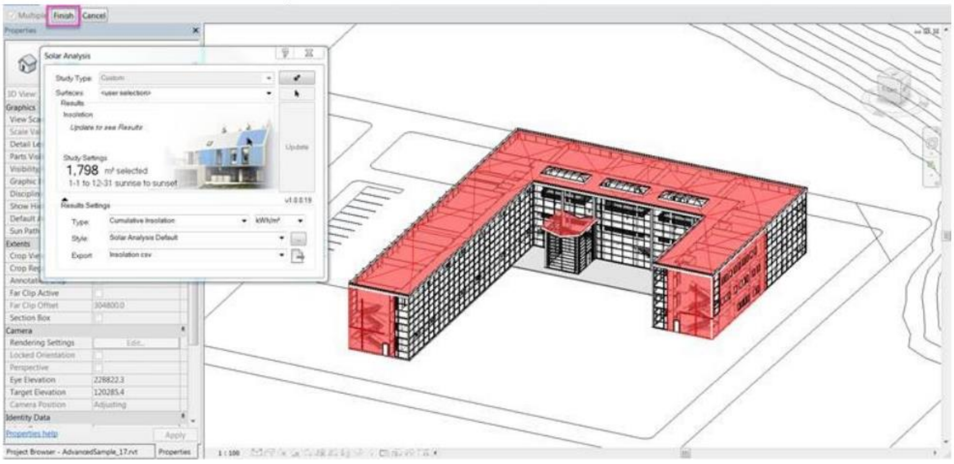

**Figure 11 - Autodesk Solar Analysis Software**

### 2.5. Barriers

Brewer et al. (2011, p. 244) emphasize that the widespread adoption of Building Information Modeling (BIM) is hindered by several barriers, resulting in its infrequent use as the intended solution and central data repository for all project participants. They argue that BIM may be more feasible for secondary participants in construction projects who have self-contained supply chains independent of the project itself. The success of BIM in a Team Production Organization (TPO) depends on the presence of participant firms that share compatible technologies, business processes, and cultures, guided by individuals who possess collaborative attitudes and behaviors (Brewer et al., 2011, p. 246).

The implementation of Digital Twin Technology can be perceived as complex, challenging, and costly (Eastman et al., 2011; Lu and Li, 2011; Roper, 2012). Despite the clear benefits it offers, there are significant difficulties associated with its adoption. Brewer (2010) highlights these challenges, emphasizing the gap between the conceptual promise of BIM and the practical realities of its implementation. This aligns with Succar's (2009) notion of "BIM-Wash," which denotes the deceptive use of BIM without fully embracing its potential.
In their literature review, Ullah and Witt (2019) identified various barriers to the adoption of Digital Twin and BIM technology, which include:

**Table 2 - Barriers to implementation**

| ***Barriers*** | ***Reference*** |
|---|---|
| *High initial cost* | *Ismail et al., 2017* |
| *Lack of awareness about BIM benefits* | *Latiffi et al., 2016, Gerges et al., 2017* |
| *Inadequate training on the use of BIM* | *Eadie et al., 2014, Park and Kim, 2017* |
| *Resistance to change current construction industry culture* | *Ganah and John, 2015, Sahil, 2016* |
| *Insufficient governmental support* | *Enshassi et al., 2016* |
| *Legal issues* | *Bosch-Sijtsema et al., 2017* |
| *Lack of interest from clients* | *Sahil, 2016* |
| *Lack of support from top management* | *Ganah and John, 2015* |
| *Doubts about ROI* | *Eadie et al., 2014* |
| *Lack of BIM experts* | *McAuley et al., 2017* |
| *Data ownership issues* | *Park and Kim, 2017* |
| *Longer process (takes longer time to develop the model)* | *Ismail et al., 2017* |

| | |
|---|---|
| *Lack of demand from the contractors* | *Gerges et al., 2017* |
| *Sub-contractors are not interested in using BIM* | *Hosseini et al., 2016* |
| *Absence of contractual requirement for BIM implementation* | *Ahmed et al., 2014* |
| *Complexity of the BIM model* | *Ahmed et al., 2014* |
| *Interoperability between software programs* | *Park and Kim, 2017* |
| *Lack of standardized tools and protocols* | *McAuley et al., 2017* |

## 2.6. Solutions to Barriers

### 2.6.1. Data management & Interoperability

The utilization of Digital Twin technologies in commercial construction projects introduces a significant volume of data, thereby increasing the complexity of data management. Effectively managing and analyzing this data becomes challenging for organizations, potentially resulting in errors and inaccuracies.

To address the issue of interoperability, recent studies by Leite (2020) et al. and Sampaio & Flores-Colen (2022) propose the adoption of a Cloud-based BIM system. This innovative approach facilitates the exchange of design and construction information among project participants, regardless of the software used, through a web-based Cloud system.

Figure 14.0 illustrates the architecture of a BIM-based Cyber-Physical system, demonstrating the potential of this approach in integrating data and processes.

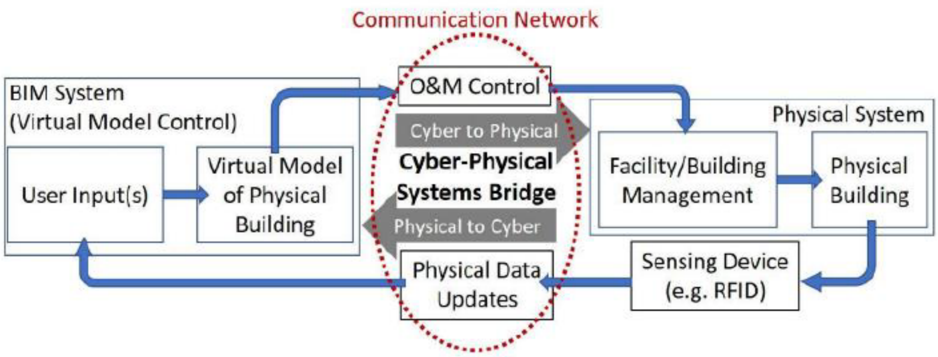


**Figure 12 - Proposed Cloud Based System by Leite et al. (2020)**

Autodesk provides software solutions that align with this concept. Revit Cloud Work-sharing with BIM 360 enables teams to collaboratively work on Revit models in real-time, ensuring synchronization with the latest approved work.

The implementation of Cloud-based BIM systems holds promise in addressing interoperability challenges and enhancing collaboration among stakeholders in building services. By leveraging these advancements, organizations can effectively manage data and streamline workflows, ultimately improving project outcomes.

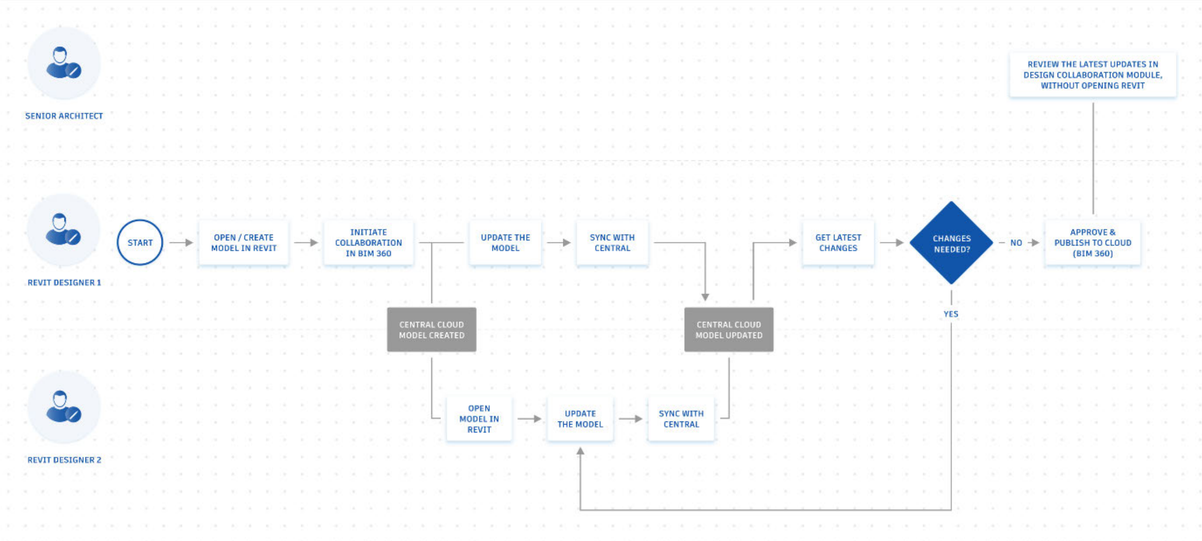


**Figure 13 – Cloud Based System implemented by AutoDesk**

#### 2.6.2. Standards & Guidelines

To overcome issues relating to standards and guidelines, the GBCA, or Engineers Australia can assist in the adoption of digital modelling technologies by providing training and resources to designers and engineers. The GBCA and Engineers Australia can also develop standards and guidelines for the use of digital modelling technologies in building services design to ensure that the technology is used effectively and efficiently.

### 2.7. Limitations & Challenges

#### 2.7.1. Technical Challenges

One of the main challenges associated with the adoption of digital modelling and optimization technologies is technical in nature. This includes issues such as data management, interoperability, and compatibility with existing software and systems. For example, different BIM software may use different data formats, which can make it difficult to share data between different systems. In addition, the use of advanced modelling and simulation tools requires significant computational power and can be resource-intensive, which can be a challenge for smaller firms with limited resources.

These challenges include technical issues, such as data management and interoperability, as well as organizational and cultural issues, such as resistance to change and lack of collaboration among stakeholders.

#### 2.7.2. Organizational and Cultural Challenges

Another significant challenge associated with the adoption of digital modelling and optimization technologies is organizational and cultural in nature. This includes issues such as resistance to change and lack of collaboration among stakeholders. Building services professionals may be accustomed to using traditional design and engineering methods and may be hesitant to adopt new technologies. In addition, there may be a lack of collaboration among stakeholders, including architects, engineers, contractors, and building owners, which can impede the adoption and implementation of digital modelling and optimization technologies.

#### 2.7.3. Lack of Standards

The lack of standards for digital modelling and optimization technologies is also a challenge that hinders their widespread adoption in the building services industry. There are currently no universally accepted standards for BIM or energy modelling software, which can make it difficult to compare results from different software tools or to exchange data between different systems. This can lead to inconsistencies in the data and models used for building design and operation, which can affect the accuracy of simulations and lead to errors in building performance predictions.

#### 2.7.4. Training, Education, skills & knowledge

The effective use of digital modelling and optimization technologies requires specialized skills and knowledge, which may not be available within the organization. The need for experts in fields such as data science, computational fluid dynamics, and building performance analysis can make it difficult for organizations to implement these technologies.

#### 2.7.5. Cost

The cost of implementing digital modelling and optimization technologies can also be a challenge for some building services firms. The cost of purchasing and maintaining advanced software tools, as well as the cost of training personnel to use them effectively, can be significant. In addition, the use of digital modelling and optimization technologies may require additional staff resources and time, which can further increase costs.

#### 2.7.6. Privacy and Security

The use of digital modelling and optimization technologies requires the collection and sharing of large amounts of data, which can raise privacy, security, and ownership concerns. Building owners and operators may be hesitant to share sensitive data related to building operations and energy usage with external stakeholders, which can limit the usefulness of these technologies. There are several types of digital modelling and optimization technologies that have been applied in the building services industry. Each technology and software has its own capabilities, limitations, and potential benefits.

### 2.7.7. Interoperability

Another technical challenge is ensuring that different BIM software and systems can communicate and share information effectively. This requires the use of open standards and protocols for data exchange, as well as the adoption of common data environments to enable collaboration and coordination among different stakeholders.

### 2.7.8. Limitations

The use of BIM requires significant investment in software, hardware, and training. BIM also requires collaboration among different stakeholders, which can be difficult to achieve. Integration with Existing Systems: The integration of digital modelling and optimization technologies with existing building services systems can also pose challenges. This can include issues related to data sharing, software compatibility, and technical limitations of the existing systems.

### 2.7.9. Resistance to Change

Finally, there may be resistance to change among stakeholders, particularly those who are used to traditional methods of building services design and operation. This can make it difficult to implement new technologies and processes, even if they are more efficient and effective.

## 2.8. Summary

Digital Twin technology in the AEC industry stands as a crucial catalyst for enhancing efficiency, productivity, information management, and quality within various processes. Undoubtedly, the significance of digital modelling and optimization technologies in the building services industry cannot be overstated. This literature review has demonstrated the capacity of Digital Twin technology to enhance the efficiency, sustainability, and performance of building systems and services, offering a more effective and efficient approach to address the industry's challenges.

Nonetheless, the adoption and implementation of digital modelling and optimization technologies in the building services industry still encounter certain challenges. These encompass technical aspects such as data management and interoperability, alongside organizational and cultural factors like resistance to change and limited collaboration among stakeholders. Resolving these challenges will be pivotal in maximizing the benefits offered by digital modelling and optimization technologies in the building services industry.

# 3. CHAPTER 3 – RESEARCH AND DESIGN METHODOLOGY

### 3.1. Survey Design

In this dissertation, a multifaceted approach has been adopted to answer the research questions and delve into the transformative potential of Digital Twins in promoting sustainable practices across various industries and domains. To begin with, a literature review has been conducted to explore existing studies, articles, and reports related to the integration of Digital Twins in different sectors. The literature review aimed to provide a solid foundation by examining how Digital Twins are being applied in diverse industries and the extent of their impact on sustainability practices.

In conjunction with the literature review, a survey questionnaire has been developed. This survey was developed to capture valuable data on practitioners' experiences with Digital Twins and their perspectives on commercial construction projects. The questionnaire dives into various key aspects, including the industries the practitioners belong to, their level of experience with the technology, specific applications of the technology, perceived benefits, and encountered challenges. Additionally, the survey seeks to gather insights into the practitioners' views on the opportunities and challenges of Digital Twins in commercial construction projects.

The survey targets a diverse group of practitioners to ensure a well-rounded perspective, encompassing individuals with varying levels of experience. By doing so, the study endeavors to gain a comprehensive understanding of how Digital Twins are being embraced and applied in real-world settings, and how they contribute to sustainable practices across different industries.

Furthermore, to improve the research inquiry, two explorative case studies have been undertaken. These case studies delve into practical applications of Digital Twins in different contexts, and countries, shedding light on the real-life challenges and opportunities that emerge during their implementation during the different stages of a projects lifecycle. The insights collected from these case studies will complement the survey findings, providing a more holistic and grounded understanding of Digital Twin technology's role within the AEC industry.

By adopting a combined approach of literature review, survey, and explorative case studies, this dissertation aspires to contribute significantly to the discourse surrounding Digital Twins and sustainability practices. The findings are expected to provide valuable insights and practical implications for practitioners, policymakers, and researchers, facilitating the effective integration of Digital Twin technology to advance sustainable development across various domains.

### 3.2. Create the Survey/Questionnaire

In this dissertation, a crucial aspect of the research methodology involves the development of a comprehensive survey questionnaire aimed at exploring the opportunities and challenges of Digital Twin technologies in construction projects. The formulation of these survey questions is designed to extract valuable insights and perspectives from a diverse range of participants, including practitioners, experts, and professionals across various sectors of the industry.

The survey questions have been developed to delve into essential aspects of Digital Twin technologies and their potential impact on sustainable practices within the Architecture, Engineering, and Construction (AEC) industry. By addressing topics such as the integration of digital twins in different sectors, the benefits they offer in terms of efficiency, collaboration, and cost reduction, as well as the perceived challenges encountered during implementation, the survey aims to generate a robust discussion.

### 3.3. Target Audience

In this dissertation, the research methodology includes a comprehensive survey and interview approach designed to ensure the collection of accurate and diverse data from various stakeholders within the Architecture, Engineering, and Construction (AEC) industry. The target participants for the survey encompass an array of professionals, including members of the Green Building Council of Australia (GBCA), architects, engineers, construction managers, project managers, and builders. This diverse selection of participants aims to capture a broad range of perspectives and experiences within the AEC industry.

The survey & questionnaire is designed to prompt valuable insights into the participants' views and experiences concerning Digital Twin technology and its potential implications in commercial construction projects. By gathering data from practitioners of different ages and varying experience levels, the study seeks to obtain a well-rounded perspective on the challenges, benefits, and opportunities associated with Digital Twins in promoting sustainability across the AEC industry.

To complement the survey data, the dissertation incorporates qualitative research through a series of interviews. Approximately 10 individuals from various professional backgrounds were selected for the interview phase. These interviews were conducted to delve deeper into the participants' experiences and perspectives, allowing for a greater understanding of the practical and real-life applications and challenges faced in implementing digital twin technology in commercial construction projects.

The inclusion of these diverse stakeholders and practitioners in the survey and interview phases strengthens the research methodology, ensuring a comprehensive exploration of the research questions. By engaging with professionals from different roles and experience levels, this study aims to shed light on the potential of Digital Twins in transforming sustainable practices across the AEC industry and provide valuable insights for industry stakeholders, researchers, and decision-makers.

The Target Audience for the survey included the following stakeholders:

- Architects & Engineers
- Construction Managers and Contractors
- Facility Managers and Operations Teams
- End-Users & Occupants
- Project Owners and Investors
- Regulatory Authorities
- Community Representatives

### 3.5. Sample Space

In this dissertation, the significance of a diverse sample in understanding the multifaceted impact of Digital Twin technology on the construction industry is emphasized. Digital Twins, involving the creation of virtual replicas of physical assets and processes, hold the potential to transform construction practices by fostering collaboration, efficiency, and cost reduction. However, to comprehensively evaluate the opportunities and challenges posed by this technology, it is important to gather insights from a wide array of stakeholders representing various industries and experience levels.

The adoption of a survey-based research approach allows for the inclusion of practitioners welcoming diverse backgrounds, each offering unique perspectives on the subject matter. By engaging with professionals from different industries such as architecture, engineering, construction management, and others, this study aims to capture a rich tapestry of viewpoints that collectively contribute to a holistic understanding of the opportunities and capabilities of Digital Twin technology in the context of sustainable development.

Furthermore, considering respondents with varying experience levels, spanning from novices to professionals, ensures that the research covers the breadth of insights available in the industry. The perspectives of newcomers may reveal fresh challenges and untapped potential, while those of experienced practitioners may highlight sophisticated approaches and nuanced considerations.

By welcoming this inclusive research methodology, the dissertation endeavors to uncover the diverse range of applications and implications of Digital Twin technology across the AEC industry. The findings are expected to shed light on how this technology can drive innovation, streamline processes, and foster sustainable practices in the industry.

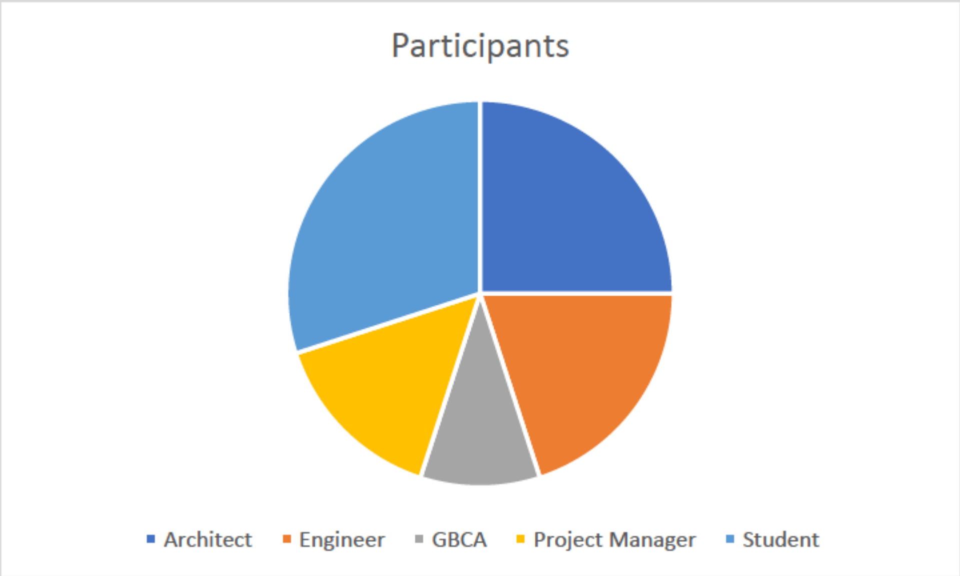


**Figure 14 - Participants of Survey**

The following table provides an outline of the variety of participants used in the survey and their years of experience.

**Table 3 - Table of survey participants**

| ***Survey Participant*** | ***Position*** | ***Years of Experience*** |
|---|---|---|
| ***1*** | *Architect* | *5* |
| ***2*** | *Architect* | *7* |
| ***3*** | *Architect* | *5* |
| ***4*** | *Architect* | *3* |
| ***5*** | *Architect* | *5* |
| ***6*** | *Engineer* | *8* |
| ***7*** | *Engineer* | *6* |
| ***8*** | *Engineer* | *6* |
| ***9*** | *Engineer* | *5* |
| ***10*** | *GBCA* | *3* |
| ***11*** | *GBCA* | *3* |
| ***12*** | *Project Manager* | *7* |
| ***13*** | *Project Manager* | *10* |
| ***14*** | *Project Manager* | *15* |
| ***15*** | *Student/Junior Architect* | *1* |
| ***16*** | *Student* | *1* |
| ***17*** | *Student* | *2* |
| ***18*** | *Student* | *2* |
| ***19*** | *Student* | *2* |
| ***20*** | *Student* | *1* |

### 3.6. Interview Design

In this dissertation, the data collection process plays a critical role in gaining valuable insights into the subject. To achieve a comprehensive understanding of the opportunities and challenges presented by Digital Twin technology in the construction industry, an interview has been developed for the Target Audience.

To ensure the interviews effectiveness and accuracy, several critical steps have been considered during its development. First and foremost, a pilot test of the interview was conducted. This pilot test enabled the author to assess the survey's clarity, relevance, and overall structure. Feedback received from a small sample group during the pilot phase was helpful in refining the interview, guaranteeing that the final version is well-suited to capture the necessary qualitative data.

Additionally, careful attention has been given to preparing the email and communication that accompanies the interview. This communication serves as a formal introduction to the interview, outlining its purpose, significance, and confidentiality assurances. Communication is crafted in a way that encourages participation from the target audience, outlining the importance of their contributions to the research.

Finally, the interview questions are distributed electronically to the target audience prior to the interview. This digital distribution method ensures efficiency and allows for an interviewee to prepare for the interview prior to be interviewed and enables the author to collect and manage interview responses in a secure and organized manner, facilitating data analysis and interpretation.

By implementing these steps in the data collection process, this dissertation aims to obtain high-quality and meaningful data that contributes substantially to the knowledge base on digital twin technology in the construction industry. The findings are expected to provide valuable insights, benefiting industry practitioners, researchers, and stakeholders alike.

### 3.7. Interview

In this dissertation, gathering insights from various industry practitioners is essential to explore the integration of digital twin technology in the construction industry. To achieve this, a structured interview approach has been adopted, where interviewees were carefully selected based on their experience and expertise in the construction domain.

The criteria for selection ensured that participants possess knowledge and familiarity with Digital Twin technology.

Interviews were conducted virtually with seven construction practitioners with construction experience ranging from 2 years to 15 years.

**Table 4 - Table of interview participants**

| **Interviewee** | **Company Type** | **Position** | **Years of Experience** | **Interview Duration** |
|---|---|---|---|---|
| *A* | *Architect Firm* | *Architect* | *10* | *1h* |
| *B* | *Interior Designer* | *Architect* | *8* | *1h* |
| *C* | *Engineer Firm* | *Engineer* | *15* | *2h* |
| *D* | *Commercial Construction* | *Project Manager* | *13* | *1.5h* |
| *E* | *Commercial Construction* | *Project Manager* | *12* | *2h* |
| *F* | *Architect Firm* | *Student* | *2* | *2h* |
| *G* | *Builder* | *Student* | *2* | *1.5h* |

### 3.8. Ethical Considerations & Consequences

In this paper the adherence to ethical principles and securing approval from the Human Research Ethics Committee is essential to commencing research which involves human participants. The ethics clearance serves as an indispensable prerequisite, ensuring that the study is conducted ethically and in compliance with established guidelines and standards.

Throughout the planning and development stages of the research project, careful consideration has been given to various ethical consequences that may arise during data collection and analysis. These ethical considerations encompass a broad range of aspects, such as informed or implied consent from the participants, safeguarding data privacy and confidentiality, ensuring voluntary participation, avoiding potential harm to participants, and ensuring the validity and reliability of the collected data.

Moreover, the research considers the significance of cultural sensitivity, transparency, and fairness in handling and reporting research findings. Economic considerations and social implications are also acknowledged to ensure that the research outcomes align with broader societal interests.

To mitigate ethical issues and uphold participant rights, a series of robust strategies have been adopted. Firstly, both informed and implied consent mechanisms have been put in place, wherein participants are fully informed about the research and have the autonomy to participate voluntarily. The University of Southern Queensland's Participation Information Sheet serves as a critical tool in providing participants with details about the research, which enables them to make informed decisions.

To further protect participant identities, anonymity and confidentiality measures have been implemented to ensure that individual responses cannot be traced back to specific participants. Additionally, data sensitivity and security measures are in place to prevent unauthorized access and maintain the integrity of the data. To gain ethics clearance and streamline data management, an ethics application was completed and submitted. As part of this process, a data management plan was developed, serving as a roadmap for handling sensitive data responsibly and ethically.

By adhering to these ethical considerations and implementing the strategies throughout the research process, the study aims to uphold the principles of research ethics, prioritize participant rights, and ensure the validity and reliability of the collected data. Through this ethical approach, the dissertation seeks to contribute to the field of digital modeling and optimization technologies in the design of sustainable construction projects, while fostering trust and accountability in the research community.

### 3.9. Invite Participants and Distribute the Survey

The process of inviting and recruiting potential participants for the survey has been carefully coordinated to ensure ethical considerations and adherence to research standards. Invitations were extended to potential participants via email, or phone call, wherein a concise overview of the study was provided along with a detailed participant information sheet.

The participant information sheet serves as a vital component of the process, offering essential details about the survey's purpose, benefits, potential risks, and the assurance of confidentiality. This transparency aims to inform prospective participants about the research's significance and how their contributions will be instrumental in advancing the knowledge in the field.

To ensure a diverse sample space, the recruitment strategy leveraged professional networks and strong affiliations with industry associations and academic institutions. By reaching out to these established networks, the research aimed to access a wide range of potential participants, encompassing professionals from various sectors and expertise levels within the targeted audience.

The participation information sheet serves as a comprehensive guide for potential participants, providing them with a clear understanding of the survey's objectives and the potential implications of their involvement. It further addresses privacy and confidentiality concerns, reassuring participants that their responses will be treated with the utmost care and that their identities will remain anonymous throughout the research.

By employing such a recruitment process and ensuring complete transparency, the dissertation seeks to establish a foundation of trust and respect with the participants. This ethical approach is crucial in safeguarding participant rights, promoting voluntary participation, and upholding confidentiality throughout the research journey.

Overall, this well-structured recruitment strategy aims to secure a high-quality and diverse group of participants, generating meaningful data for the study's objectives. The findings are expected to offer valuable insights into the subject matter and contribute to the broader body of knowledge in the scope of digital modeling and optimization technologies in the context of sustainable construction projects.

### 3.10. Data Analysis & Reporting

In this dissertation, the analysis and reporting of survey data provides valuable insights concerning the opportunities and capabilities of Digital Twin technology in the AEC industry. The utilization of suitable statistical techniques enables a thematic exploration of the data, facilitating the identification of trends, patterns, and correlations that are directly relevant to the research objectives.

The data analysis and reporting process will involve a comprehensive examination of the survey responses, with a specific focus on key themes such as the integration of Digital Twins in various industries, the impact & challenges associated with the implementation of Digital Twin technology within the operation, design, and construction of construction projects.

The application of data analysis techniques ensures that the research outcomes are firmly grounded, credible, and supported by empirical evidence. Through a thematic approach, this dissertation aims to advance the understanding and application of Digital Twin technology as a transformative enabler for sustainable development across the AEC industry.

### 3.11. Research Question 1:

**How can Digital Twin Technology be used in the operation, design, and construction phases of a construction project?**

**LITERATURE REVIEW**

The literature review serves as the foundation for the research, providing valuable insights into the current state of knowledge surrounding Digital Twin technology's applications, benefits, and challenges in the context of operation, design, and construction phases of commercial construction projects. By examining a diverse range of scholarly works, research articles, reports, and industry publications, the study aims to gain a comprehensive understanding of how Digital Twin technology is harnessed in the operation, design, and construction phases of construction projects to drive sustainability objectives.

The literature review explores various key aspects, including the implementation of Digital Twins in operation, design and planning processes, their role in optimizing resource utilization, enhancing energy efficiency, minimizing waste generation, and their impact on overall project performance and lifecycle management. Additionally, the review seeks to identify successful case studies and best practices where Digital Twin technology has been effectively applied to achieve community engagement, and sustainability goals in construction projects.

### 3.12. Research Question 2

**What are the opportunities of Digital Twin Technology for in the operation, design, and construction phases of a sustainable construction project.**

**SURVEY APPROACH**

Various stakeholders were asked the following questions: -

- Have you heard of Digital Twin technology before this survey?
- What are the opportunities for implementation of Digital Twin technology in the design stages of a construction project?
- What are the opportunities for implementation of Digital Twin technology during the construction phases of a sustainable construction project?
- What are the opportunities for implementation of Digital Twin technology during the operation phases of a sustainable project?
- Do you think Digital Twin technology can contribute to sustainable development?
- In your opinion, what are the potential benefits of using Digital Twin technology for sustainable development?

### 3.13. Research Question 3:

**What are the perceived challenges of the implementation of Digital Twins for in the design and construction stages of a sustainable construction project?**

**SURVEY APPROACH**

Various stakeholders were asked the following questions: -

- In your opinion, what is the biggest challenge facing sustainable development today?
- What are the challenges or limitations of using digital twin technology for sustainable development?
- What are the challenges of implementation of Digital Twin technology in the design stages of a sustainable construction project?
- What are the challenges of implementation of Digital Twin technology during the construction phases of a sustainable construction project?
- What are the challenges of implementation of Digital Twin technology during the operation phases of a sustainable construction project?
- What potential unintended consequences do you think may arise from the use of digital twin technology in sustainable development?

### 3.14. Research Question 2,3,4:

**What are the opportunities of Digital Twin Technology for in the operation, design, and construction phases of a sustainable construction project.**

**What are the perceived challenges of the implementation of Digital Twins for in the design and construction stages of a sustainable construction project?**

**What are the practical approaches and applications for implementing Digital Twins in the design & construction phases of construction projects?**

### 3.15. INTERVIEW/CASE STUDYAPPROACH

To confirm interviewees, understand the concept of Digital Twin technology, the interviewer took proactive measures to address any questions or doubts raised by the participants regarding the concept. This step was crucial in ensuring that all interviewees possessed a clear and common understanding of the technology before proceeding with the discussions.

The interviews then delved into understanding the perspectives of the participants on various aspects related to Digital Twin technology in the construction industry.

### 3.16. Advantages and Potential Challenges

Participants were encouraged to articulate the advantages and potential challenges encountered while implementing Digital Twin technology in real-world construction projects. By capturing both positive experiences and hurdles faced, the questions asked aimed to gain a comprehensive understanding of the technology's practical implications.

Based on interviews with various stakeholders involved in real-world construction projects, the advantages, and potential challenges of implementing Digital Twin technology were explored. The interviewees shared their experiences, both positive and challenging, providing valuable insights into the practical implications of Digital Twins in the construction industry. The following is a summary of their responses.

Interviewees elaborated that the implementation of Digital Twin technology offered significant advantages in improving project collaboration and communication. They explained that Digital Twins provided a common data environment, enabling real-time access to project information for all stakeholders. This streamlined communication, reduced misunderstandings, and enhanced collaboration among architects, engineers, contractors, and project managers.

For instance, interviewees mentioned that the use of Digital Twins facilitated remote collaboration on complex projects. By sharing a virtual model of the project, team members from different locations could simultaneously visualize and contribute to the project's development. This real-time collaboration capability was particularly valuable during the COVID-19 pandemic, when travel restrictions and remote work arrangements were in place.

Interviewees then elaborated that with Digital Twins, they can better use data for informed decision-making. By integrating data from multiple sources, such as BIM models, sensor data, and historical project data, they gained valuable insights into project performance, resource utilization, and progress tracking. This data-driven approach empowered them to make proactive decisions, optimize construction schedules, and identify potential risks.

Interviewees mentioned that their projects faced major challenges when dealing with complex project geometries, and intricate architectural detail. In such scenarios, clash detection and coordination between different building systems became more challenging, leading to potential conflicts and clashes during construction execution. The use of VR technology, digital twin technology and live BIM models, project teams could instantaneously identify the impact of design changes on clash detection and constructability.

Overall, the insights provided by the interviewees highlight the practical applications and implications of Digital Twin technology in real-world construction projects. The advantages of enhanced collaboration, data-driven decision-making, and proactive simulations demonstrate the transformative potential of Digital Twins in the construction industry. At the same time, the challenges related to complex geometries and clash detection underscore the importance of continuous improvement and refinement of Digital

Twin implementations. By addressing these challenges and leveraging the identified capabilities, stakeholders in the construction industry can unlock the full potential of Digital Twins to drive innovation, efficiency, and sustainability in their projects.

During the literature review, a significant challenge that emerged was related to the management of data and its interoperability. We approached interviewees to gain a deeper understanding of their experiences and insights regarding this issue. The focus encompassed examining how technology integration influences design, planning, construction execution, and project management processes.

Furthermore, the interview inquired about the types and sizes of files they used for their projects. The collected data is as follows:

**Table 5 - File types used in the industry.**

| File Type | Size of File (megabytes) |
|---|---|
| DWG | 10-20 |
| OBJ | 1000-2000 |
| IFC | 1000-2000 |

From our conversations, it became evident that interviewees encountered minor challenges when transferring data from larger Digital Twin models and IFC files. However, these challenges were less prominent with file formats such as DWG. It's worth noting that interviewees expressed that modern internet speeds, available in the 21st century, have significantly reduced the issues associated with transferring various file types. As a result, the overall transfer of data was not considered a major concern. Furthermore, the emergence of cloud platforms specifically designed for exploring point cloud information has further mitigated data-related issues and data transfer barriers.

Throughout the interviews, which included perspectives from architects, engineers, project managers, and students, we delved into the utilization of Digital Twins across different phases of construction projects. Interviewees openly shared their experiences and insights regarding data sharing and the management of confidential information. This integration has been particularly significant in design, planning, construction execution, and project management processes.

Interviewees were asked to elaborate on how concerned they were about the potential risks to privacy and data security associated with the use of Digital Twin technology within government, military, and defense projects. By asking this question, the interviewers aimed to gauge interviewees' perceptions and apprehensions regarding the potential privacy and data security risks that may arise with the adoption and utilization of Digital Twin technology in these types of construction projects. The question is designed to elicit interviewees' views on the balance between the benefits of utilizing Digital Twins and the need to safeguard sensitive data and privacy rights.

Based on interviews with various stakeholders in the construction industry, their concerns about the potential risks to privacy and data security associated with the use of Digital Twin technology in operation, design, and construction phases of a construction project. The interviewees shared their views on the balance between the benefits of utilizing Digital Twins and the need to safeguard sensitive data and privacy rights. The following is a summary of their responses.

Interviewees elaborated that they have significant concerns about the potential risks to privacy and data security associated with the use of Digital Twin technology for projects where this data and information is sensitive, such as the construction of government or defense projects, or the construction of buildings that store sensitive information or valuable items, such as jails, banks, or the storage of military equipment. They highlighted the nature of the data within the Digital Twin, such as building performance, materials used, occupant behavior, and environmental conditions, which require robust protection to prevent unauthorized access and misuse. Interviewees then elaborated that a solution to this would be to encrypt and secure data storage to protect sensitive information. By implementing stringent security measures, project teams can minimize the risks of data breaches and cyber-attacks, thus safeguarding the privacy of individuals and organizations involved in commercial construction.

Interviewees highlighted that data privacy regulations are crucial in ensuring the responsible and ethical use of data in Digital Twins. Compliance with such regulations becomes paramount to build trust among stakeholders and ensure that privacy rights are respected. The information within the Digital Twin could be used for conflicts of interest or for illegal use.

Further to this, interviewees mentioned that their projects faced major challenges when dealing with interoperability of data and integration of different software and file formats within Digital Twin models. For example, some contractors may use a variety of software, identified in section 1.0 of this paper in the literature review. Although a greater part of this software has been developed by Auto Desk, the software and the file formats which are exported may not be interchangeable. In a future with widespread adoption, standardization and seamless data exchange protocols will be essential to maximize the potential of Digital Twins across various projects and urban environments. Interviewees mentioned that their projects faced major challenges in data integration and interoperability between different Digital Twin models. As the adoption of Digital Twins becomes more widespread, standardization and data exchange protocols will be essential to ensure seamless communication and collaboration.

Interviewers also mentioned that the ownership of data or intellectual property was not an issue on their projects, and the collaborative approach and sharing of data and IP was used as all stakeholders within the project had one common goal – to finish and complete the project successfully.

Although interviewees were aware of the complications associated with this, they mentioned that they had not worked on projects which faced major challenges when dealing with data breaches and unauthorized access to sensitive information.

When project teams could not predict potential data security risks and lacked adequate measures to protect sensitive data, they faced difficulties in gaining stakeholder trust and support for Digital Twin adoption. Ensuring data security and privacy become essential prerequisites for the successful and sustainable implementation of Digital Twins. Based on this, the use of Digital Twin technology for government or defense projects was not seen as a large risk. However standard risk mitigation strategies should be incorporated into the project to mitigate the potential security risks for using Digital Twin technology in these types of projects.

### 3.17. Challenges

Interviewees were asked to elaborate on challenges the construction industry face and their perception on how Digital Twin can assist in addressing these challenges. By asking this question, the interviewers sought to delve into interviewees' perspectives on the significant challenges that the construction industry encounters.

The question aimed to elicit insights into a wide range of challenges, such as productivity issues, project delays, cost overruns, safety concerns, sustainability goals, and complex coordination among diverse stakeholders.

Interviewees elaborated that one of the significant challenges the construction industry faces are project delays, which can result from unforeseen issues, coordination problems, or changes in design.

For instance, interviewees mentioned that with Digital Twins, they can better use real-time data and simulations to identify potential bottlenecks and clashes early in the project. By detecting these issues beforehand, project teams can proactively address them and reduce the likelihood of delays.

For instance, interviewees mentioned that Digital Twins provides a collaborative platform where all stakeholders can access and contribute to the virtual model. This centralized approach streamlines communication, fosters collaboration, and ensures everyone is on the same page, reducing misunderstandings and conflicts.

Overall, the insights provided by the interviewees highlight a range of challenges faced by the construction industry, such as project delays and complex design coordination between architects and services consultants. Digital Twin technology offers capabilities like real-time data analytics, simulations, and centralized collaboration to address these challenges effectively. By leveraging these capabilities, stakeholders in the construction industry can improve project efficiency, mitigate risks, enhance sustainability practices, and achieve better overall project outcomes. Embracing digital twin technology can pave the way for a more efficient, collaborative, and sustainable construction industry.

Interviewees were asked to discuss the challenges faced with the implementation of Digital Twin technology within their company or business. By asking this question, the interviews strive to dive into the opinions and thought processes on the significant challenges that are encountered with the implementation of the technology.

Interviewee identified several challenges which hindered the implementation of Digital Twin technology such as formal training and education. With the range of software available for use, interviewees said that they struggled to find people who were trained at using the software for use within their company. Interviewees wanted to adopt the software within their company to maximise efficiency, however, were not able to find employees that were able to use it. Therefor this limited their capacity to implement the variety of software available to them.

### 3.18. Practical approaches and applications for implementation

Interviewees were invited to share their experiences and insights on the practical approaches and applications for implementing Digital Twin in the different phases of construction projects. This encompassed exploring the technology's integration in design, planning, construction execution, and project management processes.

Based on interviews with various stakeholders, including architects, engineers, project managers, and students, the utilization of Digital Twins in different phases of construction projects was explored. The interviewees shared their experiences and insights on how Digital Twins have been integrated into design, planning, construction execution, and project management processes.

Interviewees then elaborated that Digital Twins have been extensively utilized during the design phase of construction projects. They explained that Digital Twins enable them to create virtual representations of the proposed structures, facilitating real-time simulations and analyses. This capability allows them to optimize design decisions, evaluate different design alternatives, and visualize potential challenges or opportunities in the early stages of the project.

For instance, when engineers who were asked about this, mentioned that their projects have utilized Digital Twins to analyze complex structural designs. By simulating various load scenarios and material choices, they were able to identify the most efficient and sustainable design solutions. Digital Twins also played a significant role in creating responsive and adaptable building designs to meet changing requirements throughout the project's lifecycle.

Interviewees were asked how the practical approaches required to develop a Digital Twin Model if accurate as built information was not present during the design stages of construction. Interviewees provided their experience using 3D scanning during the design, and construction phases of a construction project. The literature review identified the AEC sector uses BIM during the planning, design, and construction stages of a building's lifecycle. Interviewees elaborated that the BIM model, which is almost always an object or a part of it that is being developed, is the first stage of the process for manufacturing the product and is where the Digital Twin is easily incorporated into future-built or produced things. When a BIM model cannot be present, interviewees said they can use 3D scanning technology to identify as built model and already-existing services to build a point cloud and integrate them into a BIM model. This has been valuable thanks to advancements and the affordability of 3D laser scanning technology.

The figures below provide a snapshot of a point cloud used by interviewees to confirm as built conditions and existing services at 80 Ann Street Building in Brisbane. By using 3D scanning tools, services consultants, engineers, and architects can quickly and accurately capture the dimensions and layout of existing services such as HVAC systems, plumbing, and electrical components. This information can then be integrated into BIM software, creating the Digital Twin Model which allows designers and contractors to create more accurate architectural plans to identify potential conflicts between existing services and proposed changes. The interviewees confirmed the notion identified during the literature review that as-built drawings and models, are necessary records utilized by facility managers in the operational administration of buildings to oversee facility spaces, maintenance, and energy systems. The management and analysis of a building's efficiency must begin with an as-built information model.

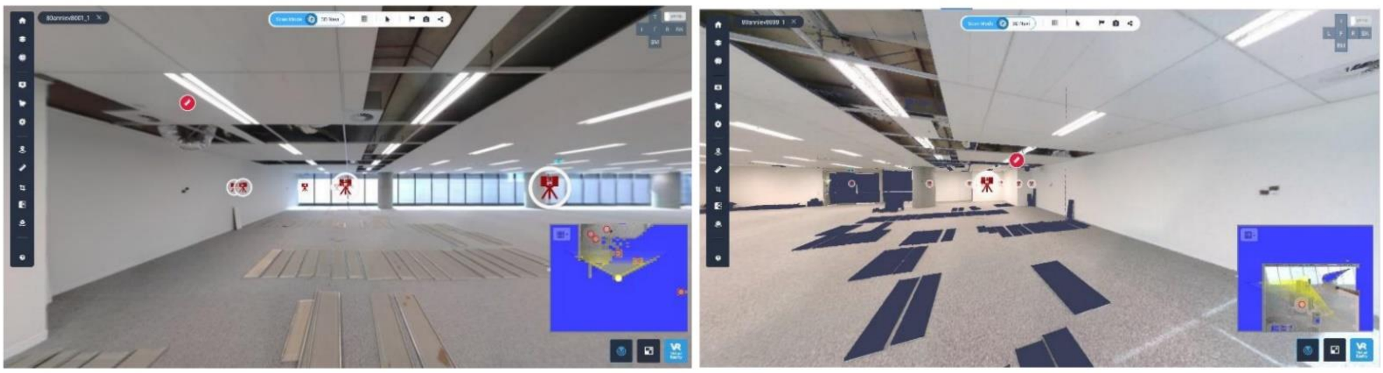

**Figure 15 - 3D scan at 80 Ann Street – Auto Desk Recap Software used to identify and confirm accuracy of As-Built Documentation.**

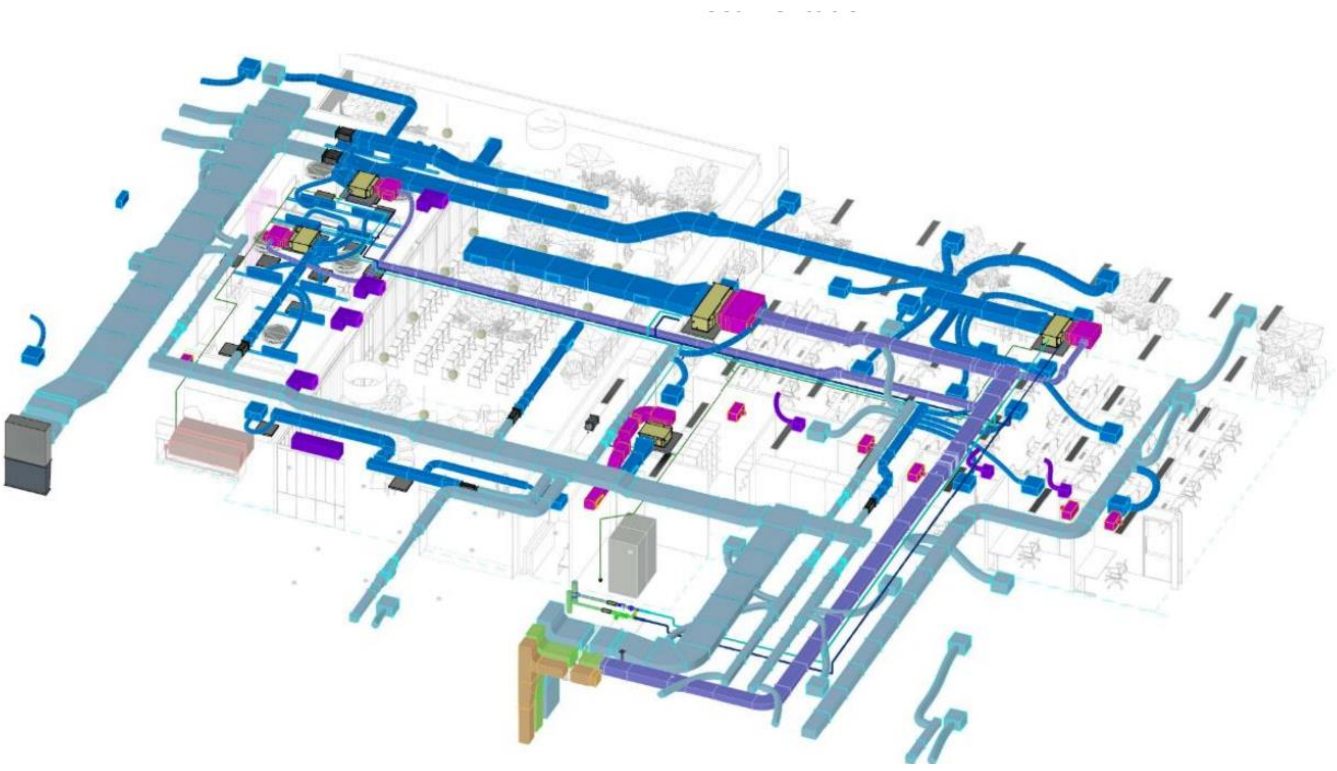

**Figure 16 - A schematic of Mechanical Shop Drawings developed using Autodesk's Revit at 80 Ann Street from a 3D Scan.**

Interviewees further provided practical examples of how they have used Digital Twin technology on live construction projects. Interviewers referenced the use of virtual reality goggles and live BIM models for enhancing collaboration and ensuring quality assurance on a construction site. The benefits of this technology can create a live digital environment which can be used to identify issues and resolve clashes. The two figures below provide an example and visual representation of how these advances in technology and how they can be used on a live construction site to manage and resolve these issues. The ability to simulate construction processes virtually allowed them to anticipate clashes, safety hazards, and logistical challenges. This proactive approach enabled them to implement preventive measures, avoiding costly rework and delays.


**Figure 17 - QR Code to integrate a live BIM model into a construction project.**

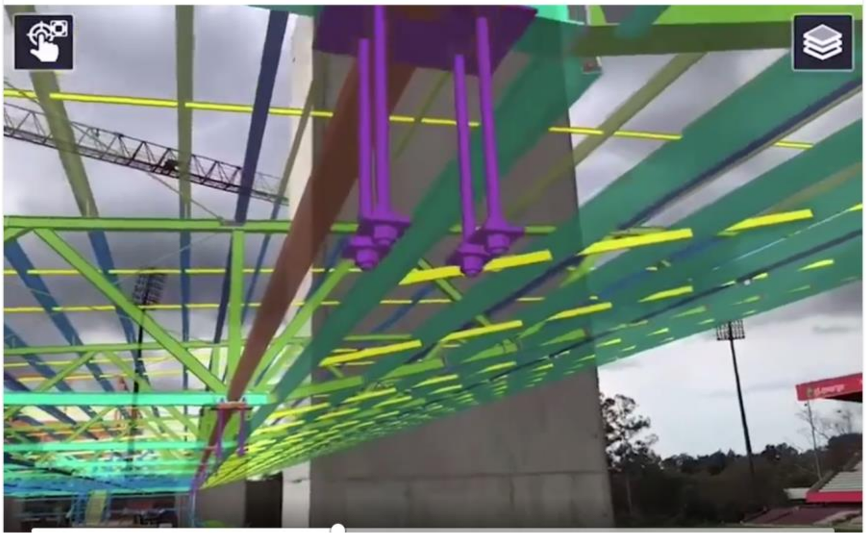

**Figure 18 - Live Digital Twin Model integrated into a live construction project using VR and Digital Twin technology.**

Interviewees then elaborated that with Digital Twins, they can be better prepared for unforeseen challenges during construction execution. By virtually simulating the construction process, they can anticipate potential clashes, logistical challenges, and safety hazards. This proactive approach allows them to identify and address issues before they arise on the construction site, leading to significant time and cost savings.

Interviewees elaborated that one of the most practical and innovative uses of Digital Twin technology during the operation phase of a construction project is its application in "smart building" design and management. They explained that Digital Twins enable the integration of real-time sensor data with building models, allowing buildings to dynamically adapt to changing environmental conditions and occupant needs.

For example, interviewees mentioned that in a smart building project, Digital Twins were used to optimize energy usage by automatically adjusting lighting, heating, and cooling systems based on an expected occupancy patterns and ambient conditions. This data-driven approach resulted in significant energy savings and reduced environmental impact.

Interviewees then elaborated that with Digital Twins, they can better use predictive analytics to anticipate maintenance needs and optimize building performance. By continuously monitoring equipment and systems, Digital Twins can identify and detect potential maintenance issues before they escalate, leading to proactive maintenance and extended asset and project life expectancy.

When designers could not predict the long-term impact of energy-efficient design choices on building performance, they faced difficulties in achieving optimal energy savings. Digital Twins can address this challenge by providing real-time performance feedback and facilitating iterative improvements in energy efficiency.

### 3.19. Implementation

Based on interviews with various stakeholders in the construction industry, the importance & implementation of Digital Twin technology during the early contractor involvement phases & design phases of a construction project was explored. The interviewees shared their perspectives on the significance and impact of stakeholder, contractor, and consultant engagement in the successful adoption and utilization of Digital Twins to achieve successful construction projects. The following is a summary of their responses.

Interviewees elaborated that stakeholder engagement is crucial when implementing Digital Twin technology within construction projects. They explained that involving all relevant stakeholders, including clients, project teams, contractors, regulators, consultants, and local communities, fosters a collaborative approach to sustainability and ensures that diverse perspectives are considered in decision-making.

For instance, interviewees mentioned that stakeholder engagement is vital during the early stages of a project when defining sustainability objectives and performance indicators. By involving all stakeholders in the goal-setting process, the project aligns with their priorities and values, increasing the likelihood of successful implementation and long-term sustainability.

In addition to this, interviewees also said that the engagement of contractors early in on the design and construction of projects was helpful in ensuring the project’s buildability. Combining this with the use of Digital Twin technology created an environment focused on collaboration and efficiency.

Interviewees then elaborated that with Digital Twins, they can better use real-time data to inform stakeholders about project design progress, performance, and sustainability metrics. By providing accessible and transparent information, Digital Twins promote open communication and allow stakeholders to actively contribute to the project's sustainability initiatives. A real-life example, some interviewees from the GCBA said they were approached as a consultant to assess the Green Star rating of a project during the design phases of a project. By adjusting certain inputs of the Digital Twin model, consultants were able to identify an output, such as combined energy use, combined water usage, or return on investment over time. Using the advancements in Digital Twin technology, the client, consultants, and designers were able to achieve the projects’ goal Green Star Rating.

Interviewees then elaborated that with Digital Twins, they can be better prepared for addressing stakeholder concerns and feedback in real-time. By integrating stakeholder inputs into the Digital Twin model, project teams can quickly assess and identify the impact of proposed changes, through outputs of the model. Interviewees said that changing the elements or material used within a project can reduce the overall cost of the project during the operation stages.

For instance, interviewees mentioned that their projects faced major challenges when stakeholder engagement was lacking or inadequate. In such cases, the project's goals might not align with heritage standards, green star ratings, stakeholder expectations, leading to undesirable outcomes, such as reduced occupancy and reduced leasing opportunities once the project had finished being constructed.

More often than ever before, industry professionals, government practitioners, decision makers, developers and industry wide experts are promoting Green Building programs and driving the notion for sustainable development within the construction industry. Companies and organizations are prioritizing sustainability and wellness within workplaces, this drive can be motioned with the implementation of Digital Twin technology to further implement sustainability within the AEC sector.

When project teams could not predict the long-term impact of design decisions on stakeholder communities and environments, they faced difficulties in achieving sustainable outcomes. Digital Twins can address this challenge by facilitating real-time impact assessments and enabling adjustments to meet client & stakeholder expectations.

### 3.20. Conclusion

The insights gained from these interviews are invaluable in providing a holistic view of Digital Twin technology's adoption and impact within the construction industry. By drawing upon the firsthand experiences and perspectives of industry experts, the interview provided an insight into the practical applications, the opportunities and challenges of Digital Twin technology during the operation, design, and construction phases of a project. .

This step resulted in the identification of several themes, which are referred to as Digital Twins capabilities. These themes include real-time data analytics, simulations, early issue detection, and centralized collaboration. These themes will be further discussed in the next section of the report.

### 3.21. Case Study

#### 3.21.1. NTU EcoCampus, Singapore.

**Case Sutdy 1: NTU EcoCampus, Singapore**

IES undertook a significant project commissioned by Nanyang Technological University (NTU) to develop a comprehensive 3D master planning and visualization model for NTU's flagship Eco Campus. This project, executed in two distinct phases, leveraged IES's cutting-edge Integrated Environmental Solutions (IES) technology to provide advanced visual insights and analytical capabilities regarding testbed energy reduction innovations on-site. It also involved detailed simulations and precisely calibrated models for 21 specific campus buildings.

NTU's primary objective was to gain a comprehensive understanding of the performance of various testbed solutions at the campus level, identifying the most effective ones and determining the optimal scale and placement for their deployment. The progression into Phase 2 marked a shift into the implementation phase, where the most promising solutions identified during Phase 1's testbed stage were embraced and applied.

Spanning NTU's extensive 200-hectare campus and the adjacent 50-hectare JTC Corporation CleanTech Business Park, the Eco Campus initiative encompassed over 200 structures with a combined floor area of 1.1 million $m^2$.

The collaboration between IES and NTU was marked by a profound symbiotic and collaborative connection. IES contributed its latest IES technology alongside relevant training and consultation, while NTU provided invaluable technological feedback and an expansive real-world implementation context.

The primary phase of the project focused on creating a master planning model for the Eco Campus, including distinctive energy profiles for each building on the campus. This model achieved remarkable accuracy, with a precision rate of 91% for overall energy consumption and 97% for chiller energy consumption. Simultaneously, an online cloud-based Campus Information Model (iCIM) was established to facilitate communication and engagement with campus staff and students, seamlessly linked to the master planning model for automatic updates.

Building upon the master planning model, the subsequent step involved simulating and inspecting a range of testbed technologies, including enhancements to the building envelope's thermal performance, lighting sensors, chiller optimization, and smart plugs for restricting equipment usage beyond operational hours. The cumulative impact of these interventions resulted in a significant 10% reduction in campus-wide energy consumption, equivalent to a monetary saving of $3.9 million and a reduction in carbon emissions by 8.2 kt.

Following this, virtual models for each of the 21 buildings were generated within the Virtual Environment (VE) and finely calibrated using operational data. These closely aligned models established an accurate performance baseline for the operational buildings, enabling IES to perform a comparative analysis and estimate potential savings during the 'Invest' phase.

In the 'Collect' and 'Investigate' phases, relevant building data was gathered, and operational statistics were integrated into iSCAN to scrutinize issues and anomalies within a selection of 21 campus structures. This endeavour revealed concerns such as fluctuating CO2 levels, unstable off-coil temperatures, deviations in return air temperatures, malfunctioning energy consumption meters, and discrepancies in temperature settings for staff offices and meeting rooms.

A curated selection of novel technologies encompassing building envelope enhancements, lighting and occupancy sensors, efficient plug load management, and optimized high-performance chillers were used to provide information within the simulation and calibrated models to ascertain prospective savings. The outcomes underscored the substantial potential, with these technologies predicted to yield an average energy savings of 31% alongside a collective cost reduction approximating $4.7 million when deployed within the buildings.

In summary, the NTU Eco Campus project serves as a compelling case study showcasing the practical application and benefits of cutting-edge technology, including

Digital Twin and Building Information Modelling (BIM), in the realm of sustainable construction. The success of this venture not only demonstrates the positive impact of these technologies on energy efficiency and carbon reduction but also highlights their potential to revolutionize construction practices and contribute to a more sustainable built environment.

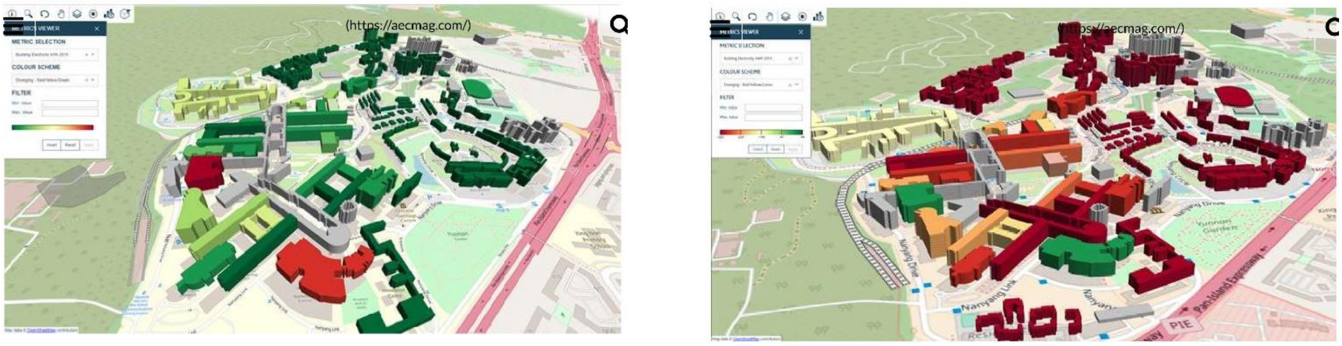


**Figure 19 – NTU's Master Planning Model**

#### 3.21.2. Project SCENe: Trent Basin

**Case Study 2: Project SCENe: Trent Basin**

Project SCENe, which stands for "Sustainable Community Energy Networks," embodies a association uniting construction and energy supply chain entities with the research community and prospective homebuyers at Nottingham's Trent Basin development. Trent Basin, located in the UK, is a pioneering development that exemplifies the positive outcomes of integrating BIM and Digital Twin Technology with sustainable practices. The utilization of BIM during the design and construction phases enabled enhanced collaboration among stakeholders, promoting sustainable decision-making. Furthermore, the deployment of Digital Twin Technology in the operation phase facilitated real-time performance monitoring of renewable energy systems and energy consumption patterns. This data-driven approach empowered residents to make informed decisions to optimize energy usage and minimize their carbon footprint. The findings from this case study provide concrete indication of how BIM and Digital Twin Technology can empower communities to adopt sustainable practices.

IES has pioneered an interactive platform designed to empower the Trent Basin community with real-time visualization of their energy data, making use of Digital Twin technology. This cutting-edge platform not only provides insights into renewable energy generation, energy storage, and consumption but also furnishes general information about the homes in the community.

Situated along the River Trent within Nottingham Waterside, Trent Basin stands as a low-energy community. This development has received support from the Energy Research Accelerator and Project SCENe, an Innovate UK-funded initiative led by the University of Nottingham and ATKearney. Notably, it hosts a groundbreaking energy venture, where Europe's largest community energy battery stores energy on-site.

The 3D Community Interaction Model's primary goal was to introduce a visual tool that stimulates public engagement with the community energy scheme and effectively communicates the outcomes of this innovative low-energy housing project.

This endeavor leverages IES's iCIM, iCD, and iSCAN technologies to seamlessly integrate real-time data on energy usage, generation, and storage at Trent Basin. This integration enables residents to compare their household-level energy data with the community average and observe the energy produced by the project, as well as its contributions to the grid.

IES was selected to develop this pioneering software platform after showcasing their advanced interactive smart city technology to key university personnel. The platform enables residents and potential buyers to interact with a model of the community, exploring its dynamics and engaging with energy in ways previously unattainable. Furthermore, users can actively influence the platform's future enhancements.

The project's foundation rests on cutting-edge smart home and IoT technologies, which facilitate an enhanced understanding and prediction of energy consumption patterns and behaviors. This newfound knowledge empowers residents to make informed decisions and contribute to optimizing the community energy scheme for the greater good.

Whether accessed through the online interface or the expansive 147 Inch Touch Screen, community members can virtually navigate the real-world site, observing energy generation in real-time and monitoring the battery's charging status. These observations can be contrasted with other real-time data such as weather conditions.

Positioned within the Trent Basin's "Community Hub" space, the 147-inch touch screen provides a unique avenue for everyone to engage with the site and deepen their understanding of its energy dynamics. Its user-friendly design ensures accessibility for individuals of all abilities. The objective here is to render energy easily comprehensible and engaging, thereby highlighting its significance for well-being and resilience, transcending its role as an invisible aspect of daily life with limited societal or sustainability benefits. This touch screen forms part of a suite of approaches to achieve this, including voice-activated assistants, tailored social media platforms, a customizable smart metering app compatible with various devices, and community-centered activities.

"In presenting averages of household energy consumption data along with monetary and carbon cost comparisons, residents can more readily translate energy behaviors into meaningful impacts and benchmark their data against the broader community, providing an immediate local standard for personal assessment." - Lewis Cameron, Research Fellow, Project SCENe, University of Nottingham

Project SCENe's overarching vision is clear: to facilitate the integration of renewables in all future housing developments, thereby reducing energy expenses and carbon footprints without burdening homeowners or developers.

Trent Basin, situated within Nottingham Waterside, is an innovative low-energy community that has received support from the Energy Research Accelerator and the Project SCENe initiative, funded by Innovate UK and led by the University of Nottingham and ATKearney. This pioneering development houses a groundbreaking energy project that entails on-site energy storage in Europe's largest community energy battery.

To facilitate effective community engagement with the energy scheme, IES employed digital twin technology to create an interactive platform (see Figure 12.0) at Trent Basin. This platform offers real-time visualization of energy data, providing insights into renewable energy generation, energy storage, energy consumption, and general information about the homes in the community.

The primary objective of the 3D community interaction model is to serve as a visual tool that encourages public engagement in the community's energy scheme. By integrating real-time data on energy usage, generation, and storage at Trent Basin, residents can compare their household-level data with the community average and observe the amount of energy being produced and sold back to the grid. The aim is to simplify and enhance the understanding of energy, enabling citizens to recognize its potential as a vital element for well-being and resilience.


**Figure 20 - Trent Basin Interactive Platform (2022).**

Evidence from real-life examples, such as the NTU EcoCampus in Singapore and Project SCENe: Trent Basin, showcases the tangible impact of Building Information Modelling (BIM) and Digital Twin Technology in reducing the carbon footprint of the built environment. As more building professionals recognize the social, environmental, and economic benefits of integrating these technologies with performance analysis tools, the adoption and positive outcomes are steadily increasing.

# 4. CHAPTER 4 – RESULTS AND DISCUSSION

## 4.1. Analysis

The analysis of all interview data resulted in a variety of approaches for implementing Digital Twin in the design, operation, and construction phases of construction projects. The next step in the thematic analysis was to review the data and applications to detect any patterns or themes that present an interpretation of how Digital Twins is perceived to be used (i.e., what Digital Twin can do and how it can used in design, operation, and construction phases of a construction project.

To elaborate on opportunities in the construction industry face and their perception on how Digital Twin can assist in addressing these maximizing these opportunities. The feedback collected from the literature review, survey and interviewees was then broken down and analysed based on each of the research questions.

## 4.2. Discussion

### 4.2.1. RQ1:

**How can Digital Twin Technology be used in the operation, design, and construction phases of a construction project?**

**LITERATURE REVIEW**

The literature review has served as the foundation for the research, providing valuable insights into the current state of knowledge surrounding the practical applications of Digital Twin technology's, benefits, and challenges in the context of operation, design, and construction phases of commercial construction projects. By examining a diverse range of scholarly works, research articles, reports, and industry publications, the study has gained a comprehensive understanding of how Digital Twin technology is harnessed in the operation, design, and construction phases of construction projects to drive sustainability objectives.

The literature review identified various key aspects, including the implementation of Digital Twins in operation, design and planning processes, their role in optimizing resource utilization, enhancing energy efficiency, minimizing waste generation, and their impact on overall project performance and lifecycle management. Additionally, the literature review has identified successful case studies and best practices where Digital Twin technology has been effectively applied to achieve community engagement, and sustainability goals in construction projects.

The research delves into various technologies and software used in operation, design and construction phases building design and operations. These include BIM, Revit, EnergyPlus, Grasshopper, IESVE, eQuest, and computational fluid dynamics software like AutoDesk CFD, AutoDesk Revit Insight Solar analysis software, and Ansys Fluent. The study also emphasizes the importance of IoT sensing in the built environment.

It also outlines how Digital Twin technology can be used in the operation, design and construction phases, various examples such as schematic design to detailed design and construction detailing. These technologies applications, and their advancements within the industry and proving and demonstrating to be highly valuable. The integration of IoT sensing in the built environment offers real-time data on building performance, which proves crucial for optimizing building services operations.

Particularly, IoT devices play a significant role in building services operations by providing constant data on building performance. This data empowers building managers to enhance building services efficiency. By closely monitoring energy consumption patterns, building managers can utilize this data to make informed adjustments to HVAC and lighting systems, effectively reducing overall energy usage. In essence, the research showcases how these technologies, including IoT sensing, contribute to efficient building design and operation by offering valuable insights and enabling data-driven decision-making.

The literature review has identified how Digital Twin Technology can be used in the operation design, and construction phases of a construction project and has served as the foundation for the paper providing valuable insights into the current state of knowledge surrounding the practical applications of Digital Twin technology.

#### 4.2.2. RQ2:

**What are the opportunities of Digital Twin Technology for in the operation, design, and construction phases of a sustainable construction project.**

The survey results indicate a unanimous and positive response from all 20 participants, including architects, engineers, GBCA representatives, project managers, and students, regarding their awareness and views on Digital Twin technology in sustainable construction. The participants were asked about their familiarity with Digital Twin technology and its potential opportunities and contributions to sustainable development, including its role in minimizing waste generation.

The following themes were identified from the results of the survey:

- Awareness of Digital Twin technologies
- Design opportunities
- Construction Opportunities
- Operation Opportunities
- Contribution to sustainable development
- Benefits for Sustainable development
- Minimize waste generation.

Table 6 – Summary of challenges to the implementation of Digital Twin Technology in sustainable construction projects

| Category | ID | Challenge |
|---|---|---|
| **Awareness of Digital Twin technology** | | 100% of participants |
| | | |
| **Design Opportunities** | | Create a virtual representation of the project |
| | | Enabling Real-time simulations and analyses to optimize design decisions |
| | | Streamline processes |
| | | Enhance Collaboration among team members |
| | | |
| **Construction Opportunities** | | Real time insights into construction progress |
| | | Material Usage |
| | | Resource management |
| | | |
| **Operational Opportunities** | | Continuously assess building performance |
| | | Monitor energy consumption |
| | | Occupant Comfort |
| | | Optimizing operations and maintenance strategies |
| | | |
| **Contribution to Sustainable Development** | | Contribute to sustainable development |
| | | Support data driven decision making |
| | | Optimize resource utilization |
| | | Enhance building performance |
| | | Energy efficiency |
| | | Environmental Conservation |
| | | Social Equity |
| | | |
| **Benefits for Sustainable Development** | | Enhanced project-efficiency |
| | | Reduced environmental impact |
| | | Improved occupant comfort |
| | | Increased building resilience |
| | | Long term resource management |

| | |
|---|---|
| **Minimize waste generation** | Minimize Material Waste |
| | Reduces Overall environmental footprint of construction activities |
| | |

The following section provides a discussion on the themes identified during the thematic analysis.

All participants, regardless of their professional background, indicated that they have heard of Digital Twin technology. This high level of awareness suggests that the concept of Digital Twin has gained significant recognition and interest across the architectural, engineering, project management, and student communities.

Every participant acknowledged that Digital Twin technology presents opportunities in the design stages of construction projects. The adoption of Digital Twin during design allows stakeholders to create a virtual representation of the project, enabling real-time simulations and analyses to optimize design decisions, streamline processes, and enhance collaboration among team members.

Similarly, all participants recognized the potential opportunities that Digital Twin technology offers during the construction phases of sustainable construction projects. Digital Twin's application in construction provides stakeholders with real-time insights into construction progress, material usage, and resource management. This ensures more efficient and data-driven decision-making, leading to reduced construction time and cost.

The survey responses indicated that Digital Twin technology also provides opportunities during the operational phases of sustainable construction projects. By utilizing real-time data from sensors and monitoring systems, stakeholders can continuously assess building performance, energy consumption, and occupant comfort, thereby optimizing operations and maintenance strategies.

All participants agreed that Digital Twin technology has the potential to contribute significantly to sustainable development. Its ability to support data-driven decision-making, optimize resource utilization, and enhance building performance aligns well with sustainability goals, including energy efficiency, environmental conservation, and social equity.

All participants recognized various benefits of using Digital Twin technology for sustainable development. These include enhanced project efficiency, reduced environmental impact, improved occupant comfort, increased building resilience, and better long-term resource management.

The survey responses revealed that Digital Twin technology is seen as an effective tool to minimize waste generation in construction projects. By enabling precise planning and real-time monitoring, Digital Twin helps minimize material waste and reduces the overall environmental footprint of construction activities.

**Conclusion**

The unanimous agreement among the participants, including architects, engineers, GBCA representatives, project managers, and students, regarding the awareness, opportunities, and contributions of Digital Twin technology to sustainable construction, underscores its potential transformative impact on the construction industry. The findings of this survey emphasize the significance of Digital Twin in driving sustainability initiatives, waste minimization efforts, and optimizing the entire lifecycle of construction projects. The collective positive response from diverse stakeholders reaffirms the importance of incorporating Digital Twin technology as a vital tool in advancing sustainable development practices within the construction sector.

Overall, this survey indicates that Digital Twin technology is increasingly recognized and embraced as an asset in achieving sustainable construction goals, creating a foundation for further research and implementation in the field of construction and beyond.

In the context of this dissertation, interviewees were not explicitly requested to rank the opportunities they encountered. Consequently, the findings presented in this section serve an exploratory purpose, offering a comprehensive overview of the primary concerns and issues expressed by practitioners.

#### 4.2.3. RQ3:

**What are the perceived challenges of the implementation of Digital Twins for in the design and construction stages of a sustainable construction project?**

Participants acknowledged certain technological limitations associated with Digital Twin implementation, such inadequate file and software integration, and limited expertise and training.

The survey results provide valuable insights into the challenges and limitations associated with the adoption of Digital Twin technology in sustainable development across diverse stakeholders, including architects, engineers, GBCA representatives, project managers, and students. The participants were asked about the challenges they foresee in sustainable development, challenges specific to Digital Twin technology, and implementation challenges during design, construction, and operation stages. Additionally, they were asked about potential unintended consequences and technological limitations. The authors collected several themes from the survey and grouped them into the following categories including:

**Table 7 – Summary of challenges to the implementation of Digital Twin Technology in sustainable construction projects**

| Category | ID | Challenge |
|---|---|---|
| **Challenges of Digital Twin technology** | | Limited understanding of the technology |
| | | Limited Industry-wide data standards |
| | | Inadequate data for parameters |
| | | Limited Scalability for large projects |
| | | Insufficient data integration |
| | | |
| **Challenges in implementation during design, construction, and operation phases** | | |
| **Design** | | Integrating with design processes & existing workflows |
| | | Ensuring data accuracy |
| | | Dealing with data privacy and security concerns |
| | | Increased Cyber Risks |

| | |
|---|---|
| | Reduced Human involvement |
| | Managing real-time data flow |
| **Construction** | Data security |
| | Interoperability with legacy systems |
| **Operation** | Building expertise in managing Digital Twin data |
| | Addressing data ownership and sharing issues. |

| **Potential Unintended Consequences** | |
|---|---|
| | Dependence on technology |
| | Privacy concerns |
| | Ethical concerns |
| | Increased cyber risks |
| | Reduced human involvement |
| | |
| **Technological limitations** | Limited Computational Resources |
| | Inadequate data integration |
| | Limited expertise and training |
| | |

The following is a discussion of the survey responses.

The survey respondents pointed out several challenges specific to Digital Twin technology. These challenges include limited awareness and understanding of the technology, limited industry-wide data standards, inadequate data for parameters, limited scalability for large projects, and insufficient data integration. These challenges underscore the importance of educational and collaborative efforts to enhance the adoption and implementation of Digital Twin technology.

Participants recognized implementation challenges at different stages of a construction project. Challenges in design implementation included integrating with design processes and existing workflows, ensuring data accuracy, and dealing with data privacy and security concerns. Construction implementation challenges involved managing real-time data flow, data security, and interoperability with legacy systems. Operation implementation challenges centered on building expertise in managing digital twin data and addressing data ownership and sharing issues.

Survey participants also highlighted potential unintended consequences arising from the use of Digital Twin technology in sustainable development. These consequences included an increased dependence on technology, privacy concerns, ethical concerns, increased cyber risks, and reduced human involvement. This suggests the need for cautious and ethical application of Digital Twin technology to mitigate potential negative impacts.

Participants acknowledged certain technological limitations associated with Digital Twin implementation, such as inadequate data integration, and limited expertise and training. Addressing these limitations may require investment in technological infrastructure and skill development to fully leverage the potential of Digital Twin technology.

Some participants mentioned organizations that have already implemented Digital Twin technology in their sustainable construction projects. Organizations such as A, N, and O were cited as having adopted the technology. These organizations can serve as valuable case studies for others looking to implement Digital Twin technology in their projects.
The authors collected several themes from the survey and grouped them into the following categories.

During the thematic analysis the following categories were identified:

- Data Integration
- Data Understanding and interoperability
- Privacy Concerns
- Training and Education

#### 4.2.4. RQ4:

The interviews with various stakeholders in the construction industry revealed valuable insights into the challenges faced by the sector and the potential of Digital Twin technology to address these challenges. One of the significant issues identified was project delays, which can result from unforeseen issues, coordination problems, or changes in design. However, interviewees highlighted that Digital Twins offer a promising solution by leveraging real-time data and simulations to detect potential bottlenecks and clashes early in the project. This proactive approach allows project teams to address issues promptly and reduce the likelihood of delays.

Another key challenge discussed was managing complex coordination among diverse stakeholders involved in construction projects. Interviewees emphasized that Digital Twins provide a collaborative platform where architects, engineers, contractors, and suppliers can access and contribute to the virtual model. This centralized approach streamlines communication, fosters collaboration, and ensures everyone is well-informed, minimizing misunderstandings and conflicts.

Through the interview process, several recurring themes emerged, referred to as Digital Twins capabilities.
These capabilities include:

- Real-time data
- Analytics, simulations,
- Early issue detection,
- Centralized collaboration,

- Education & experience,
- Implementation during ECI phases.

These themes collectively showcase the potential of Digital Twins in addressing industry challenges and improving construction processes.

In conclusion, the interviews revealed that Digital Twin technology has the potential to revolutionize the construction industry by enhancing project efficiency, mitigating risks, and promoting sustainable development. By leveraging the capabilities offered by Digital Twins, stakeholders in the construction sector can achieve better project outcomes, optimize resource usage, and foster a collaborative and sustainable approach to construction projects. Embracing Digital Twin technology opens new possibilities for a more efficient, integrated, and environmentally conscious construction industry.

#### 4.2.5. Case Study Approach

The construction industry plays a pivotal role in shaping sustainable development practices. In recent years, the integration of Building Information Modelling (BIM) and Digital Twin Technology has emerged as a promising approach to enhance sustainability in the built environment. This section of the report investigates two real-life case studies that exemplify the potential impact of these technologies on reducing the carbon footprint of buildings.

The case study is a part of the ongoing research titled NTU EcoCampus in Singapore and the Project SCENe: Trent Basin. These will be discussed in the sections below.

#### 4.2.6. Case Study 1: NTU Eco Campus

The case study revolves around Nanyang Technological University's (NTU) Eco Campus project, which aimed to leverage cutting-edge technology, including Digital Twin and Building Information Modelling (BIM), to enhance energy efficiency and reduce carbon emissions in a sprawling 200-hectare campus.

The project was conducted in two phases. Phase 1 focused on the development of a master planning model for the Eco Campus, including energy signatures for each building. Phase 2 involved the simulation and analysis of various testbed technologies within 21 specific campus buildings.

The master planning model achieved impressive accuracy levels, with a 91% precision for overall energy consumption and a remarkable 97% accuracy for chiller energy consumption. This indicates the reliability of Digital Twin and BIM technology in accurately modelling and predicting energy usage.

Cloud-Based Campus Information Model (iCIM): An online cloud-based Campus Information Model was established to facilitate communication and engagement with campus staff and students. This model allowed for seamless updates and interaction, enhancing collaboration and communication among stakeholders.

The implementation of various technologies, including enhancements to building envelopes, lighting sensors, chiller optimization, and smart plugs, resulted in a substantial 10% reduction in campus-wide energy consumption. This reduction translated into significant cost savings of $3.9 million and a reduction in carbon emissions by 8.2 kt.

The collaboration between IES (Integrated Environmental Solutions) and NTU demonstrated a mutually beneficial partnership. IES provided cutting-edge technology and expertise, while NTU offered a real-world implementation context and valuable feedback.

Detailed analysis of operational buildings on the campus revealed various issues and anomalies, including fluctuations in $CO_2$ levels, unstable temperatures, malfunctioning meters, and discrepancies in temperature settings. These findings highlighted areas for potential improvement and optimization.

The simulation and calibrated models projected significant energy savings of approximately 31% and cost reductions of $4.7 million when deploying various technologies within the buildings.

The NTU Eco Campus case study provides valuable insights into the transformative impact of Digital Twin and BIM technology in the realm of sustainable construction. Several key findings emerge from this study:

The high precision and accuracy achieved by the Digital Twin and BIM models in predicting energy consumption and performance metrics demonstrate the robustness of these technologies. This reliability is crucial for decision-making in sustainable construction projects. The establishment of a cloud-based Campus Information Model (iCIM) exemplifies the potential of technology in facilitating communication and engagement among stakeholders. Such platforms enable real-time updates and enhance collaboration, reducing misunderstandings.

The substantial 10% reduction in energy consumption across the entire campus underscores the tangible benefits of implementing energy-efficient technologies. These reductions not only contribute to cost savings but also align with sustainability goals by reducing carbon emissions. The successful collaboration between IES and NTU highlights the importance of partnerships between technology providers and institutions. This collaboration led to the development and application of innovative solutions.

In-depth analysis of operational buildings identified areas for improvement, ranging from temperature control issues to malfunctioning equipment. Addressing these concerns can lead to further energy savings and enhanced building performance.

The projected energy savings of approximately 31% and cost reductions of $4.7 million demonstrate the potential return on investment when implementing energy-efficient technologies. These findings can guide decision-makers in prioritizing investments.

In conclusion, the NTU Eco Campus case study illustrates the concrete benefits of integrating Digital Twin and BIM technology in sustainable construction. The study emphasizes the potential for energy savings, cost reduction, and carbon emission reduction when leveraging these technologies. Additionally, it highlights the importance of collaboration, accuracy, and real-time communication in driving sustainable construction practices. These findings have broader implications for the construction industry's adoption of technology for sustainable development.

#### 4.2.7. Case Study 2: Project SCENe: Trent Basin

The case study of Project SCENe: Trent Basin highlights the significant impact of integrating BIM and Digital Twin Technology with sustainable practices in the construction and operation phases. Several key findings emerge from this study.

The use of BIM during the design and construction phases fosters enhanced collaboration among stakeholders. It allows for comprehensive visualization and optimization of building components, which, in turn, promotes sustainable design features. This finding underscores the importance of BIM in promoting sustainability in construction projects.

The deployment of Digital Twin Technology during the operation phase facilitates real-time performance monitoring of renewable energy systems and energy consumption patterns. This data-driven approach empowers residents to make informed decisions regarding energy usage and carbon footprint reduction. It highlights the role of Digital Twin Technology in promoting sustainability and involving communities in energy optimization.

IES has developed an interactive platform that provides real-time visualization of energy data, making use of Digital Twin technology. This platform not only offers insights into renewable energy generation, energy storage, and consumption but also provides general information about homes in the community. It serves as a visual tool for public engagement in the community's energy scheme, emphasizing the importance of making energy information accessible and engaging for residents.

The study demonstrates how technology can empower communities to adopt sustainable practices. By comparing household-level energy data with the community average and observing energy production, residents can actively participate in optimizing the community energy scheme. This community involvement contributes to greater awareness of energy usage and its impact on well-being and sustainability.

Project SCENe's vision of integrating renewables into future housing developments to reduce energy expenses and carbon footprints without burdening homeowners or developers sets a promising precedent. It highlights the potential for similar sustainable initiatives in housing projects worldwide.

The platform's presentation of household energy consumption data along with monetary and carbon cost comparisons enables residents to translate energy behaviors into meaningful impacts and benchmark their data against the broader community. This transparency fosters a sense of responsibility and encourages individuals to take steps toward reducing their carbon footprint.

Overall, the case study of Project SCENe: Trent Basin exemplifies how BIM and Digital Twin Technology can play pivotal roles in promoting sustainability, community engagement, and informed decision-making in construction and energy projects. These findings reinforce the growing recognition among building professionals of the social, environmental, and economic benefits associated with these technologies and their potential for widespread adoption in future projects.

#### 4.2.8. Discussion

The two case studies present compelling evidence of how BIM and Digital Twin Technology are revolutionizing the construction industry's approach to sustainability. These technologies enable enhanced design visualization and iteration, simulation and performance prediction, clash detection and coordination, construction planning and sequencing, remote monitoring and quality assurance, real-time monitoring, predictive maintenance and lifecycle monitoring, data-driven decision-making, resulting in reduced carbon emissions and increased energy efficiency. The successful integration of BIM and Digital Twin Technology in the NTU EcoCampus and Project SCENe: Trent Basin showcases their potential as game-changers within the AEC industry.

#### 4.2.9. Conclusion

The evidence from the NTU EcoCampus and Project SCENe: Trent Basin demonstrates that Building Information Modelling and Digital Twin Technology are essential components in reducing the carbon footprint of the built environment. The positive outcomes of these technologies in enhancing sustainability, energy efficiency, and community engagement highlight their increasing adoption within the AEC industry. As building professionals recognize the social, environmental, and economic benefits of these technologies, their widespread integration is likely to contribute significantly to sustainable development in the future.

The collaborative endeavor between by the NTU exemplifies the capacity of innovation in shaping sustainable construction projects. The simulations and precision-calibrated models not only equips NTU with an instrument for identifying energy usage but also assists with reducing energy use and underscores the remarkable promise inherent in digital twins to create awareness and foster a sustainable future.

Digital Twin technology used in these projects has provided a tool for empowering community and stakeholder engagement and provides the dynamics of energy reduction technologies via sophisticated visualizations and insightful analysis. The ensuing progression of simulations and aligned models which supplements comprehension by providing data-backed perspectives to facilitate informed decision making. This blend not only facilitates the judgement of optimal energy solutions but also streamlines their integration across the AEC industry.

As digital twin technology evolves, the two case studies discussed provide insight into the potential of Digital Twin technology in construction projects. The achievement realized by IES and NTU stands as an inspiring archetype for global institutions prepared to leverage Digital Twins to actualize more streamlined, ecologically sound, and resilient infrastructures.

Further evidence from real-life examples, such as the NTU EcoCampus in Singapore and Project SCENe: Trent Basin, showcases the tangible impact of Building Information Modelling and Digital Twin Technology in reducing the carbon footprint of the built environment. As more building professionals recognize the social, environmental, and economic benefits of integrating these technologies with performance analysis tools, the adoption and positive outcomes are steadily increasing.

## 4.3. Implications and Recommendations

### 4.3.1. Implications

The dissertation highlights the increasing adoption and recognition of Digital Twin Technology in the AEC industry. The empirical evidence from case studies like the NTU EcoCampus and Project SCENe: Trent Basin showcases the tangible impact of integrating Digital Twins with performance analysis tools, leading to reduced carbon footprint and improved sustainability practices, and increased community and stakeholder engagement.

The use of Digital Twin Technology enables real-time data analytics and simulations, empowering stakeholders to make informed and accurate decisions. It also facilitates collaboration among project teams, architects, engineers, contractors, and residents, leading to more efficient coordination and sustainable outcomes.

The research paper identifies various challenges in the construction industry, such as project delays, complex coordination, sustainability goals, privacy, and data security risks. Digital Twin Technology offers solutions to address these challenges through early issue detection, centralized collaboration, predictive analysis, and data-driven decision-making.

### 4.3.2. Recommendations

To encourage wider adoption of Digital Twin Technology, the construction industry should prioritize awareness campaigns and training programs to equip professionals with the necessary skills to leverage the technology effectively.

Industry bodies and organizations should work towards standardizing data formats and ensuring interoperability among different Digital Twin platforms, enabling seamless data exchange and integration.

Policymakers should formulate supportive policies that incentivize and promote the use of Digital Twin Technology for design, operation, and construction in construction projects. This may include tax incentives, grants, or certification programs. As Digital Twin Technology involves sensitive data, robust privacy and data security measures should be implemented to protect stakeholders' information and address any potential concerns.

Further research and monitoring are essential to assess the long-term impacts and scalability of Digital Twin Technology in diverse construction projects. Continuous evaluation will provide valuable insights for improvement and optimization.

The paper highlights the positive outcomes of integrating Building Information Modelling (BIM) and Digital Twin Technology in sustainable construction practices. Building professionals and stakeholders should prioritize the adoption of these technologies to maximize their potential benefits for the environment, society, and the construction industry.

In conclusion, the dissertations implications and recommendations underscore the potential of Digital Twin Technology in sustainable construction practices. By prioritizing technology awareness, collaboration, data security, and policy support, stakeholders can leverage Digital Twins to achieve improved environmental sustainability, energy efficiency, and project outcomes in the construction industry. Embracing these technologies is crucial for addressing challenges, optimizing resource usage, and fostering environmentally conscious practices in the built environment.

# 5. CHAPTER 5 – CONCLUSIONS

### 5.1. Introduction

Digital twin technology has rapidly gained popularity across various industrial sectors, providing an innovative way to simulate, visualize, and optimize physical systems in a virtual environment. With increasing concerns about sustainability, the potential of digital twin technology to enable sustainable development has gained significant attention in recent years. The aim of this dissertation is to investigate the opportunities and challenges of leveraging digital twin technology for sustainable development.

The research explored the existing literature on digital twin technology and sustainability, identifying the key concepts and themes in the field. The study then conducts a systematic review of the existing literature of Digital Twin applications in the AEC industry. Through case studies and qualitative interviews with experts and practitioners, the research has identified the benefits and challenges, and practical applications of Digital Twin technology during the design, construction, and operation phases of a construction project.

### 5.2. Conclusions

The findings of the paper research found Digital Twin technology enhances sustainability practices, reduces project delays, and costs, and reduces life cycle costs, driving a pathway to a sustainable future.

One of the most significant findings of the research paper is the potential of these software tools is limitless, dependent only on the user's understanding and expertise.

The findings further emphasize the usefulness of other technologies, such as sensors and IoT, in supporting these applications. Most of the applications mentioned are applied across the entire project, emphasizing the premise that Digital Twins must be included in the early stages of the construction project.

In conclusion, the significance of research findings is multifaceted and depends on their contribution to knowledge, applicability, worth, and potential for real-world impact. Researchers and the academic community assess the significance of findings based on these criteria to determine their value and importance within their respective fields of study.

## 5.3. What is the significance of your findings.

Digital Twin in the AEC industry stands as a crucial catalyst for enhancing efficiency, productivity, information management, and quality within various processes. Undoubtedly, the significance of digital modelling and optimization technologies for sustainable development cannot be overstated. This dissertation has demonstrated the capacity Digital Twin technology to enhance the efficiency, sustainability, and performance of building systems and services, offering a more effective and efficient approach to address the industry's challenges.

### 5.3.1. RQ1:

In response to RQ1, the study defined a Digital Twin as a real-time digital representation of a physical process. The literature review highlighted the use of various software for optimization in construction design stages. Additionally, it emphasized the role of IoT technology in the operational phase, especially in reducing energy consumption through data-driven decision-making. Building Information Modeling (BIM) applications were identified in project design, including schematic, detailed design, and construction details. These technologies help reduce carbon emissions, minimize waste, and incorporate renewable energy sources. BIM's applications in construction phases include clash detection in complex geometries. The study stressed the significance of cost reduction in the operational phases and identified various barriers to implementation and challenges, such as high initial costs, lack of awareness, resistance to change, and interoperability issues.

During the literature review it was found there is a variety of software which can be used for optimization during the design stages of a construction project. We also found that the operation stages rely on IOT technology. Energy consumption can be substantially reduced using IoT technology. IoT Sensors give building managers the ability to make data-driven decisions, leveraging real-time energy usage information to implement targeted energy-saving measures.

BIM applications and benefits in project design phases include schematic design, detailed design and construction detailed. There is a variety of Bim technologies and software which can be used to reduce carbon emissions, minimizing waste, and using renewable energy sources.  BIM applications during the building operation phases include IoT devices, which provide real time data on building performance. BIM applications during the construction phases include clash detection within complex geometries.

The operational phases of a building represent the highest costs within the context of the building life cycle therefore reducing these costs at the design phase is essential to prolonged reduction in overall costs.  The following barriers to implementation were identified in the literature review.

- High initial cost
- Lack of awareness about BIM benefits
- Inadequate training on the use of BIM
- Resistance to change current construction industry culture
- Insufficient governmental support
- Legal issues
- Lack of interest from clients
- Lack of support from top management
- Doubts about ROI
- Lack of BIM experts
- Data ownership issues
- Longer process (takes longer time to develop the model)
- Lack of demand from the contractors
- Sub-contractors are not interested in using BIM

- Absence of contractual requirement for BIM implementation
- Complexity of the BIM model
- Interoperability between software programs
- Lack of standardized tools and protocols

### 5.3.2. RQ2:

**Summarize the key findings and contributions of the research.**

The unanimous agreement among the participants, including architects, engineers, GBCA representatives, project managers, and students, regarding the awareness, opportunities, and contributions of Digital Twin technology to sustainable construction, underscores its potential transformative impact on the construction industry. The findings of this survey emphasize the significance of Digital Twin in driving sustainability initiatives, waste minimization efforts, and optimizing the entire lifecycle of construction projects. The collective positive response from diverse stakeholders reaffirms the importance of incorporating Digital Twin technology as a vital tool in advancing sustainable development practices within the construction sector.

During the thematic analysis, the following Digital Twin opportunities were identified. The authors collected several themes from the survey and grouped them into the following categories including: -

- Awareness of Digital Twin Technology
- Design Opportunities
- Construction opportunities
- Operation opportunities
- Benefits for Sustainable development
- Minimize waste generation.

### 5.3.3. RQ3:

Despite the potential benefits, the research acknowledged challenges in adopting Digital Twin technologies in design, construction, and operations phases. It emphasized the importance of continuous education, collaboration, and technological advancements to overcome these challenges and maximize the technology's potential.

Overall, the survey results underscore the importance of continuous education, collaboration, and technological advancements to maximize the potential of Digital Twin technology in addressing the complex challenges of sustainable development in the construction sector. The findings presented in this survey can inform further research, policy development, and industry practices to drive sustainable and innovative solutions in the built environment.

Resolving these challenges will be pivotal in maximizing the benefits offered by Digital Twin technology, Building Information Modelling, and optimization technologies in the AEC industry.

During the thematic analysis, the following Digital Twin challenges were identified. The authors collected several themes from the survey and grouped them into the following categories including: -

- Standards & Guidelines
- Technical Challenges
- Organization and Cultural Challenges
- Lack of Standards
- Training Education skills & knowledge
- Cost
- Privacy and Security
- Interoperability - data exchange and common data environments to enable collaboration and coordination among different stakeholders.

## 5.4. RQ4/ INTERVIEW

The interviews with construction professionals provided valuable insights. Opportunities identified included improving collaboration and communication, implementing common data environments, utilizing IoT sensors for insights, and enabling clash detection in complex projects. Challenges revolved around data interoperability, privacy, and security. Practical approaches included addressing data interoperability issues, centralizing collaboration, enhancing education and experience, mitigating risks, and increasing project efficiency.

The interview process served as a vital means to acquire rich and diverse perspectives on digital twin technology from experienced construction professionals. The findings derived from these interviews offer valuable implications and practical applications for industry stakeholders, policymakers, and researchers, fostering a deeper understanding of how Digital Twins can drive promote improved construction practices. The findings of the interview process are listed below.

### 5.4.1. Opportunities

The findings derived from the interviews conducted as part of this dissertation reveal insights into the potential transformative impact of digital twin technology within the construction industry, particularly in the domains of collaboration and communication.

The implementation of digital twin technology emerges as a promising avenue for enhancing collaboration and communication among stakeholders in construction projects. A key prerequisite for this transformation is the establishment of a common data environment that enables remote access to project information for all involved parties. This infrastructure facilitates streamlined communication and significantly reduces the occurrence of miscommunications, ultimately fostering a more efficient and harmonious project environment.

Furthermore, the interviews highlighted the valuable role that IoT sensors can play in gaining insights into project performance, resource utilization, and progress tracking. These sensors emerge as powerful tools for project management and decision-making, enhancing transparency and facilitating informed choices.

Another notable advantage of Digital Twin technology is its ability to enable clash detection, particularly when confronted with design changes and complex project geometries featuring intricate architectural details. This capability ensures that potential conflicts are identified and resolved proactively, thereby preventing costly delays and rework.

#### 5.4.2. Challenges to implementation

Despite the evident potential of this technology, interviewees also highlighted certain challenges. A recurrent theme was the difficulty in locating the necessary resources and skilled personnel to effectively implement Digital Twin software. This underscores the pressing need for comprehensive training initiatives within the industry, aimed at equipping professionals with the requisite expertise, particularly in the utilization of 3D modeling software.

Additionally, the interviews emphasized the importance of common data environments, which are crucial for facilitating data sharing and collaboration among stakeholders. The adoption of cloud platforms has emerged as a viable solution to overcome challenges related to data transfer and large file sizes, further enhancing the accessibility and usability of Digital Twin technology.

Lastly, Digital Twin technology has the potential to revolutionize building design by enabling "smart" designs that can dynamically adapt to changing environmental conditions and occupant needs. This adaptive approach not only enhances comfort and efficiency but also aligns with sustainable and eco-friendly building practices.

Interviewees expressed a clear awareness of the capabilities and advantages that these software tools bring to the construction domain. However, a recurrent theme emerges wherein the practical utilization of these technologies is hindered by the scarcity of essential resources and the availability of skilled personnel within the industry.

One requirement that emerges from the interview findings is the need for enhanced training initiatives. The construction sector necessitates a more comprehensive and accessible training environment to develop a skilled workforce proficient in the use of 3D modeling software and Digital Twin technology. This requirement excels just awareness and highlights the requirement for a mutual effort to bridge the skills gap within the industry.

The interview findings provide a critical statement which the construction industry continuously finds itself — an acknowledgment of the potential of advanced software solutions compared with the practical challenges of resource scarcity and skill deficiency. Addressing these challenges, particularly through training programs and workforce development, represents a pivotal step forward in harnessing the full capabilities of these technologies, ultimately shaping a more efficient and sustainable future for the construction sector.

In summary, the insights earned from these interviews underscore the advantages of Digital Twin technology in construction, particularly in terms of collaboration, communication, and project management. While challenges exist, including resource allocation and training, the potential for transformative change within the industry is palpable. These findings serve as a valuable foundation for further research, policy development, and industry practices aimed at harnessing the full potential of Digital Twin technology in construction projects.

#### 5.4.3. Practical approaches to implementation

The key findings from the provided information on practical approaches to implementing digital twin technology are as follows:

- Utilization in Complex Structural Design Analysis
- Addressing Lack of Accurate As-Built Information
- Integration with BIM
- Point Cloud Data for Existing Services
- Operational Importance of As-Built Records

- Enhanced Collaboration and Quality Assurance
  Proactive Issue Identification

Engineers have successfully employed Digital Twins to analyze complex structural designs. They simulate various load scenarios and material choices to identify efficient and sustainable design solutions. Digital Twins also enable the creation of responsive and adaptable building designs to meet changing requirements throughout a project's lifecycle.

Interviewees discussed the challenge of developing a Digital Twin Model when accurate as-built information is absent during the design stages of construction. They highlighted the use of 3D scanning technology during the design and construction phases to capture as-built information and integrate it into Building Information Modeling (BIM) software.

BIM models serve as the foundation for creating Digital Twins. When a BIM model is not available, 3D scanning technology is used to identify as-built conditions, which can then be integrated into the BIM model. This approach has become more feasible due to advancements and affordability in 3D laser scanning technology.

Interviewees demonstrated the use of point cloud data generated through 3D scanning tools to confirm as-built conditions and existing services within a building. This information is essential for creating accurate architectural plans and identifying potential conflicts between existing services and proposed changes.

As-built drawings and models are crucial records used by facility managers to oversee facility spaces, maintenance, and energy systems. The management and analysis of a building's efficiency start with an as-built information model.

Digital Twin technology, including virtual reality goggles and live BIM models, can be used to enhance collaboration and ensure quality assurance on construction sites. This technology creates a live digital environment that helps identify issues, resolve clashes, and anticipate safety hazards and logistical challenges.

By simulating construction processes virtually using Digital Twins, construction professionals can anticipate potential clashes, logistical challenges, and safety hazards.

This proactive approach enables them to address issues before they occur on-site, leading to significant time and cost savings.

Overall, Digital Twins are proving to be valuable tools in the construction industry, enabling efficient design analysis, accurate as-built data capture, improved collaboration, and proactive issue resolution during construction projects.

### 5.5. CASE STUDY

The empirical evidence drawn from real-world case studies, specifically the NTU EcoCampus in Singapore and Project SCENe: Trent Basin, provides compelling substantiation of the substantial impact that the integration of Building Information Modeling (BIM) and Digital Twin Technology can have on reducing the carbon footprint within the built environment. As these case studies vividly illustrate, more professionals within the construction industry are increasingly recognizing the multifaceted advantages, encompassing social, environmental, and economic dimensions, that arise from amalgamating these advanced technologies with performance analysis tools.

Furthermore, these case studies underscore the practical applicability of Digital Twin technology, aligning with the findings established during the literature review phase. Notably, they serve as tangible examples of its efficacy, showcasing its potential for real-time performance assessment, community engagement, and predictive accuracy. The utility of Digital Twin technology as a visual tool for stimulating and fostering community involvement becomes evident, as it facilitates a deeper understanding of energy behaviors and their tangible impacts.

One of the remarkable revelations from these case studies is the high degree of accuracy achieved in predicting outcomes during the design stage, ranging from an impressive 91% to 97%. This precision empowers residents and stakeholders to effectively translate energy-related behaviors into meaningful, real-world consequences. Consequently, it not only bolsters economic, environmental, and social awareness but also enhances comprehension regarding energy utilization, storage, and conservation.

Moreover, these case studies clarify the capacity of Digital Twin technology to translate energy consumption data into monetary and carbon cost comparisons, serving as the foundation for simulating and analyzing various testbed technologies. This analytical prowess has the potential to revolutionize decision-making processes within the construction industry by providing invaluable insights into the cost-effectiveness and environmental impact of different strategies and technologies.

The visible outcomes achieved in terms of energy consumption reduction, up to 10%, and carbon emissions reduction, up to 8.2kt, underscore the transformative potential of Digital Twin technology when applied judiciously and comprehensively. As the adoption and implementation of these technologies continue to evolve, it is imperative for practitioners and stakeholders to recognize the substantial benefits they offer in shaping a more sustainable and efficient built environment.

The case studies also reinforce the of the findings of the literature review – that there's a large range of software which can be used for optimization during the design stages. In addition to this it reinforced the fact that IoT devices are heavily relied upon during the operation phases to provide outputs that facilitate and encourage decision making.

In summary, the evidence from these case studies not only validates the findings of the literature review but also accentuates the practicality and significance of Digital Twin technology within the construction industry. It serves as a testament to the transformative potential of these technologies in mitigating environmental impact, enhancing community engagement, and optimizing resource utilization. As the industry evolves, these insights can guide future research, policy development, and industry practices, steering in a new era of sustainable and innovative construction practices.

### 5.6. Knowledge Gap:

The research acknowledged a knowledge gap related to artificial intelligence (AI) and its potential applications within the AEC industry. Further exploration of AI's role in construction could be a valuable avenue for future research.

Overall, the study contributes to a deeper understanding of Digital Twin technology's potential and challenges in the construction industry, highlighting opportunities for sustainable development and waste minimization.

### 5.7. RECOMMENDATIONS

Based on the dissertation, the following recommendations have been identified.

The GBCA and Engineers Australia should consider providing comprehensive training and resources to designers and engineers to facilitate the adoption of digital modelling technologies. This training should cover both the technical aspects of using digital modelling tools and best practices in utilizing them effectively in building services design.

The GBCA and Engineers Australia should take the initiative to develop standards and guidelines specific to the use of digital modelling technologies in building services design. These standards should address issues such as data formats, interoperability, and quality control to ensure consistent and efficient use of technology across the industry.

To address concerns about data security, project teams should implement stringent security measures for data storage. This includes encryption and secure storage protocols to protect sensitive information. Regular cybersecurity audits and updates should also be part of the strategy to minimize the risk of data breaches and cyber-attacks.

The issue of interoperability and data exchange between different Digital Twin models should be addressed through industry-wide standardization efforts. Collaborative organizations, including government bodies and industry associations, should work toward establishing common protocols and data formats to maximize the potential of Digital Twins across various projects and urban environments.

While the interviewees mentioned that ownership of data or intellectual property was not a significant issue in their projects, it's essential to recognize that this may vary in different contexts. For government or defence projects, standard risk mitigation strategies should be incorporated to address potential security risks associated with the use of Digital Twin technology. This includes clear data ownership agreements and security measures.

The importance of as-built information models for facility managers is well-established. Therefore, it is recommended that organizations involved in construction and project management prioritize the creation and maintenance of accurate as-built information models. These models should be easily accessible to facility managers to support efficient building administration, maintenance, and energy system management.

The collaborative approach mentioned by interviewees, where all stakeholders share data and intellectual property, should be encouraged, and promoted within the construction industry. This collaborative mindset can lead to more successful project outcomes and minimize disputes over data ownership.

By implementing these recommendations, organizations and professionals in the construction and engineering industry can enhance the adoption and utilization of digital modelling technologies, improve data security, and promote effective collaboration in the construction and facility management processes.

### 5.8. REFLECTION

Reflecting on the role of digital modelling and optimization technologies in the operation, design and construction lifecycle of a project, the author has gained a deeper understanding of their significance and potential. These technologies offer a range of benefits, including improved accuracy, reduced errors, increased efficiency, and support for sustainable practices. Through this reflection, I have identified the positive impact they can have on various project phases.

By harnessing the potential of these technologies, engineers, designers, architects and building owners can create sustainable, efficient, and resilient buildings that effectively meet the needs of occupants and stakeholders alike. This paper provides valuable insights into the power of Digital Twin technologies in the building services industry, paving the way for future advancements and innovation. The findings of this study can inform decision-makers and industry stakeholders about the potential of Digital Twins as a transformative tool for promoting sustainable practices across various sectors.

However, the author also recognizes the challenges associated with the adoption and implementation of these technologies. Technical hurdles, such as data management and interoperability, require attention. Additionally, organizational, and cultural factors, including resistance to change and limited collaboration among stakeholders, must be addressed for successful implementation.

Overall, the author has personally experienced the value of Building Information Modelling (BIM) and AutoDesk technology throughout my career, utilizing them across various project stages. The ability to visualize projects in 3D and interpret drawings accurately has proven invaluable. Engaging with software like AutoDesk's recap and Revit has expanded my capabilities and understanding of their potential applications.

This dissertation has challenged and developed the authors technical skills and emphasized the importance of lifelong learning and critical reflection. It has also reinforced the need for personal and professional accountability in managing and monitoring performance. This critical reflection highlights the role Digital Twin technology has in the design, construction, and operation life cycle.

The utilization of Digital Twin technologies, including BIM, assumes growing importance in designing and operating sustainable buildings. Overall, this paper indicates that Digital Twin technology is increasingly recognized and embraced as an asset in achieving sustainable construction goals, creating a foundation for further research and implementation in the field of construction and beyond.

### 5.9. Conclusion

In conclusion, the utilization of digital modelling and optimization technologies, including BIM, assumes growing importance in designing and operating building services systems. These technologies yield significant advantages in terms of energy efficiency, occupant comfort, indoor air quality, environmental sustainability, and operational cost reduction. By harnessing the potential of these technologies, designers and building owners can create sustainable, efficient, and resilient structures that effectively meet the needs of occupants and stakeholders alike. This paper provides valuable insights into the power of digital modelling and optimization technologies during the operation, design, and construction phases of a construction project, paving the way for future advancements and innovation.

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# 7. APPENDIX

## 7.1. Survey Email

**Subject: Invitation:** Participate in a Digital Twin Technology Survey

Dear [Recipient's Name],

I hope this message finds you well. We are excited to invite you to participate in a survey that explores Digital Twin technology and its opportunities and challenges.

**Purpose of the Survey:**

The digital twin concept has been transforming industries, enabling innovative solutions across various domains, from manufacturing and healthcare to smart cities and beyond. This survey aims to gain valuable insights into how professionals perceive and utilize digital twin technology in their respective fields. By sharing your experiences and expertise, you will contribute to a better understanding of the opportunities and challenges associated with digital twins.

**Survey Topics:**

During the survey, we will delve into various aspects of digital twin technology, including but not limited to:

- Opportunities
- Challenges

**Why Your Input Matters:**

Your participation is vital, as it will help us gather diverse perspectives and industry insights. The findings from this survey will be instrumental in shaping the future of digital twin technology, influencing research, development, and innovation in this dynamic field.

**How to Participate:**

To join the survey, please download the document attached and respond to the questions and return at your earliest convenience.

We anticipate that your valuable input will provide a comprehensive understanding of digital twin technology's current landscape and its potential evolution.

If you have any questions or require further information, please do not hesitate to contact us at [redacted] or [redacted]

Your contribution to this survey is appreciated, and we look forward to your valuable insights.

Thank you for your time and consideration. We eagerly await your participation in this exciting exploration of Digital Twin technology.

Best regards,

Zack Davis

### 7.2. Surveys

**Architect 1:**

Have you heard of digital twin technology before this survey?
Yes, I am familiar with digital twin technology. It's a virtual representation of a physical building or infrastructure.

What are the opportunities for implementation of Digital Twin technology in the design stages of a construction project?

Digital twins can offer detailed simulations and analysis of design alternatives, enabling better decision-making and design optimization.

What are the opportunities for implementation of Digital Twin technology during the construction phases of a sustainable construction project?

Digital twins can assist in real-time monitoring of construction progress and resource usage, helping achieve sustainability goals.

What are the opportunities for implementation of Digital Twin technology during the operation phases of a sustainable project?

Digital twins can facilitate ongoing performance monitoring, predictive maintenance, and energy optimization for sustainable operation.

Do you think digital twin technology can contribute to sustainable development?
Absolutely. It provides valuable data and insights to support sustainable practices and decision-making.

In your opinion, what are the potential benefits of using digital twin technology for sustainable development?

Improved building performance, reduced environmental impact, enhanced occupant comfort, and extended building lifespan.

Do you think Digital Twin technology can be used to minimize waste generation in construction projects?

Yes, digital twins can optimize construction processes, leading to reduced waste generation and increased efficiency.

Challenges of Digital Twin for Sustainability may include limited awareness and understanding of digital twin technology among stakeholders may slow down its adoption for sustainability.

Challenges in Design Implementation include gaining stakeholder buy-in and providing adequate training for using digital twin tools are important challenges during the design phase.

Challenges in Construction Implementation in ensuring real-time data flow and managing complex data workflows during construction are critical considerations.

Challenges in Operation Implementation in integrating digital twins with legacy systems for facility management and maintenance requires careful planning.

The participant mentioned potential unintended consequences include ethical concerns related to data usage and privacy as potential unintended consequences.

Yes, the participant believes that technological limitations and data interoperability issues may affect the implementation of Digital Twin technology in sustainable construction projects.

Yes, Organization B has successfully implemented digital twin technology for sustainable construction projects.

**Architect 2:**

Have you heard of digital twin technology before this survey?

Yes, I am familiar with digital twin technology and its applications in the construction industry.

What are the opportunities for implementation of Digital Twin technology in the design stages of a construction project?

Digital twins can enable collaborative design reviews, clash detection, and simulation of design concepts for better decision-making.

What are the opportunities for implementation of Digital Twin technology during the construction phases of a sustainable construction project?

Digital twins can support real-time progress monitoring, resource management, and construction site safety, contributing to sustainability.

What are the opportunities for implementation of Digital Twin technology during the operation phases of a sustainable project?

Digital twins can help in monitoring energy usage, indoor air quality, and overall building performance for sustainable operations.

Do you think digital twin technology can contribute to sustainable development?

Certainly. It offers valuable insights and data to drive sustainable construction practices.

In your opinion, what are the potential benefits of using digital twin technology for sustainable development?

Enhanced collaboration among project stakeholders, reduced environmental impact, and improved building efficiency.

Do you think Digital Twin technology can be used to minimize waste generation in construction projects?

Yes, by optimizing construction processes and materials usage, digital twins can help minimize waste generation.

The participant believes limited awareness and understanding of digital twin technology among stakeholders may hinder its widespread adoption for sustainability.

Challenges in Construction Implementation include ensuring real-time data availability and accuracy during construction pose challenges for implementing digital twins.

Challenges in Operation Implementation include building and maintaining expertise in managing digital twin data for ongoing building performance analysis is essential.

The participant mentioned potential unintended consequences and issues related to data ownership and sharing as potential unintended consequences.

The participant believes that technological limitations and data interoperability issues may affect the implementation of Digital Twin technology in sustainable construction projects.

Yes, Organization C has successfully implemented digital twin technology for sustainable construction projects.

**Architect 3:**

Have you heard of digital twin technology before this survey?

Yes, I am familiar with digital twin technology and its potential in the AEC (Architecture, Engineering, and Construction) industry.

What are the opportunities for implementation of Digital Twin technology in the design stages of a construction project?

Digital twins can aid in exploring design alternatives, conducting energy simulations, and facilitating informed decision-making.

What are the opportunities for implementation of Digital Twin technology during the construction phases of a sustainable construction project?

Digital twins can assist in monitoring construction progress, analysing site logistics, and ensuring sustainable material usage.

What are the opportunities for implementation of Digital Twin technology during the operation phases of a sustainable project?

Digital twins can support ongoing facility management, energy optimization, and predictive maintenance for sustainable operations.

Do you think digital twin technology can contribute to sustainable development?

Absolutely. It aligns well with sustainable practices and can lead to better environmental outcomes.

In your opinion, what are the potential benefits of using digital twin technology for sustainable development?

Improved project coordination, reduced carbon footprint, enhanced building performance, and better occupant satisfaction.

Do you think Digital Twin technology can be used to minimize waste generation in construction projects?

Yes, digital twins can optimize construction workflows and resource usage, contributing to waste reduction.

The participant believes there are challenge in sustainable development, social inequality is a significant challenge that needs attention in sustainable development efforts.

The participant believes some challenges of Digital Twin for Sustainability include scalability for large projects and the lack of industry-wide data standards pose challenges in using digital twin technology for sustainability.

The participant mentioned that challenges in design implementation include integrating digital twin tools with BIM platforms and ensuring seamless data flow during the design phase can be challenging.

The participant mentioned that ensuring data security and managing multiple data sources are obstacles that need to be overcome during construction.

The participants believed the lack of interoperability and compatibility with legacy systems may hinder the successful implementation of digital twins for ongoing building operations.

The participant mentioned privacy concerns related to digital twin data usage and access as potential unintended consequences.

The participant does not believe that technological limitations will hinder the implementation of Digital Twin technology in sustainable construction projects.

The participant did not mention any specific organizations using digital twin technology for sustainable construction projects.

**Architect 4:**

Have you heard of digital twin technology before this survey?

Yes, I have come across digital twin technology in the context of construction and architecture.

What are the opportunities for implementation of Digital Twin technology in the design stages of a construction project?

Digital twins can provide real-time design visualization, collaboration, and analysis, which can lead to more informed design decisions.

What are the opportunities for implementation of Digital Twin technology during the construction phases of a sustainable construction project?

Digital twins can assist in monitoring construction progress, ensuring adherence to sustainability targets, and optimizing resource usage.

What are the opportunities for implementation of Digital Twin technology during the operation phases of a sustainable project?

Digital twins can support ongoing building performance analysis, energy management, and occupant comfort for sustainable operation.

Do you think digital twin technology can contribute to sustainable development?
Certainly. It offers valuable data and insights to promote sustainable practices in the construction industry.

In your opinion, what are the potential benefits of using digital twin technology for sustainable development?

Improved project efficiency, reduced environmental impact, better building maintenance, and increased overall sustainability.

Do you think Digital Twin technology can be used to minimize waste generation in construction projects?

Yes, digital twins can optimize construction processes, leading to reduced waste generation and increased sustainability.

The lack of awareness and understanding of digital twin technology among stakeholders may hinder its adoption for sustainability initiatives.

The participant mentioned that integrating digital twin tools with existing design workflows and ensuring data accuracy are important challenges during the design phase.

The participant believed managing real-time data flow and addressing the initial setup cost are crucial considerations during the construction phase.

The participants believed challenges in implementation during operation include ensuring continuous data accuracy and maintenance are important for implementing digital twins during the operation phase.

The participant mentioned potential consequences related to an increased dependence on technology and reliance on algorithms.

Yes, the participant believes that technological limitations and data interoperability issues may affect the implementation of Digital Twin technology in sustainable construction projects.

The participant did not mention any specific organizations using digital twin technology for sustainable construction projects.

**Architect 5:**

Have you heard of digital twin technology before this survey?

Yes, I am familiar with digital twin technology. It's a virtual representation of a physical building or infrastructure.

What are the opportunities for implementation of Digital Twin technology in the design stages of a construction project?

Digital twins can help in real-time visualization and simulation of designs, enabling better decision-making and collaboration among stakeholders.

What are the opportunities for implementation of Digital Twin technology during the construction phases of a sustainable construction project?

Digital twins can facilitate real-time monitoring and analysis of construction progress, leading to more efficient resource management and reduced waste.

What are the opportunities for implementation of Digital Twin technology during the operation phases of a sustainable project?

During the operation phase, digital twins can provide valuable data for predictive maintenance, energy optimization, and overall sustainability performance analysis.

Do you think digital twin technology can contribute to sustainable development?
Absolutely. It has the potential to improve resource efficiency, reduce environmental impact, and enhance the overall sustainability of construction projects.

In your opinion, what are the potential benefits of using digital twin technology for sustainable development?

Some benefits include optimized energy consumption, reduced carbon footprint, improved building lifecycle management, and enhanced occupant comfort and well-being.

Do you think Digital Twin technology can be used to minimize waste generation in construction projects?

Yes, by enabling better planning and coordination, digital twins can help minimize waste generation and increase construction efficiency.

The lack of standardized data formats and interoperability poses obstacles to using digital twin technology for sustainability.

Integrating digital twin tools with existing design processes and ensuring data accuracy are important challenges.

Managing real-time data flow and the initial setup cost are challenges during the construction phase.

Ensuring continuous data accuracy and maintenance are important challenges for implementing digital twins during the operation phase.

The participant mentioned an increased dependence on technology as a potential consequence.

Yes, the participant believes that technological limitations and data interoperability issues may affect the implementation of Digital Twin technology in sustainable construction projects.

Yes, Organization A has implemented digital twin technology for sustainable construction projects.

**Engineer 1:**

Have you heard of digital twin technology before this survey?

Yes, I'm familiar with digital twin technology, especially in the context of engineering and construction.

What are the opportunities for implementation of Digital Twin technology in the design stages of a construction project?
Digital twins can aid in detailed simulations and analysis of structural integrity, ensuring safer and more robust designs.

What are the opportunities for implementation of Digital Twin technology during the construction phases of a sustainable construction project?

Digital twins can assist in monitoring construction processes, optimizing logistics, and tracking sustainable material usage.

What are the opportunities for implementation of Digital Twin technology during the operation phases of a sustainable project?

Digital twins can support condition monitoring, predictive maintenance, and energy management, leading to long-term sustainability benefits.

Do you think digital twin technology can contribute to sustainable development?
Definitely. It enables data-driven decision-making and fosters sustainable practices across the entire construction lifecycle.

In your opinion, what are the potential benefits of using digital twin technology for sustainable development?

Improved project efficiency, reduced operational costs, minimized environmental impact, and extended infrastructure lifespan.

Do you think Digital Twin technology can be used to minimize waste generation in construction projects?

Yes, digital twins can optimize construction processes, leading to reduced waste generation and improved material usage.

Integrating digital twin tools with existing design workflows and ensuring data accuracy are important challenges during the design phase.

Challenges in Construction Implementation: Managing real-time data flow and addressing the initial setup cost are crucial considerations during the construction phase.

Ensuring continuous data accuracy and maintenance are important for implementing digital twins during the operation phase.

The participant mentioned potential consequences related to an increased dependence on technology and reliance on algorithms.

Yes, the participant believes that technological limitations and data interoperability issues may affect the implementation of Digital Twin technology in sustainable construction projects.

Organizations Using Digital Twin: The participant did not mention any specific organizations using digital twin technology for sustainable construction projects.

**Engineer 2:**

Have you heard of digital twin technology before this survey?

Yes, I am familiar with digital twin technology and its applications in engineering and construction.

What are the opportunities for implementation of Digital Twin technology in the design stages of a construction project?

Digital twins can enable advanced simulations and analysis, helping engineers make data-driven design decisions for optimal outcomes.

What are the opportunities for implementation of Digital Twin technology during the construction phases of a sustainable construction project?

Digital twins can support real-time construction monitoring, quality control, and resource efficiency, promoting sustainability.

What are the opportunities for implementation of Digital Twin technology during the operation phases of a sustainable project?

Digital twins can aid in predictive maintenance, energy optimization, and lifecycle analysis for sustainable building operation.

Do you think digital twin technology can contribute to sustainable development?
Absolutely. It aligns well with sustainable engineering practices and can lead to more efficient and eco-friendly projects.

In your opinion, what are the potential benefits of using digital twin technology for sustainable development?

Enhanced construction and operational efficiency, reduced energy consumption, and better infrastructure performance.

Do you think Digital Twin technology can be used to minimize waste generation in construction projects?

Yes, digital twins can optimize construction workflows, leading to reduced waste generation and improved material utilization.

Waste management is a pressing challenge that requires effective solutions in sustainable construction practices.

Limited industry-wide data standards and complexity in data analysis pose challenges in using digital twin technology for sustainability.

It is essential to manage the interplay between design aesthetics and the integration of digital twin technology in a design-phase manner.

Ensuring data privacy and security, especially with the use of IoT devices, is a challenge during construction.

Managing large data volumes and ensuring continuous data monitoring are challenges in operationalizing digital twin technology.
Potential Unintended Consequences: The participant mentioned potential consequences related to increased cyber risks.

Yes, the participant believes that technological limitations and data interoperability issues may affect the implementation of Digital Twin technology in sustainable construction projects.

Organizations Using Digital Twin: Yes, Organization E has implemented digital twin technology for sustainable construction projects.

**Engineer 3:**

Have you heard of digital twin technology before this survey?

Yes, I am familiar with digital twin technology and its relevance in engineering and construction.
What are the opportunities for implementation of Digital Twin technology in the design stages of a construction project?

Digital twins can facilitate better coordination between design disciplines, leading to more integrated and sustainable designs.

What are the opportunities for implementation of Digital Twin technology during the construction phases of a sustainable construction project?

Digital twins can assist in tracking construction progress, resource allocation, and site safety, contributing to sustainability goals.

What are the opportunities for implementation of Digital Twin technology during the operation phases of a sustainable project?

Digital twins can provide real-time building performance monitoring, predictive maintenance, and energy management.

Do you think digital twin technology can contribute to sustainable development?

Certainly. It provides valuable data and insights to support sustainable engineering practices.
In your opinion, what are the potential benefits of using digital twin technology for sustainable development?

Improved project coordination reduced environmental impact, enhanced building performance, and better life-cycle management.

Do you think Digital Twin technology can be used to minimize waste generation in construction projects?

Yes, digital twins can optimize construction processes and material usage, leading to reduced waste generation and increased efficiency.

Energy efficiency is a significant challenge that requires focus in sustainable engineering practices.

Inadequate data for certain parameters may limit the effectiveness of digital twin technology for sustainability projects.

Integrating design and analysis data for informed decision-making poses challenges during the design phase.

Handling data from multiple sources and ensuring real-time synchronization with digital twins during construction are critical considerations.

The reliability of sensor data and ongoing data integrity are important challenges during the operational phase.

The participant mentioned potential consequences related to reduced human involvement and an over-reliance on algorithms.

Yes, the participant believes that technological limitations and data interoperability issues may affect the implementation of Digital Twin technology in sustainable construction projects.

Yes, Organization F has implemented digital twin technology for sustainable construction projects.

Air pollution and its impact on the environment are significant challenges that require attention in sustainable development practices.

Data accuracy and reliability during the design phase is crucial for successful digital twin implementation.

Ensuring real-time data availability and accuracy during construction pose challenges for implementing digital twins.

: Building and maintaining expertise in managing digital twin data for ongoing building performance analysis is essential.

The participant mentioned issues related to data ownership and sharing as potential unintended consequences.

Yes, the participant believes that technological limitations and data interoperability issues may affect the implementation of Digital Twin technology in sustainable construction projects.

The participant did not mention any specific organizations using digital twin technology for sustainable construction projects.

**Engineer 4:**

Have you heard of digital twin technology before this survey?

Yes, I am familiar with digital twin technology and its potential applications in engineering projects.

What are the opportunities for implementation of Digital Twin technology in the design stages of a construction project?

Digital twins can enable better design visualization, simulation, and analysis for more sustainable and efficient outcomes.

What are the opportunities for implementation of Digital Twin technology during the construction phases of a sustainable construction project?

Digital twins can assist in real-time progress tracking, resource management, and adherence to sustainable construction practices.

What are the opportunities for implementation of Digital Twin technology during the operation phases of a sustainable project?

Digital twins can support ongoing performance monitoring, predictive maintenance, and energy optimization for sustainability.

Do you think digital twin technology can contribute to sustainable development?

Absolutely. It aligns well with the principles of sustainable engineering and can lead to better environmental outcomes.

In your opinion, what are the potential benefits of using digital twin technology for sustainable development?

Enhanced project understanding, reduced environmental impact, improved operational efficiency, and better lifecycle management.

Do you think Digital Twin technology can be used to minimize waste generation in construction projects?

Yes, digital twins can optimize construction processes and material usage, leading to reduced waste generation and increased sustainability.

The complexity of data analysis and inadequate data integration pose a challenge in using digital twin technology for sustainability.

The design phase necessitates careful consideration of how design aesthetics and digital twin technology work together.

Ensuring real-time data synchronization with digital twins and addressing data privacy and security concerns are critical during construction.

Ensuring data accuracy and reliability for ongoing building performance analysis are important during the operational phase.

The participant mentioned potential consequences related to data misinterpretation and over-reliance on technology.

No, the participant does not believe that technological limitations will hinder the implementation of Digital Twin technology in sustainable construction projects.

Organizations Using Digital Twin: The participant did not mention any specific organizations using digital twin technology for sustainable construction projects.

**Engineer 5:**

Have you heard of digital twin technology before this survey?

Yes, I'm familiar with digital twin technology, especially in the context of engineering and construction.

What are the opportunities for implementation of Digital Twin technology in the design stages of a construction project?

Digital twins can aid in detailed simulations and analysis of structural integrity, ensuring safer and more robust designs.

What are the opportunities for implementation of Digital Twin technology during the construction phases of a sustainable construction project?

Digital twins can assist in monitoring construction processes, optimizing logistics, and tracking sustainable material usage.
What are the opportunities for implementation of Digital Twin technology during the operation phases of a sustainable project?

Digital twins can support condition monitoring, predictive maintenance, and energy management, leading to long-term sustainability benefits.

Do you think digital twin technology can contribute to sustainable development?

Definitely. It enables data-driven decision-making and fosters sustainable practices across the entire construction lifecycle.

In your opinion, what are the potential benefits of using digital twin technology for sustainable development?

Improved project efficiency, reduced operational costs, minimized environmental impact, and extended infrastructure lifespan.

Do you think Digital Twin technology can be used to minimize waste generation in construction projects?

Yes, digital twins can optimize construction processes, leading to reduced waste generation and improved material usage.

The limited knowledge and comprehension of digital twin technology among stakeholders could hinder its utilization in sustainability endeavours.

digital twin tools with existing design workflows and ensuring data accuracy are important challenges during the design phase.

Challenges in Construction Implementation: Managing real-time data flow and addressing the initial setup cost are crucial considerations during the construction phase.

Ensuring continuous data accuracy and maintenance are important for implementing digital twins during the operation phase.

The participant mentioned potential consequences related to an increased dependence on technology and reliance on algorithms.

Yes, the participant believes that technological limitations and data interoperability issues may affect the implementation of Digital Twin technology in sustainable construction projects.

The participant did not mention any specific organizations using digital twin technology for sustainable construction projects.

**GBCA (Green Building Council of Australia) Representative:**

Have you heard of digital twin technology before this survey?

Yes, I am familiar with digital twin technology and its potential applications in engineering projects.

What are the opportunities for implementation of Digital Twin technology in the design stages of a construction project?

Digital twins can enable better design visualization, simulation, and analysis for more sustainable and efficient outcomes.

What are the opportunities for implementation of Digital Twin technology during the construction phases of a sustainable construction project?

Digital twins can assist in real-time progress tracking, resource management, and adherence to sustainable construction practices.
What are the opportunities for implementation of Digital Twin technology during the operation phases of a sustainable project?

Digital twins can support ongoing performance monitoring, predictive maintenance, and energy optimization for sustainability.

Do you think digital twin technology can contribute to sustainable development?
Absolutely. It aligns well with the principles of sustainable engineering and can lead to better environmental outcomes.

In your opinion, what are the potential benefits of using digital twin technology for sustainable development?

Enhanced project understanding, reduced environmental impact, improved operational efficiency, and better lifecycle management.

Do you think Digital Twin technology can be used to minimize waste generation in construction projects?

Yes, digital twins can optimize construction processes and material usage, leading to reduced waste generation and increased sustainability.

Water pollution and its impact on aquatic ecosystems are significant challenges that need attention in sustainable development practices.

The limited knowledge and comprehension of digital twin technology among stakeholders could hinder its utilization in sustainability efforts.

Ensuring data accuracy and reliability during the design phase is crucial for successful digital twin implementation.

Ensuring real-time data availability and accuracy during construction pose challenges for implementing digital twins.

Building and maintaining expertise in managing digital twin data for ongoing building performance analysis is essential.

The participant mentioned issues related to data ownership and sharing as potential unintended consequences.

No, the participant does not believe that technological limitations will hinder the implementation of Digital Twin technology in sustainable construction projects.

The participant did not mention any specific organizations using digital twin technology for sustainable construction projects.

**GBCA (Green Building Council of Australia) Representative:**

Have you heard of digital twin technology before this survey?

Yes, digital twin technology is gaining attention in sustainable construction practices. What are the opportunities for implementation of Digital Twin technology in the design stages of a construction project?

Digital twins can aid in evaluating sustainable design alternatives, predicting energy performance, and ensuring green building certifications.

What are the opportunities for implementation of Digital Twin technology during the construction phases of a sustainable construction project?

Digital twins can assist in tracking sustainable material sourcing, monitoring construction practices, and ensuring compliance with green standards.

What are the opportunities for implementation of Digital Twin technology during the operation phases of a sustainable project?

Digital twins can support ongoing monitoring of energy usage, indoor environmental quality, and occupant comfort to maintain sustainability targets.

Do you think digital twin technology can contribute to sustainable development? Absolutely. It aligns well with the principles of green building and can significantly improve sustainability outcomes.

In your opinion, what are the potential benefits of using digital twin technology for sustainable development?

Enhanced performance analysis, reduced energy consumption, better resource management, and improved occupant satisfaction.

Do you think Digital Twin technology can be used to minimize waste generation in construction projects?

Yes, by enabling data-driven decision-making and optimizing construction processes, digital twins can help minimize waste in sustainable projects.

Loss of biodiversity and its impact on ecosystems are significant challenges that need to be addressed in sustainable development efforts.

Limited awareness and understanding of digital twin technology among stakeholders may hinder its adoption for sustainability initiatives.

Ensuring accuracy of as built construction information and reliability during the design phase is crucial for successful digital twin implementation.

Ensuring real-time data availability and accuracy during construction pose challenges for implementing digital twins.

Building and maintaining expertise in managing digital twin data for ongoing building performance analysis is essential.

The participant mentioned issues related to data ownership and sharing as potential unintended consequences.

No, the participant does not believe that technological limitations will hinder the implementation of Digital Twin technology in sustainable construction projects.

The participant did not mention any specific organizations using digital twin technology for sustainable construction projects.

**Project Manager 1:**

Have you heard of digital twin technology before this survey?

Yes, I am familiar with digital twin technology and its potential benefits in construction management.

What are the opportunities for implementation of Digital Twin technology in the design stages of a construction project?

Digital twins can aid in collaborative design reviews, clash detection, and design visualization for better project planning.

What are the opportunities for implementation of Digital Twin technology during the construction phases of a sustainable construction project?

Digital twins can assist in real-time progress tracking, resource management, and adherence to sustainability targets.

What are the opportunities for implementation of Digital Twin technology during the operation phases of a sustainable project?
Digital twins can support ongoing facility management, predictive maintenance, and energy optimization for sustainable operation.

Do you think digital twin technology can contribute to sustainable development?

Absolutely. It provides valuable data for informed decision-making and promotes sustainability throughout the project lifecycle.

In your opinion, what are the potential benefits of using digital twin technology for sustainable development?

Improved project efficiency, reduced operational costs, enhanced sustainability performance, and better risk management.

Do you think Digital Twin technology can be used to minimize waste generation in construction projects?

Yes, digital twins can optimize construction workflows and material usage, leading to reduced waste generation and increased efficiency.

Social equity and addressing disparities in access to resources are significant challenges in sustainable development efforts.

Limited industry-wide data standards and complexity in data analysis pose challenges in using digital twin technology for sustainability.

Ensuring data privacy and security, especially with the use of IoT devices, is a challenge during construction.

Managing large data volumes and ensuring continuous data monitoring are challenges in operationalizing digital twin technology.

The participant mentioned potential consequences related to increased cyber risks.

Yes, the participant believes that technological limitations and data interoperability issues may affect the implementation of Digital Twin technology in sustainable construction projects.

Yes, participant G has implemented digital twin technology for construction projects within their organization

**Project Manager 2:**

Have you heard of digital twin technology before this survey?

Yes, I am familiar with digital twin technology and its applications in construction and project management.
What are the opportunities for implementation of Digital Twin technology in the design stages of a construction project?

Digital twins can enable better design coordination, simulation, and analysis, leading to more informed design decisions.

What are the opportunities for implementation of Digital Twin technology during the construction phases of a sustainable construction project?

Digital twins can support real-time progress monitoring, resource optimization, and adherence to sustainability goals.

What are the opportunities for implementation of Digital Twin technology during the operation phases of a sustainable project?

Digital twins can aid in ongoing facility management, energy optimization, and predictive maintenance for sustainable operation.
Do you think digital twin technology can contribute to sustainable development?

Certainly. It provides valuable tools for promoting sustainable practices and achieving project sustainability objectives.

In your opinion, what are the potential benefits of using digital twin technology for sustainable development?

Enhanced project collaboration, reduced environmental impact, better resource management, and increased project resilience.

Do you think Digital Twin technology can be used to minimize waste generation in construction projects?

Yes, digital twins can optimize construction processes and material usage, leading to reduced waste generation and increased sustainability.

Economic stability and addressing economic inequalities are significant challenges in sustainable development efforts.

Ensuring data accuracy and reliability during the design phase is crucial for successful digital twin implementation.

Ensuring real-time data availability and accuracy during construction pose challenges for implementing digital twins.

Building and maintaining expertise in managing digital twin data for ongoing building performance analysis is essential.

The participant mentioned potential consequences related to an increased dependence on technology and reliance on algorithms.

Yes, the participant believes that technological limitations and data interoperability issues may affect the implementation of Digital Twin technology in sustainable construction projects.

Yes, Organization H has implemented digital twin technology for sustainable construction projects.

**Project Manager 3:**

Have you heard of digital twin technology before this survey?

Yes, I've come across digital twin technology and its potential applications in construction management.

What are the opportunities for implementation of Digital Twin technology in the design stages of a construction project?

Digital twins can facilitate better communication and coordination among project stakeholders, leading to streamlined design iterations.

What are the opportunities for implementation of Digital Twin technology during the construction phases of a sustainable construction project?

Digital twins can aid in real-time progress tracking, resource allocation, and identifying potential construction bottlenecks that impact sustainability goals.

What are the opportunities for implementation of Digital Twin technology during the operation phases of a sustainable project?
Digital twins can assist in facility management, predictive maintenance, and energy optimization to ensure long-term sustainability.

Do you think digital twin technology can contribute to sustainable development?
Certainly. It offers valuable insights and data for informed decision-making throughout the project lifecycle.

In your opinion, what are the potential benefits of using digital twin technology for sustainable development?

Improved project efficiency, reduced risks, enhanced collaboration, and better adherence to sustainable practices.

Do you think Digital Twin technology can be used to minimize waste generation in construction projects?

Yes, by providing real-time data on construction progress and resource usage, digital twins can help minimize waste generation and increase overall efficiency.

Limited computational resources and insufficient data integration might impede the effective use of digital twin technology for sustainability.

Collaborative data sharing and ensuring data compatibility among various design disciplines are crucial during the design phase.

Ensuring accurate sensor data during construction and real-time data synchronization with digital twins pose challenges.

Integrating digital twins with facility management systems and ensuring data accuracy and reliability are important for successful operation implementation.

The participant mentioned potential risks of increased reliance on technology and reduced human involvement.

Yes, the participant believes that technological limitations and data interoperability issues may affect the implementation of Digital Twin technology in sustainable construction projects.

Yes, Organization I has implemented digital twin technology for sustainable construction projects.

**Student:**

Have you heard of digital twin technology before this survey?
Yes, I have heard about digital twin technology in the context of construction and engineering.

What are the opportunities for implementation of Digital Twin technology in the design stages of a construction project?

Digital twins can aid in exploring innovative and sustainable design solutions, making use of simulation and analysis.

What are the opportunities for implementation of Digital Twin technology during the construction phases of a sustainable construction project?

Digital twins can provide valuable learning experiences for students, helping them understand construction processes and sustainable practices better.

What are the opportunities for implementation of Digital Twin technology during the operation phases of a sustainable project?

Digital twins can be used as educational tools for facility management and sustainable operation practices.

Do you think digital twin technology can contribute to sustainable development?
Absolutely. It aligns well with sustainable practices and can be a powerful tool for future sustainable development.

In your opinion, what are the potential benefits of using digital twin technology for sustainable development?

Improved design understanding, enhanced sustainability knowledge, and greater awareness of the impact of construction activities.

Do you think Digital Twin technology can be used to minimize waste generation in construction projects?

Yes, by encouraging more efficient construction practices and better planning, digital twins can help reduce waste generation in construction projects.

Lack of public awareness and education about sustainable practices is a significant challenge.

Insufficient data integration and limited interdisciplinary collaboration pose challenges in using digital twin technology for sustainability.

Achieving a synergy between design aesthetics and the incorporation of digital twin technology is critical in the design process.

Ensuring accurate data representation and real-time data synchronization with digital twins during construction are critical.

Ensuring data accuracy and reliability for ongoing building performance analysis pose challenges during the operational phase.

The participant mentioned potential consequences related to over-reliance on technology and reduced human involvement.

Yes, the participant believes that technological limitations and data interoperability issues may affect the implementation of Digital Twin technology in sustainable construction projects.

Yes, Organization J has implemented digital twin technology for sustainable construction projects.

**Student 2:**

Have you heard of digital twin technology before this survey?
Yes, I have heard about digital twin technology, especially in the context of construction and engineering.

What are the opportunities for implementation of Digital Twin technology in the design stages of a construction project?

Digital twins can aid in exploring design alternatives, conducting simulations, and facilitating collaborative design reviews.

What are the opportunities for implementation of Digital Twin technology during the construction phases of a sustainable construction project?

Digital twins can support real-time progress tracking, resource optimization, and adherence to sustainability targets.

What are the opportunities for implementation of Digital Twin technology during the operation phases of a sustainable project?

Digital twins can assist in ongoing building performance monitoring, predictive maintenance, and energy optimization.

Do you think digital twin technology can contribute to sustainable development?
Absolutely. It aligns well with sustainable practices and can lead to better environmental outcomes.

In your opinion, what are the potential benefits of using digital twin technology for sustainable development?

Improved project understanding, reduced environmental impact, enhanced building performance, and better resource management.

Do you think Digital Twin technology can be used to minimize waste generation in construction projects?

Yes, digital twins can optimize construction workflows and resource usage, leading to reduced waste generation and increased sustainability.

Political resistance to change and ensuring policy implementation are significant challenges in achieving sustainable development goals.

Limited scalability for large projects and lack of industry-wide data standards pose challenges in using digital twin technology for sustainability.

Inadequate data visualization and data privacy and security concerns are important considerations during the design phase.

Ensuring data privacy and security during construction and managing multiple data sources pose challenges for implementing digital twins.

Challenges in Operation Implementation: Data management and storage and potential data breach risks are challenges during the operational phase.

The participant mentioned potential consequences related to increased cyber risks and data breach vulnerabilities.

Yes, the participant believes that technological limitations and data interoperability issues may affect the implementation of Digital Twin technology in sustainable construction projects.

Yes, Organization K has implemented digital twin technology for sustainable construction projects.

**Student 3:**

Have you heard of digital twin technology before this survey?

Yes, I am familiar with digital twin technology and its relevance in the construction industry.
What are the opportunities for implementation of Digital Twin technology in the design stages of a construction project?

Digital twins can facilitate collaborative design reviews, simulations, and analysis, leading to better-informed design decisions.

What are the opportunities for implementation of Digital Twin technology during the construction phases of a sustainable construction project?

Digital twins can assist in real-time progress monitoring, resource optimization, and adherence to sustainability goals.

What are the opportunities for implementation of Digital Twin technology during the operation phases of a sustainable project?

Digital twins can support ongoing building performance monitoring, predictive maintenance, and energy optimization.

Do you think digital twin technology can contribute to sustainable development?
Certainly. It provides valuable data and insights to support sustainable construction practices.
In your opinion, what are the potential benefits of using digital twin technology for sustainable development?

Enhanced project coordination, reduced environmental impact, improved building performance, and better occupant comfort.

Do you think Digital Twin technology can be used to minimize waste generation in construction projects?

Yes, digital twins can optimize construction processes and material usage, leading to reduced waste generation and increased sustainability.

Political resistance to change and ensuring policy implementation are significant challenges in achieving sustainable development goals.

Limited scalability for large projects and lack of industry-wide data standards pose challenges in using digital twin technology for sustainability.

Inadequate data visualization and data privacy and security concerns are important considerations during the design phase.

Ensuring data privacy and security during construction and managing multiple data sources pose challenges for implementing digital twins.

Data management and storage and potential data breach risks are challenges during the operational phase.

The participant mentioned potential consequences related to increased cyber risks and data breach vulnerabilities.

Yes, the participant believes that technological limitations and data interoperability issues may affect the implementation of Digital Twin technology in sustainable construction projects.

Yes, Organization K has implemented digital twin technology for sustainable construction projects.

**Student 4:**

Have you heard of digital twin technology before this survey?
Yes, I have come across digital twin technology in my studies related to construction and engineering.

What are the opportunities for implementation of Digital Twin technology in the design stages of a construction project?

Digital twins can enable better design coordination, simulations, and analysis for more informed design decisions.

What are the opportunities for implementation of Digital Twin technology during the construction phases of a sustainable construction project?

Digital twins can support real-time progress tracking, resource optimization, and adherence to sustainability targets.

What are the opportunities for implementation of Digital Twin technology during the operation phases of a sustainable project?

Digital twins can aid in ongoing building performance monitoring, predictive maintenance, and energy optimization.

Do you think digital twin technology can contribute to sustainable development?
Absolutely. It aligns well with sustainable practices and can lead to better environmental outcomes.

In your opinion, what are the potential benefits of using digital twin technology for sustainable development?

Improved project coordination reduced environmental impact, enhanced building performance, and better resource management.

Do you think Digital Twin technology can be used to minimize waste generation in construction projects?

Yes, digital twins can optimize construction workflows and resource usage, leading to reduced waste generation and increased sustainability.

Consumer behaviour and education about sustainable practices are significant challenges that need attention.

The complexity of data analysis and the lack of data integration make it difficult to use digital twin technology for sustainability.

Integrating digital twin technology while maintaining design aesthetics is a significant factor to consider in design.

Ensuring real-time data synchronization with digital twins and addressing data privacy and security concerns is essential during construction.

Ensuring data accuracy and reliability for ongoing building performance analysis are important during the operational phase.

The participant mentioned potential consequences related to data misinterpretation and over-reliance on technology.

No, the participant does not believe that technological limitations will hinder the implementation of Digital Twin technology in sustainable construction projects.

The participant did not mention any specific organizations using digital twin technology for sustainable construction projects.

**Student 5:**

Have you heard of digital twin technology before this survey?

Yes, I am familiar with digital twin technology and its applications in construction and engineering.

What are the opportunities for implementation of Digital Twin technology in the design stages of a construction project?

Digital twins can enable better design visualization, simulations, and analysis for informed decision-making.

What are the opportunities for implementation of Digital Twin technology during the construction phases of a sustainable construction project?

Digital twins can support real-time progress tracking, resource optimization, and adherence to sustainability goals.

What are the opportunities for implementation of Digital Twin technology during the operation phases of a sustainable project?

Digital twins can assist in ongoing building performance monitoring, predictive maintenance, and energy optimization.

Do you think digital twin technology can contribute to sustainable development?
Certainly. It provides valuable data and insights to promote sustainable construction practices.

In your opinion, what are the potential benefits of using digital twin technology for sustainable development?

Enhanced project coordination reduced environmental impact, improved building performance, and better resource management.

Do you think Digital Twin technology can be used to minimize waste generation in construction projects?

Yes, digital twins can optimize construction workflows and material usage, leading to reduced waste generation and increased sustainability.

It's essential to weigh design aesthetics against the integration of digital twin technology when designing.

real-time data synchronization with digital twins and addressing data privacy and security concerns are critical during construction.

Ensuring data accuracy and reliability for ongoing building performance analysis are important during the operational phase.

The participant mentioned potential consequences related to data misinterpretation and over-reliance on technology.

No, the participant does not believe that technological limitations will hinder the implementation of Digital Twin technology in sustainable construction projects.

The participant did not mention any specific organizations using digital twin technology for sustainable construction projects.

**Student 6:**

Have you heard of digital twin technology before this survey?

Yes, I have heard about digital twin technology, especially in the context of construction and engineering.

What are the opportunities for implementation of Digital Twin technology in the design stages of a construction project?

Digital twins can aid in exploring design alternatives, conducting simulations, and facilitating collaborative design reviews.

What are the opportunities for implementation of Digital Twin technology during the construction phases of a sustainable construction project?

Digital twins can support real-time progress tracking, resource optimization, and adherence to sustainability targets.

What are the opportunities for implementation of Digital Twin technology during the operation phases of a sustainable project?

Digital twins can assist in ongoing building performance monitoring, predictive maintenance, and energy optimization.

Do you think digital twin technology can contribute to sustainable development?
Absolutely. It aligns well with sustainable practices and can lead to better environmental outcomes.

In your opinion, what are the potential benefits of using digital twin technology for sustainable development?

Improved project understanding, reduced environmental impact, enhanced building performance, and better resource management.
Do you think Digital Twin technology can be used to minimize waste generation in construction projects?

Yes, digital twins can optimize construction workflows and resource usage, leading to reduced waste generation and increased sustainability.

Consumer behaviour and education about sustainable practices are significant challenges that need attention.

Balancing design aesthetics and integrating data analysis are important considerations during the design phase.

Maintaining real-time data with digital twins while also addressing concerns related to data privacy and security is of utmost importance in the construction process.

The participant mentioned potential consequences related to data misinterpretation and over-reliance on technology.

No, the participant does not believe that technological limitations will hinder the implementation of Digital Twin technology in sustainable construction projects.

The participant did not mention any specific organizations using digital twin technology for sustainable construction projects.

### 7.3. Questionnaire Info Sheet

University of Southern Queensland

University of Southern Queensland
Participant Information Sheet
Survey

**UniSQ HREC Approval number: HXXREAXXX**

**Project Title**

"Leveraging Digital Twin Technology for Sustainable Development: An Exploration of Opportunities and Challenges"

**Research team contact details**


**Principal Investigator Details**

Mr Zack Davis
Email: [redacted]
Mobile: [redacted]

**[Supervisor/Co-investigator details]**

Steven Goh
Email: [redacted]
Telephone: +[redacted]


**Description**

This project is being undertaken as part of Honours Bachelor of Construction Management through the University of Southern Queensland.

The purpose of this project is to investigate the opportunities and challenges of leveraging digital twin technology for sustainable development.

**Participation**

Your participation will involve contributing your thoughts and ideas in a survey that will take approximately 30 minutes of your time.

Questions will include:

- Have you heard of digital twin technology before this survey?
- How familiar are you with the concept of sustainable development?
- Do you think digital twin technology can contribute to sustainable development?

Your participation in this project is entirely voluntary. If you do not wish to take part, you are not obliged to. If you decide to take part and later change your mind, you are free to withdraw from the project at any stage.

If you do wish to withdraw from this project prior to participating, please contact the Research Team (contact details at the top of this form).

Your decision whether you take part, do not take part, or take part and then withdraw, will in no way impact your current or future relationship with the University of Southern Queensland.

**Expected benefits**

It is expected that this project will directly benefit you by contributing to the existing understanding of digital twin technology and development of sustainable buildings.

## Risks

In participating in the survey, There are no anticipated risks beyond normal day-to-day living.

## Privacy and confidentiality

All comments and responses are confidential unless required by law

The names of individual persons are not required in any of the responses.

It is not anticipated that the raw data will be made available in the future. The data relate to interviews and survey responses that are organisation-specific, may change and have utility only in this research, as it is practice-based and investigates only current practice. It is likely that conditions in the organisation may change and that the data will not accurately represent a future state of that organisation.

Any data collected as a part of this project will be stored securely, as per University of Southern Queensland's Research Data and Primary Materials Management Procedure.

A summary of the projects results will be provided at the completion of the project.

## Consent to participate

Clicking on the "Submit" button at the conclusion of the survey is accepted as an indication of your consent to participate in this project.

## Questions

Please refer to the Research team contact details at the top of the form to have any questions answered or to request further information about this project.

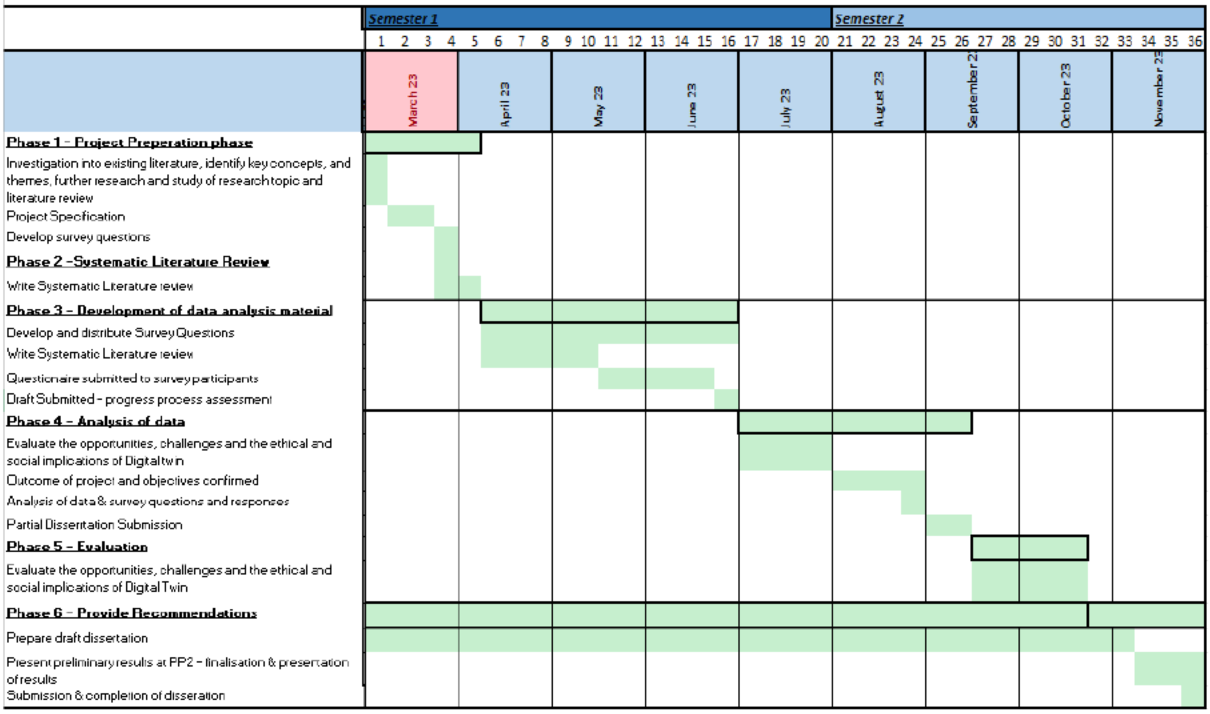
## Concerns or complaints

If you have any concerns or complaints about the ethical conduct of the project, you may contact the University of Southern Queensland, Manager of Research Integrity and Ethics on +61 7 4631 1839 or email researchintegrity@usq.edu.au. The Manager of Research Integrity and Ethics is not connected with the research project and can address your concern in an unbiased manner.

**Thank you for taking the time to help with this research project. Please keep this document for your information.**

## 7.4. Project timeline

| PROJECT DETAILS | |
|---|---|
| Course: | ENG4110 |
| Student Name: | Zack Davis |
| Student Number: | [redacted] |



### 7.5. Risk Assessment

In the development of the project question and in preparing the project specification, the following qualitative risks have been identified: -

- Analysis of data takes longer than expected/time constraints.
- Research Limitations
- Approval to commence project not given by USQ
- Insufficient time to write up and present results
- Stress/Burn Out/Repetitive Strain Injury while completing analysis.
- Other courses or assessment items/time management

| Safety Risk Management Plan – Offline Version | | | |
|---|---|---|---|
| Assessment Title: | Leveraging Digital Twin Technology for Sustainable Development: An exploration of Opportunities and Challenges | Assessment Date: | Click here to enter a date. |
| Workplace (Division/Faculty/Section): | Home or Office | Review Date:(5 Years Max) | 20/01/2023 |
| **Context** | | | |
| **Description:** | | | |
| What is the task/event/purchase/project/procedure? | Literature review and research proposal on Digital Twin Technologies | | |
| Why is it being conducted? | To meet the requirements of the University of Southern Queensland (USQ) courses ENG4111/4112 | | |
| Where is it being conducted? | The research will be conducted from a home office | | |
| Course code (if applicable) | ENG4111/4112 | Chemical name (if applicable) | |
| **What other nominal conditions?** | | | |
| Personnel involved | Zack Davis | | |
| Equipment | Computer | | |
| Environment | Home Office | | |
| Other | Nil | | |
| Briefly explain the procedure/process | Conduct Literature review and a survey tp | | |
| **Assessment Team - who is conducting the assessment?** | | | |
| Assessor(s) | Steven Goh | | |
| Others consulted: | | | |

### 7.5.1. Risk Matrix

An analysis matrix was developed to determine the risks associated with the research proposal. This is used to identify the severity of the consequences and the likelihood that it will occur. The risk assessment has been completed and adapted from the risk matrix outlined in the figure below. The risk assessment has been completed and adapted from the risk matrix outlined in the figure below.

| Likelihood | | | Consequences | | |
|---|---|---|---|---|---|
| | Catastrophic | Major | Moderate | Minor | Insignificant |
| Almost certain | Extreme | Extreme | Extreme | High | High |
| Likely | Extreme | Extreme | High | High | Moderate |
| Possible | Extreme | Extreme | High | Moderate | Low |
| Unlikely | Extreme | High | Moderate | Low | Low |
| Rare | High | High | Moderate | Low | Low |

A risk analysis was conducted during the development of the literature review and in preparing the research proposal. The risks analysis was completed using the risk matrix outlined in the table above.

# 1 Personal Risk Analysis

| | Risk/Hazard Description | Risk Mitigation Measures | Risk Score Before | Risk Score After |
|---|---|---|---|---|
| 1 | Analysis of data takes longer than expected/Time Constraints | Create a realistic timeline and set specific goals for each stage of the dissertation process. Begin writing a draft dissertation at the start of the project, before the results are collected. Make time to write your dissertation on a regular basis. Request a review of your draft dissertation. | Moderate | Low |
| 2 | Research Limitations | Conducting research on a topic might have some limitations such as access to data and information or a lack of understanding of certain concepts. This could impact the quality of the paper and the ability to draw conclusions. | Moderate | Low |
| 3 | Approval to commence project not given by USQ | Begin early negotiations with possible USQ supervisors and ESC work supervisors, and ensure approval is obtained before beginning the project. | Extreme | Moderate |
| 4 | Insufficient time to write up and present results | Ascertain that adequate time has been made available for data interpretation and analysis. Begin data analysis early. | Moderate | Low |
| 5 | Stress/Burn Out/Repetitive Strain Injury while completing analysis. | Take breaks and practice self-care regularly. Exercise, meditate, or engage in other activities to reduce stress levels. Ensure that you have a support system in place to help you through the process. Seek professional help if needed. Take regular rests when analysing. Create an ergonomic work environment. | Moderate | Low |
| 6 | Other courses or assessment items/time management | Use a project management tool or software to keep track of deadlines and milestones. Create a realistic timeline and set specific goals for each stage of the dissertation process. Break down the task into smaller achievable goals and work on them daily. | Moderate | Low |

### 7.6. Ethics Application

# Ethics ETH2023-0355 (HREC): Mr Zack Davis (Student) (Low risk)

| | |
|---|---|
| Academic/Researcher | Mr Zack Davis (Student)<br>A/Pr Steven Goh |
| Project | "Leveraging Digital Twin Technology for Sustainable Development: An Exploration of Opportunities and Challenges" |
| Division | Academic Division |
| Faculty/Department | Academic Affairs |

# Ethics application

## 2 Overview

**Application initiated by:**

Mr Zack Davis (Student)

## 3 Ethical Considerations

**Are you working with animals or humans?**

Humans

**Do you have a current approval from another Ethics Committee to conduct this project?**

No

**Project title**

"Leveraging Digital Twin Technology for Sustainable Development: An Exploration of Opportunities and Challenges"

**Project summary**

Digital twin technology is rapidly gaining popularity across various industrial sectors, providing an innovative way to simulate, visualize, and optimize physical systems in a virtual environment. With increasing concerns about sustainability, the potential of digital twin technology to enable sustainable development has gained significant attention in recent years. The aim of this dissertation is to investigate the opportunities and challenges of leveraging digital twin technology for sustainable development.

**Host department**

School of Surveying and Built Environment

**Project duration**

3 years

**Is your research being conducted within Australia?**

Yes

**Select all that apply:**

Queensland

**Does this project relate to, and/or extend on a previously approved project.**

No

**Is this project funded?**

No

# 4 Investigators

## Principal Investigator

A/Pr Steven Goh

**UniSQ ID**

[redacted]

**Person type**

Staff

**Organisational area**

School of Engineering

**Other affiliations**

Centre for Future Materials; Centre for Health Research;

**Field of Research (FoR)**

400303. Biomechanical engineering; 400304. Biomedical imaging; 400308. Medical devices; 400310. Rehabilitation engineering ; 401001. Engineering design; 401002. Engineering education; 401003. Engineering practice; 401006. Systems engineering; 401703. Energy generation, conversion and storage (excl. chemical and electrical); 401704. Mechanical engineering asset management;

# 5 Co-investigator (UniSQ Staff) Co-investigator (UniSQ Student)

Mr Zack Davis (Student)

**UniSQ Student ID**

[redacted]

**Type of student**

UGRD Student

**Program**

BCNH - Bachelor of Construction (Honours)

**Organisational area**

School of Surveying and Built Environment

**Field of Research (FoR)**

**Does the project involve co-investigators from another university or organisation?**

No

# 6 Conflict of interest

**Does the Principal Investigator have an actual, perceived, or potential personal or financial Conflict of Interest (CoI) in relation to the project?**

No

**Do any of the Co-Investigators or External Investigators have an actual, perceived, or potential personal or financial Conflict of Interest (CoI) in relation to the project?**

No

**Outline the Conflict of Interest (CoI) and advise on how it will be managed.**

# 7 Qualifications and Experience

## Principal Investigator - qualifications and experience

**Principal Investigator**

A/Pr Steven Goh

**Qualifications relevant to project**

Qualifications - BEng(Hons) Qld , MBA Deakin , MProfAcc USQ , DEng USQ

**Experience relevant to project**

BEng

# 8 Co-Investigator - qualifications and experience

**Co-Investigator**

Mr Zack Davis (Student)

**Qualifications relevant to project**

Nil

**Experience relevant to project**

Nil

# 9 Operational Items

**Does this project include:**

not applicable

*The following options were available for selection:*

- ***Genetically Modified Organism (GMO)***
- ***biological material (non-GMO), e.g. work with toxins, mutagens, teratogens, carcinogensetc.***
- ***biological material native to Australia that was (or will be) collected in Queensland for commercial purposes***
- ***radioactive substances and/or ionising radiation? (e.g. DXA, X-ray)***

**Does this project include:**

not applicable

*The following options were available for selection:*

- ***the export, supply, publishing, or brokering of controlled goods, software, or technology***
- ***an arrangement with a foreign government or foreign university that does not have institutional autonomy not applicable***
- ***not applicable***

"Leveraging Digital Twin Technology for Sustainable Development: An Exploration of Opportunities and Challenges"

First copy:
UniSQ OneDrive

Second Copy:
SharePoint

Third copy:
Secure local desktop

How will you protect your data from loss and unauthorised access?
Data will be locked behind an expired password. Restrictions on data dependant on permissions.

Who needs access to your data?
Supervisor

What is the required retention period for your data?
5 Years

At the completion of the project, where will you keep your research data in order to meet the required retention period
UniSQ One Drive.

**Additional Information**

**Do you have a UniSQ Risk Management Plan relating to the activities being undertaken in thisproject?**

No

# 10 Ethical considerations - Human Participant involvement

**In what way are human participants involved in your project:**

**Direct recruitment and/or observation of human participants**

Yes

**How many groups of participants will you be recruiting and/or observing for this researchproject?**

5

**Existing data sets and/or archival data**

No

**Existing Human biospecimens**

No

**Genomic research (includes full scope of genetic research)**

No

**Clinical trials**

No

# 11 Aims and significance

**Background**

Digital twin technology is rapidly gaining popularity across various industrial sectors, providing an innovative way to simulate, visualize, and optimize physical systems in a virtual environment. With increasing concerns about sustainability, the potential of digital twin technology to enable sustainable development has gained significant attention in recent years. The aim of this dissertation is to investigate the opportunities and challenges of leveraging digital twin technology for sustainable development.

**Aims**

The research project's goal is to understand the opportunities and challenges of Digital Twin Technology.

Another goal is to educate of students, the community, and researchers, in the uses and possibilities of digital twin technologies and their adoption in modern-day technologies, construction processes and sustainable development.

**Justification and significance**

This research will contribute to the emerging field of digital twin technology and sustainable development, providing insights into the opportunities and challenges of leveraging this technology to achieve a more sustainable future.

**Has your project been peer reviewed?**

No

# 12 Type of Research

**Do you have adequate resources available for this research project?**

Yes

**What type of research are you undertaking in this project?**

qualitative

case study

*The following options were available for selection:*

- ***medical (can be interventional, observational or lab-based)***
- ***clinical***
- ***biomedical***
- ***epidemiological***
- ***clinical trial***
- ***use of drug or therapeutic device***
- ***mental health***
- ***public health***
- ***dental***
- ***action***
- ***quantitative***
- ***qualitative***
- ***case study***
- ***social science***
- ***oral history/biographical***
- ***other***

# 13 Identifying participant group/s

**Will there be direct recruitment or use of existing data and/or tissue from any of the followingparticipant groups?**

n/a (none of the participant groups above are target groups for this project)

*The following options were available for selection:*

- ***women who are pregnant, the human foetus, or human foetal tissue***
- ***children or young people under the age of 18 years***
- ***people with a cognitive impairment, an intellectual disability, or a mental illness***
- ***people considered to be a forensic or involuntary patient***
- ***people with impaired capacity for communication***
- ***prisoners or people on parole***
- ***people highly dependent on medical care, including a person who is unconscious***
- ***military personnel***

- ***military veterans***
- ***people who would not usually be considered vulnerable but would be considered vulnerablein the context of this project***
- ***Aboriginal and/or Torres Strait Islander peoples***
- ***hospital patients***
- ***people residing outside Australia***
- ***people who would be considered to use English as a Second Language (ESL)***
- ***people who would be considered to use English as a Foreign Language (EFL)***
- ***n/a (none of the participant groups above are target groups for this project)***

# 14 Benefits and RisksBenefits

The potential benefits of the project are:

**- gains in knowledge, insight and understanding**
Yes

**Explain how this benefit will be achieved as a result of this research being conducted** Through critical analysis, practical examples, and the review of existing literature, this research willbenefit by educating on the capabilities of BIM & Digital Twin technology and its role in shaping thefuture of the construction industry.

**- improved social welfare**
Yes

**Explain how this benefit will be achieved as a result of this research being conducted** Through critical analysis, practical examples, and the review of existing literature, this research willbenefit by educating on the capabilities of BIM & Digital Twin technology and its role in shaping thefuture of the construction industry.

**- improved individual wellbeing**
Yes

**Explain how this benefit will be achieved as a result of this research being conducted**
More sustainable buildings.

**- Other**
No

# 15 Risks

**The following types of risks (either short or long term) may occur due to participation in this project:**

**- physical (including injury, illness, pain)**
No

**- psychological (including feelings of worthlessness, distress, guilt, anger or fear related, forexample, to disclosure of sensitive or embarrassing information)**
No

**- social (including damage to social networks or relationships with others; discrimination inaccess to benefits, services, employment or insurance; social stigmatisation)**
No

**- devaluation of personal worth (including being humiliated, manipulated or in other waystreated disrespectfully or unjustly)**
No

**- economic (including the imposition of direct or indirect costs on participants)**
No

**- legal (including discovery and prosecution of criminal conduct)**
No

**- inconvenience (including taking the time to fill in the survey, participate in an interview etc)**
Yes

**Expand on this risk and its relevance to your project. Outline arrangements you will put inplace to minimise this risk**

Minimal risk. Risk analysis completed.

**- discomfort (including minor side-effects of medication, the discomforts related to measuringblood pressure, and anxiety induced by an interview)**
No

**- Other**
No

**Would any of the risk factors that you have identified above be potentially considered to be more than low risk factors?**

No

# 16 Project Team

**What is the level of risk for the project team?**

Low

**Outline the strategies that you have in place to address the level of risk to the project team?**

Risk analysis -

ensure surveys are kept short (limited to 5-10 questions to reduce inconvenience to participants)

# 17 Data collection and accessData Collection

**Data Collection considerations**

none of the above apply to this project

*The following options were available for selection:*

- ***collection of data in a rural and remote setting***
- ***travelling overseas to collect data***
- ***physiological or psychological testing of participants***
- ***none of the above apply to this project***

# 18 Data Access

**Will any research data be made available or shared via open access, restricted access, mediated access or as metadata only?**

No

**Provide further details about the data that will be made available/shared, and via whatmethod.**

To protect the privacy of individuals participating in the survey questions

**Will any individual or organisation external to UniSQ (i.e. a third party) have access to theresearch data during the project?**

No

# 19 Other Considerations UniSQ Course projects

**Are you a course leader intending to undertake this project as a UniSQ Course project?**

No

**Upload any relevant or supporting documentation**

# 20 Course information

## Permissions to access participants

**Are you required to obtain permission to access your group/s of participants?**

No

**Does your project include the recruitment of UniSQ staff or students?**

No

# 21 Evidence of approval/endorsement

# Monitoring your project

**What will you do in cases where unexpected events or emergencies occur as a result of participation in this project?**

Progress report

Amendments to approvals prior to implementing changes

Advise of any complaints

Report any adverse events or unexpected outcomes.

Ensure supervisors and the ethics office are informed of any expected events or emergencies that occur.

# 22 Communication of findings Publishing your findings

**Method of Communication**

research thesis

**If providing individual test results to each participant, what arrangements will be in place todeal with participant's distress in the case of adverse results?**

N/A

*The following options were available for selection:*

- ***research thesis***
- ***journal article***
- ***book or book chapter conference presentation (not published in a proceedings)***
- ***open access dataset***
- ***published report to organisation or community group***
- ***private report to organisation or community group***
- ***report to all participants***
- ***executive summary of results***
- ***individual test results to each participant (eg from physiological or psychological testing)***
- ***media (eg article in "The Conversation")***
- ***creative output***
- ***other***

**Will the participants and/or other interested stakeholders be able to access these findings and/or request a copy of the summary of results?**

Yes

**Provide further information with regards to accessibility of these results**

Provide executive summary to the participants

**When disseminating your findings, will participants be**

non-identifiable (i.e. no individual or organisation can be identified)

*The following options were available for selection:*

- ***non-identifiable***
- ***re-identifiable***
- ***identifiable or presented in a manner which may allow some participants to be identified.***
- ***other***

# 23 Participant - Group 1

**Group 1 name**

Group 1

**How many individual participants are expected to be recruited in this group?**

10

**Describe the participants in this group:**

Work Colleagues

**Where will this group of participants be recruited from?**

Work relationships/Colleagues

**Will any potential participants in this group be under 18?**

No

**Is there a pre-existing relationship between the participants and anyone involved in recruiting and/or collecting data from this group**

Yes

**What is the nature of the pre-existing relationship and will you be implementing any special precautions if these are unequal pre-existing relationships**

Co-workers.

Equal Relationship.

**Do these participants have any cultural needs?**

No

# 24 Recruitment of Participants

**How will you recruit participants?**

Email

**Indicate how you will obtain the contact details of these participants**

from participants themselves

**If from private or third party, or other source, provide further information around the source**

**Provide details of who will be inviting participants and further explain the method/s they willuse, as identified above.**

Survey participants will be invited to the survey through the use of a third party such as HR.

**Will you be offering payment or any other incentives to this group of participants?**

No

**Recruitment information**

# 25 Data Collection

**Method of collection**

survey/questionnaire

**Provide further details for this data collection method**

Email sent through Outlook with Survey Questions.

Qualitative answers returned.

**Are particular qualifications required to use this method?**

No

**Will you be recording participants?**

No

**Documents you have referred to for this group which may include: Survey instrument, question list, protocol for administering a substance**

# 26 Data Collection documentation specific to this group Participation

**What are you asking participants in this group to do or what is to be done to them?**

Survey Questions asked.

**How much time are you asking of participants in this group and when will this time berequired?**

30minutes

**Specifically, where will this data be collected?**

Online

**Does the research involve measures or procedures that are diagnostic or indicative of any medical or clinical condition, or any other situation of concern?**

No

**Will a Participant Information Sheet be provided to the participants?**

Yes

**It is strongly recommended that you use the UniSQ template which has all required fields including purpose, risks, benefits and referral services.**

# 27 Participant Information Sheet

**If you are not using a Participant Information Sheet (or similar), how will this project becommunicated to participants?**

**Will participants be referred to support services?**

No

# 28 Consent

**Are these participants able to consent for themselves?**

Yes

**Will participants be fully informed about the true nature of the research?**

Yes

# 29 Consent type

**How will you obtain consent from this group of participants?**

Implied consent

# 30 Participant Consent Type - Group 1Implied consent

**How you will gauge that consent to participate has been implied by this group of participants?**

Voluntary participation.

Participants are being provided with a participation information sheet that outlines the details of the project. Potential participants can contact the research team if they have any questions.

# 31 Participant - Group 2

**Group 2 name**

Student Peers

**How many individual participants are expected to be recruited in this group?**

5

**Describe the participants in this group:**

Students completing the same degree

**Where will this group of participants be recruited from?**

Online correspondence

**Will any potential participants in this group be under 18?**

No

**Is there a pre-existing relationship between the participants and anyone involved in recruiting and/or collecting data from this group**

Yes

**What is the nature of the pre-existing relationship and will you be implementing any special precautions if these are unequal pre-existing relationships**

Equal

**Do these participants have any cultural needs?**

No

# 32 Recruitment of Participants

**How will you recruit participants?**

Email

**Indicate how you will obtain the contact details of these participants**

from participants themselves

**If from private or third party, or other source, provide further information around the source**

N/A

**Provide details of who will be inviting participants and further explain the method/s they willuse, as identified above.**

I will be inviting participants through an email

**Will you be offering payment or any other incentives to this group of participants?**

No

**Recruitment information**

# 33 Data Collection

**Method of collection**

survey/questionnaire

**Provide further details for this data collection method**

Questionnaire/Survey. Word Document Distributed online

**Are particular qualifications required to use this method?**

No

**Will you be recording participants?**

No

**Documents you have referred to for this group which may include: Survey instrument, question list, protocol for administering a substance**

# 34 Data Collection documentation specific to this group Participation

**What are you asking participants in this group to do or what is to be done to them?**

Completing a thought-provoking questionnaire

**How much time are you asking of participants in this group and when will this time berequired?**

30minutes

**Specifically, where will this data be collected?**

Online Correspondence

**Does the research involve measures or procedures that are diagnostic or indicative of any medical or clinical condition, or any other situation of concern?**

No

**Will a Participant Information Sheet be provided to the participants?**

Yes

**It is strongly recommended that you use the UniSQ template which has all required fields including purpose, risks, benefits and referral services.**

# 35 Participant Information Sheet

**If you are not using a Participant Information Sheet (or similar), how will this project becommunicated to participants?**

**Will participants be referred to support services?**

No

# 36 Consent

**Are these participants able to consent for themselves?**

Yes

**Will participants be fully informed about the true nature of the research?**

Yes

# 37 Consent type

**How will you obtain consent from this group of participants?**

Implied consent

# 38 Participant Consent Type - Group 2 Implied consent

**How you will gauge that consent to participate has been implied by this group of participants?**

Participation.

# 39 Participant - Group 3

**Group 3 name**

Contractors working in AEC Field

**How many individual participants are expected to be recruited in this group?**

10

**Describe the participants in this group:**

Contractors

**Where will this group of participants be recruited from?**

Online Correspondence

**Will any potential participants in this group be under 18?**

No

**Is there a pre-existing relationship between the participants and anyone involved in recruiting and/or collecting data from this group**

No

**Do these participants have any cultural needs?**

No

# 40 Recruitment of Participants

**How will you recruit participants?**

Email

**Indicate how you will obtain the contact details of these participants**

from participants themselves

**If from private or third party, or other source, provide further information around the source**

N/A

**Provide details of who will be inviting participants and further explain the method/s they willuse, as identified above.**

I will be sending an email to various contractors. Contractors are not known to the researcher

**Will you be offering payment or any other incentives to this group of participants?**

No

**Recruitment information**

# 41 Data Collection

**Method of collection**

survey/questionnaire

**Provide further details for this data collection method**

Questionnaire/Survey

**Are particular qualifications required to use this method?**

No

**Will you be recording participants?**

No

**Documents you have referred to for this group which may include: Survey instrument, question list, protocol for administering a substance**

# 42 Data Collection documentation specific to this group

# Participation

**What are you asking participants in this group to do or what is to be done to them?**

Survey/Questionaire

**How much time are you asking of participants in this group and when will this time berequired?**

30 minutes

**Specifically, where will this data be collected?**

Online Correspondence

**Does the research involve measures or procedures that are diagnostic or indicative of any medical or clinical condition, or any other situation of concern?**

No

**Will a Participant Information Sheet be provided to the participants?**

Yes

**It is strongly recommended that you use the UniSQ template which has all required fields including purpose, risks, benefits and referral services.**

# 43 Participant Information Sheet

**If you are not using a Participant Information Sheet (or similar), how will this project becommunicated to participants?**

Email Correspondence

**Will participants be referred to support services?**

No

# 44 Consent

**Are these participants able to consent for themselves?**

Yes

**Will participants be fully informed about the true nature of the research?**

Yes

# 45 Consent type

**How will you obtain consent from this group of participants?**

Implied consent

# 46 Participant Consent Type - Group 3 Implied consent

**How you will gauge that consent to participate has been implied by this group of participants?**

Participating in survey/questionnaire.

# 47 Participant - Group 4

**Group 4 name**

Teacher Survey

**How many individual participants are expected to be recruited in this group?**

5

**Describe the participants in this group:**

Examiners/Teachers

**Where will this group of participants be recruited from?**

Online Correspondence

**Will any potential participants in this group be under 18?**

No

**Is there a pre-existing relationship between the participants and anyone involved in recruiting and/or collecting data from this group**

No

**Do these participants have any cultural needs?**

No

# 48 Recruitment of Participants

**How will you recruit participants?**

Email

**Indicate how you will obtain the contact details of these participants**

from participants themselves
from a public domain source

**If from private or third party, or other source, provide further information around the source**

N/A

**Provide details of who will be inviting participants and further explain the method/s they willuse, as identified above.**

I will be sending an email to potential participants

**Will you be offering payment or any other incentives to this group of participants?**

No

**Recruitment information**

# 49 Data Collection

**Method of collection**

survey/questionnaire

**Provide further details for this data collection method**

Survey/Questionnaire

**Are particular qualifications required to use this method?**

No

**Will you be recording participants?**

No

**Documents you have referred to for this group which may include: Survey instrument, question list, protocol for administering a substance**

# 50 Data Collection documentation specific to this group Participation

**What are you asking participants in this group to do or what is to be done to them?**

Complete a survey -

Read Email

Open Attachment

Respond to the questions

Save the attachment

Respond to the email by attaching the word document

**How much time are you asking of participants in this group and when will this time berequired?**

30minutes

**Specifically, where will this data be collected?**

Online Correspondence

**Does the research involve measures or procedures that are diagnostic or indicative of any medical or clinical condition, or any other situation of concern?**

No

**Will a Participant Information Sheet be provided to the participants?**

Yes

**It is strongly recommended that you use the UniSQ template which has all required fields including purpose, risks, benefits and referral services.**

# 51 Participant Information Sheet

**If you are not using a Participant Information Sheet (or similar), how will this project becommunicated to participants?**

**Will participants be referred to support services?**

No

# 52 Consent

**Are these participants able to consent for themselves?**

Yes

**Will participants be fully informed about the true nature of the research?**

Yes

# 53 Consent type

**How will you obtain consent from this group of participants?**

Implied consent

# 54 Participant Consent Type - Group 4 Implied consent

**How you will gauge that consent to participate has been implied by this group of participants?**

By reading the information sheet and participating in the survey

# 55 Participant - Group 5

**Group 5 name**

Architects

**How many individual participants are expected to be recruited in this group?**

2

**Describe the participants in this group:**

Architects working in AEC industry

**Where will this group of participants be recruited from?**

Online Correspondence

**Will any potential participants in this group be under 18?**

No

**Is there a pre-existing relationship between the participants and anyone involved in recruiting and/or collecting data from this group**

Yes

**What is the nature of the pre-existing relationship and will you be implementing any special precautions if these are unequal pre-existing relationships**

Worked with prior

**Do these participants have any cultural needs?**

No

# 56 Recruitment of Participants

**How will you recruit participants?**

Email

**Indicate how you will obtain the contact details of these participants**

from participants themselves

**If from private or third party, or other source, provide further information around the source**

N/A

**Provide details of who will be inviting participants and further explain the method/s they willuse, as identified above.**

Email

**Will you be offering payment or any other incentives to this group of participants?**

No

**Recruitment information**

# 57 Data Collection

**Method of collection**

survey/questionnaire

**Provide further details for this data collection method**

Survey/Questionnaire

**Are particular qualifications required to use this method?**

No

**Will you be recording participants?**

No

**Documents you have referred to for this group which may include: Survey instrument, question list, protocol for administering a substance**

# 58 Data Collection documentation specific to this group Participation

**What are you asking participants in this group to do or what is to be done to them?**

Complete a survey -

Read Email

Open Attachment

Respond to the questions

Save the attachment

Respond to the email by attaching the word document

**How much time are you asking of participants in this group and when will this time berequired?**

30 minutes

**Specifically, where will this data be collected?**

Online Correspondence

**Does the research involve measures or procedures that are diagnostic or indicative of any medical or clinical condition, or any other situation of concern?**

No

**Will a Participant Information Sheet be provided to the participants?**

Yes

**It is strongly recommended that you use the UniSQ template which has all required fields including purpose, risks, benefits and referral services.**

# 59 Participant Information Sheet

**If you are not using a Participant Information Sheet (or similar), how will this project becommunicated to participants?**

**Will participants be referred to support services?**

No

# 60 Consent

**Are these participants able to consent for themselves?**

Yes

**Will participants be fully informed about the true nature of the research?**

Yes

# 61 Consent type

**How will you obtain consent from this group of participants?**

Implied consent

# 62 Participant Consent Type - Group 5Implied consent

**How you will gauge that consent to participate has been implied by this group of participants?**

By agreeing to participate in survey

# 63 Additional Documentation

**Do you need to upload any additional documentation?**

No

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