A STUDY ON ORGANIZATIONAL ATTRIBUTES AND STRATEGIES FOR PRODUCING ACCURATE DIGITAL TWINS IN THE ARCHITECTURE, ENGINEERING AND CONSTRUCTION (AEC) INDUSTRY

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ABSTRAK

Industri Senibina, Kejuruteraan dan Pembinaan (AEC) sedang mengalami pergerakan transformatif ke arah digitalisasi melalui pengadaptasian teknologi kembar digital (digital twins) untuk memacu industri ke hadapan. Walaubagaimanapun, kekurangan kemajuan teknologi telah menyebabkan wujudnya cabaran yang ketara dalam penghasilan kembar digital. Cabaran ini adalah berpunca dari kekurangan infrastruktur teknologi serta pengadaptasian teknologi yang lemah didalam industri ini. Tambahan lagi, keengganan untuk berubah dari kaedah kerja pembinaan konvesional yang sedia ada juga telah menghalang proses penghasilan kembar digital. “Digital twins” merupakan replika virtual aset dan sistem fizikal yang berpotensi untuk merevolusikan kaedah sesebuah organisasi AEC dalam merancang, membina, dan menguruskan projek pembinaan. Kajian ini secara metodologi bertujuan untuk mengenalpasti faktor organisasi berserta strategi yang diperlukan untuk penghasilan kembar digital yang tepat bagi projek pembinaan, dengan menyediakan pemahaman yang lebih mendalam dan tepat mengenai pengeluaran kembar digital untuk industri Senibina, Kejuruteraan dan Pembinaan. (AEC). Untuk mencapai matlamat ini, tiga objektif ialah: (1) untuk mengenal pasti faktor dan strategi organisasi yang sediaada di dalam tatakerja industri AEC, (2) untuk menentukan ciri-ciri faktor dan strategi utama organisasi, dan (3) untuk mengkaji hubungan struktur-struktur asas faktor organisasi dan strategi untuk menghasilkan kembar digital yang tepat bagi projek pembinaan. Fasa kualitatif awal melibatkan temuduga bersama 20 ahli profesional BIM (Building Information Modeling) Malaysia yang terdiri daripada pembantu pengurus BIM kepada pengarah organisasi, yang mempunyai pengetahuan tentang kembar digital. Penemuan kajian menekankan tiga tema untuk faktor organisasi (Manusia, Proses dan Teknologi) dan juga strategi (Polisi, Aliran kerja and Teknologi). Maklumat yang diperolehi daripada temuduga, bersama-sama dengan tinjauan 255 artikel literatur sistematik yang komprehensif berserta satu kajian rintis, telah menggariskan struktur untuk fasa kuantitatif seterusnya. Ini melibatkan pengedaran soalan soal selidik kepada pelbagai ahli profesional dalam sektor pembinaan yang lebih luas dalan konteks industri Senibina, Kejuruteraan dan Pembinaan Malaysia. Hasilnya ialah 21 faktor dan 30 strategi dari kedua-dua literatur dan temuduga ahli profesional dalam sektor pembinaan. Teknik analisis data yang teliti juga telah dijalankan. Teknik penarafan skor purata menghasilkan 11 faktor organisasi dan 20 strategi yang utama untuk menghasilkan kembar digital yang tepat bagi projek pembinaan. Analisis faktor eksploratif (EFA) mengklasifikasikan faktor-faktor organisasi ke dalam dua Kumpulan iaitu (kemampuan organisasi dalam kembar digital dan keperluan keupayaan teknologi) manakala strategi ke dalam tiga kumpulan iaitu (kumpulan daya saing dan pelaburan organisasi, pengurusan tenaga kerja organisasi dan latihan, serta kebolehan pengurusan organisasi). Enam hipotesis telah diformulasikan dan tiga hipotesis telah disokong. Kesimpulannya, kajian ini memberikan bukti baru kepada industri professional AEC dalam pengambilan keputusan yang berinformatif untuk penghasilan kembar digital yang tepat untuk projek pembinaan, membuka tahap baru kecekapan, kesinambungan, dan inovasi dalam industri Senibina, Kejuruteraan dan Pembinaan (AEC).

ABSTRACT

The Architecture, Engineering and Construction (AEC) industry is experiencing a transformative shift towards digitalization, with the adoption of digital twin technology at its forefront. However, lacking technological advancement has caused the existence of a significant challenge concerning the production of digital twins. This challenge primarily stems from a need for more technological infrastructure and a low technological uptake within the industry. Moreover, the reluctance to change from current conventional construction working method has also hindered the production of digital twins. Digital twins, virtual replicas of physical assets and systems, have the potential to revolutionize how AEC organizations design, construct, and manage construction projects. The research aims to analyze the relationship between the organizational attributes and strategies to successfully produce accurate digital twins of construction projects within the AEC industry. To achieve the aim, the three objectives are: (1) to identify the organizational attributes and strategies in current AEC practices, (2) to determine key organizational attributes and strategies, and (3) to analyze the relationship of underlying constructs of organizational attributes and strategies to produce accurate digital twins of construction projects. The initial qualitative phase involved open-ended interviews with 20 Malaysia Building Information Modeling (BIM) professionals with digital twin knowledge, from BIM assistant managers to organization directors. The findings underlined three themes for organizational attributes (People, Process, and Technology) and strategies (Policy, Workflow, and Technology). The information gained from interviews, a comprehensive systematic literature review of 255 articles and a pilot study outlined the structure for the subsequent quantitative phase. This entailed distributing questionnaires to a broader array of construction professionals in Malaysia AEC industry. The outcome extracted 21 attributes and 30 strategies from the literature and the construction professionals' interviews. Meticulous data analysis techniques were conducted. The mean score ranking technique yielded 11 key organizational attributes and 20 key strategies for producing accurate digital twins of construction projects. The Exploratory Factor Analysis (EFA) classified factors for organizational attributes into two groups (organizational digital twin capabilities and technological capabilities requirements) and organizational strategies into three groups (organizational competitiveness and investments, organizational workforce management and training, and organizational management capabilities). Six hypotheses were formulated, and three hypotheses were supported from the Partial-Least Structural Equation Modeling (PLS-SEM) analysis. In conclusion, this research provides new evidence to AEC industry professionals for well-informed decision-making in producing accurate digital twins of construction projects, unlocking new levels of efficiency, sustainability, and innovation in the AEC industry.

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LIST OF ABBREVIATIONS

AEC	Architecture, Engineering and Construction
DT	Digital Twin
BIM	Building Information Modeling
PLS-SEM	Partial Least-Squares Structural Equation Modeling
CIDB	Construction Industry Development Board
EFA	Exploratory Factor Analysis
IMD	Institute for Management Development
SME	Small Medium Enterprises
CDR	Corporate Digital Responsibility
IoT	Internet of Things
ISO	International Organization for Standardization
AI	Artificial Intelligence
DOSM	Department of Statistics Malaysia

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CHAPTER 1

INTRODUCTION

1.1 Introduction

This chapter uncovers the definitions and potentials of digital twins in the Architecture, Engineering and Construction (AEC) industry. Further discussions, as the research expands, unfold the potential organizational attributes and strategies to produce accurate digital twins of construction projects. Nevertheless, this chapter also offers an insight into research intent and motivations, scope, significance of research, and potential applications of research findings.

1.2 Definition of terms

To facilitate the comprehension of this research, various terms are defined as listed below:

a. **Digital twins**: In this research, this term refers to replications of the physical buildings or infrastructure into a virtual replica using various sources which include sensors, drones, and building information modelling (BIM), to simulate the real-world conditions.

b. **Organizational attributes**: In this research, this term refers to attributes that influence the actions of organizations by serving as restraints and amplifiers. (Hodgson, 2004)

c. **Organizational strategies**: In this research, this term refers to the strategic process and shaping it proactively with competent personnel, open discourse on new technological options, and an allotment of potential application regions. (Weber-Lewerenz, 2021)

d. **AEC industry**: In this research, this term refers to the types of professionals involved who are the architects, engineers, draftsmen, surveyors, manufacturers, and others. (Zhang et al., 2023)

1.3 Background of study

It is known that the AEC industry presents several complexities which hinder the compatibility and simple integration of the technologies. Bhattacharya & Momaya, (2021); Oesterreich & Teuteberg, (2016) highlighted challenges that impede the compatibility and straightforward integration of technologies in the AEC industry, including complexity, uncertainty, a disjointed supply chain, short-term thinking, and organizational culture. The AEC projects are inherently complex due to the involvement of numerous stakeholders in each unique project. The risks and uncertainties associated with each project further add to these complexities.

Moreover, projects' temporary and short-lived nature poses significant challenges to advancement and innovation. Companies need help recruiting skilled workers, establishing networks with contractors and suppliers, and effectively transferring knowledge within and across projects in the industry. The industry's culture is often characterized by a hesitant and sceptical attitude across the construction network (Aiyetan & Dillip, 2018). While other sectors have integrated product and process innovations at the heart of their operations, the engineering and construction industry must embrace technological advancements (Bhattacharya & Momaya, 2021; Chan & Ejohwomu, 2018; Hasan et al., 2017). Consequently, this has led to a widespread stagnation in productivity and efficiency levels.

In the current context of digitalization transformation in Malaysia, as highlighted in the Twelfth Malaysia Plan 2021-2025 (12MP), there are still obstructions to embracing digitalization, including a lack of technological infrastructure, disorganized democratic accountability, insufficient capacity and capability, and the inability to access digital services at an affordable rate. These hurdles have delayed the digital economy's expansion and exacerbated the digital gap. The modernization of the economy has been hindered by low technological uptake, inadequate investment in research and development (R&D), commercialization, and innovation, as well as skilled workforce shortages.

Additionally, local digital solution providers need more growth capabilities, particularly in cloud computing services, preventing these digital service providers from satisfying domestic demands and engaging with global competitors. Subsequently, low investments in cable landing stations also slowed down the widespread availability of fixed broadband to satisfy the rising demand for high-speed internet, particularly in data centres.

On the other hand, within Malaysia's construction industry context, the 12MP also highlighted issues involving digitalization in the construction industry. Malaysia's construction industry needs to gain knowledge and globalization readiness, as digitalization is still in its infancy. Lacking awareness of global market access and an inability to change and localize material for intended global markets have manifested in a weak worldwide digital presence. In addition, a lack of motivation to go global, inadequate product and service branding, and unappealing products have limited Malaysian construction businesses' ability to penetrate foreign markets.

Construction 4.0 Strategic Plan (2021-2025), on the other hand, emphasized that the development of the construction industry would rely heavily on the inclusion of new technologies and innovative techniques. The delivery of projects will alter due to the implementation of innovative new technologies and procedures. As the need for complex and interdependent projects increases, the construction industry must increasingly leverage new technology and innovative approaches to give better value. Technical acceptability is one of the key aspects that will substantially affect construction processes and productivity.

Department of Statistics Malaysia (2023) reported in 2023 that the construction sector's national Gross Domestic Product (GDP) rose 9.6% year-over-year, reaching RM 33.4 billion in the third quarter of 2023, up from RM 32.4 billion in the second quarter. The sector's work value grew 3.4% compared to the previous quarter. This increase in GDP indicates a growing trend in Malaysia's construction industry. The industry is expected to see further improvements in operations and reduced reliance on low-skilled labour, thanks to the integration of digital twin technology. Digital twins in construction are set to significantly enhance human involvement throughout the project lifecycle and management, leading to more efficient and productive operation and maintenance of structures.

Furthermore, the 12MP underlined that delivering upskilling and reskilling programs at educational institutions and organizations is equally important. This contributes to educating, training, and producing digital twin professionals. Consequently, the establishment of digital twin professionals helps to enhance skilled workers' employment rates following the 12MP from 28.9% (2020) to 35% (2025), and this also helps Malaysia to achieve the need to be recognized as a developed nation with targeted 45% minimum skilled workforce employment rates by the year 2030.

1.4 Motivation of study

1.4.1 Low digital adoption

The 12MP stated that digital technologies alter every industry, presenting firms with new possibilities and problems. The 12MP also highlighted that even though Malaysia was rated 26th out of 63 nations in the Institute for Management Development's (IMD) World Digital Competitiveness Ranking 2020, the degree of digitalization within the sector, particularly among SMEs, still needs to be improved. Digital adoption needs to be higher among small and medium businesses due to a need for more understanding and expensive investment. This is exacerbated by the lack of a mechanism to address e-commerce cross-border disputes.

1.4.2 Lack of readiness

According to Shahzad et al., (2022), the construction industry must accept new technologies and procedures in its working methods, which pertains to the readiness of AEC construction professionals to produce digital twins for building projects. Shahzad et al., (2022) highlighted several challenges faced by the construction industry, such as low investment in new technologies, reluctance among professionals, lack of support from upper management, insufficient evidence of the benefits of digitalization, companies' reluctance to take risks with innovations, and the unpredictability of supply chains and project teams. The Construction 4.0 Strategic Plan (2021-2025) pointed out that the Malaysian construction industry has hesitated over the past five decades to fully adopt the latest technological and innovative advancements, leading to a plateau or even a decrease in productivity.

1.4.3 Improve construction industry competency

By improving the quality, productivity, and modernity of Malaysia's construction industry is essential for fostering a sustainable sector. This advancement will enable the industry to successfully manage complex domestic projects and compete in large international ventures. However, the construction industry faces numerous challenges that must be identified and addressed (Dehdasht et al., 2021; Aziz & Hafez, 2013). The construction industry is plagued by cost overruns, time delays, fragmentation, hazards, and inefficiency (Dehdasht et al., 2021; Nahmens & Ikuma, 2011). Thus, Malaysia construction industry still needs to accelerate the effectiveness to compete with the global players and improve the profits of the domestic market (Dehdasht et al., 2021; Razak Bin Ibrahim et al., 2010).

In addition, human resources and labour productivity are the main challenging factors in the construction industry because they have a critical role in competitiveness to attain goals and meet the stakeholder propositions (Dehdasht et al., 2021). The key factors affecting construction labour productivity include insufficient materials at the project site, delayed payments to suppliers due to financial issues, which in turn hinder material delivery, project delays caused by frequent order changes from consultants, late issuance of construction drawings by consultants, and poor coordination of site activities due to inadequate site management by contractors (Dehdasht et al., 2021; Abdul Kadir et al., 2005). Changes made to resolve current issues in AEC practices are required not only to enhance the capabilities of the current workforce but also to increase the workforce's diversity, and the capacity to generate new opportunities and economic growth.

The overall performance rate will increase by boosting the construction industry's work efficiency. This includes the work's quality and the labour's efficiency to meet the deadline. Productivity performance measurement covers a system's methods, efforts, and efficiency to determine its performance as per the Construction 4.0 Strategic Plan (2021-2025). By incorporating digital twin technology in the construction industry could lead to more effective collaborations and a higher likelihood of successful, efficient project completions. Integrated technology, which combines multiple technological solutions, can enhance productivity and success rates, and offer long-term advantages throughout a project's lifecycle. Such a transformation would rely heavily on advanced technologies, robust infrastructure systems, and secure and reliable security networks..

1.5 Problem statement

Lacking technological advancement has caused the existence of a significant challenge concerning the production of digital twins. This challenge primarily stems from a need for more technological infrastructure and a low technological uptake within the industry. As the AEC industry evolves, it must increasingly leverage new technology and innovative approaches to deliver better value. Moreover, Qi et al., (2021) emphasized that conventional databases cannot manage the rising complexity and amount of digital twin data from many sources. This hampers the incorporation of varied models with different parametric values, geographical values, and temporal scales into the digital twin. The reliance on traditional methods, without the inclusion of new technologies and innovative techniques, hinders the industry's capacity to create and implement digital twins efficiently. This scenario necessitates a paradigm shift where the delivery of projects will alter significantly by allowing for a more integrated and technologically advanced approach to the production and utilization of digital twins. According to Turner et al., (2021), the global construction industry has used digital technology in recent years for operational and productivity improvements. Broo & Schooling (2023) stated that digital twins allow the gathering and integration of data to improve the design, building, operations, and maintenance of physical infrastructure assets, hence promoting sustainable construction development.

Moreover, a skilled workforce needs to contribute to the production of digital twins in the AEC industry. This challenge is about the immediate need for more professionals and the long-term sustainability of skill development in this area. The upskilling and reskilling programs at educational institutions and organizations play a pivotal role in this context for educating and training the next generation of digital twin professionals. However, the effectiveness of these programs is crucial to prepare individuals adequately for the complexities of digital twin production. This situation highlights the need for a more focused and robust approach to developing these programs. It underscores the importance of aligning educational objectives with industry requirements to produce a workforce capable of handling the sophisticated demands of digital twin projects in the AEC industry. The increase in the skilled workforce in digital twin projects will facilitate digital transformation and provide valuable decision assistance in enhancing structural management, reliability, and sustainability of construction projects (Love & Matthews, 2019).

Furthermore, globalization challenges in digital twins are primarily due to a deficit in knowledge and globalization readiness in the AEC industry. This situation has left the digitalization of the construction industry still in its infancy due to a notable lack of awareness regarding access to global markets, compounded by an inability to adapt and localize materials for intended global audiences. These factors have culminated in a weak worldwide digital presence for the industry. Additionally, there needs to be more motivation within the AEC industry to pursue global expansion, which is further exacerbated by inadequate product and service branding.

Nonetheless, Cecconi et al., (2017) identified the need for agreed standards as another contributing problem towards the organizational readiness of digital twins' usage in facilities management. These issues underscore the urgent need for a strategic shift in the AEC industry towards embracing globalization and enhancing digital twin production to stay competitive and relevant in the evolving global market. Seaton et al., (2022) stated that digital twins not only offer significant benefits and advantages in optimizing results but also have several performance indicators, which include time, cost, environmental impact, social outcomes under designer control, cost management by professionals and construction managers, thus boosting globalization readiness in digital twins' productions.

Therefore, amid current challenges related to digitalization in the Malaysian construction industry, this research bolsters the necessity of analyzing the relationship between organizational attributes and strategies needed to produce accurate digital twins towards better working optimization and work productivity in the AEC industry.

Nevertheless, this research also offers a broad understanding that's relevant to digital twins' productions in construction projects.

1.6 Research questions

Based on the problem statement and motivation of the research, the following three (3) research questions were developed:

i. What are the organizational attributes and strategies involved in current AEC practices to produce accurate digital twins of construction projects?

ii. What are the key organizational attributes and strategies to produce accurate digital twins in the construction industry?

iii. What is the relationship between underlying constructs of organizational attributes and strategies to produce accurate digital twin construction projects?

1.7 Aims and objectives

This research aims to analyze the relationship between the organizational attributes and strategies to produce accurate digital twins of construction projects successfully. Thus, to achieve the aim, three (3) research objectives were identified:

i. To identify the organizational attributes and strategies in current AEC practices to produce accurate digital twins of construction projects.

ii. To determine key organizational attributes and strategies to produce accurate digital twins of construction projects.

iii. To analyze the relationship of underlying constructs of organizational attributes and strategies to produce accurate digital twins of construction projects.

1.8 Scope of research

The scope of this research is discussed as follows:

i. AEC industry: Pre-construction stage

In the AEC industry, the construction project development stages generally consist of pre-construction, during-construction and post-construction stages. This research is limited to the pre-construction stage which involved the design development, scheduling, and cost estimations. According to research by Bakar & Embi (2016), the pre-construction phase is one of the crucial stages that impact the success of a building project. Additionally, Bakar & Embi (2016) also noted that several academics have previously underlined the need for effective planning methodologies and work coordination between the designer and contractor at the commencement of the life cycle of a building project.

According to Nisa Lau et al., (2018), the detailed data necessary in the pre-construction phase, especially for current data modelling and site analysis, should be adequate to guarantee that severe risks cannot be anticipated with acceptable certainty. Before beginning work on a project, the architect and contractor must gather all necessary information needed throughout the project. Hence, this research was limited to the production of digital twins during the pre-construction stage because this stage of construction is vital for ensuring that a construction project is well-planned, financially viable, and legally compliant. It sets the stage for successful project execution by addressing potential issues early and ensuring that all stakeholders are aligned on the project's objectives and plans. Consequently, this anticipates the need to undertake this research at this construction phase.

ii. Target group of population

This research focuses on the organizations rather than the projects. The organizations chosen are those from AEC professionals, mainly from architectural, engineering and construction experts. However, the nature of the business process will be documented so that the context of digital twins can be comprehended and any bias in data gathering can be identified.

This research gathers two (2) primary data sets: i) the attributes needed to produce digital twins within the organizations and ii) the strategies required to achieve them. Data is collected to depict organization interactions, information sharing, and communications to produce a digital twin. Therefore, it necessitates a respondent with the capacity to comprehend the operations of digital twins. For open-ended interviews, assistant managers to directors of organizations who have knowledge in Building Information Modelling (BIM) and have the capacity to understand the operations to produce accurate digital twins were selected as respondents due to their authority to revise the company's policy, direction, and objectives. Meanwhile, for the questionnaire survey, respondents from AEC professionals were selected.

iii. Field of study: Organizational assets, people, activities, and their links

Conceptually, this research concentrates on the attributes and strategies that organizations must possess to produce accurate digital twins. According to Parmar et al., (2020), the data from organizational assets, people, activities, and their links may be merged to create a complete digital representation of an organization's digital twin. Consequently, it is essential to investigate the organizational attributes and strategies involved and the relationship between major attributes and potentially significant strategies.

1.9 Significance of research

1.9.1 Novel theories and new findings

Achieving the research aims and objectives will provide the following novel theories and new findings:

i. Novel theories:

This research may generate an analysis describing the relationships between the organizational attributes and strategies in producing accurate digital twins for the construction industry in Malaysia. This will prepare our Malaysia AEC industry professionals to create a cohesive strategy for integrating digital twin technology into their existing systems, to apply agile methodologies to the management of digital twin projects which can increase flexibility and responsiveness to changes in managing the lifecycle of digital twins effectively through regular updates and refinements based on real-time data and feedback. Moreover, this research may help to encourage a culture of learning, experimentation, and openness to new technologies that can facilitate smoother production of digital twins. Consequently, preparing Malaysia's AEC industry to become a Southeast Asia hub for digital transformation in the construction industry towards the CIDB Construction 4.0 vision.

ii. New findings:

This research may help to generate a list of organizational attributes and strategies of digital twins in the built environment for AEC industry practitioners. With the list produced, it hopes to act as the basis for developing a theoretical framework that acts as a guideline to produce accurate digital twins. These findings may help in cultivating an innovative culture, fostering interdisciplinary collaboration, making strategic technological investments, securing leadership endorsement, and standardizing processes where AEC industry practitioners can boost their capabilities in producing and utilizing digital twins, leading to improved project outcomes and operational efficiency.

1.10 Thesis organization

The thesis organization are as follows:

i. Chapter 1: Introduction focuses on the introduction section, where the background of the research will be discussed, highlighting the research problem statement and purpose, significance of research, and scope of research.

ii. Chapter 2: Literature review provides a comprehensive study of previous research related to the research topic.

iii. Chapter 3: Methodology highlights the research methods used to collect and analyze data. Note that the research methods mentioned in this section are thoroughly carried out for the research.

iv. Chapter 4: Results and discussion provide the research findings, which include all data, figures, or tables. This section also highlights the outcomes of data analysis, conclusions driven by the results and how the results are related to the research objectives. The process begins with identifying the organizational attributes and strategies to produce accurate digital twins of construction projects. Then, the key organizational attributes and strategies were distinguished. Lastly, the relationship between organizational attributes and strategies was analyzed.

v. Chapter 5: Conclusion summarizes the research findings and highlights the recommendations for future findings related to the research topic.

1.11 Summary

This chapter provides an overall summary of the whole thesis. A brief background was discussed. The problem statement was well-defined, led to the research questions, and further articulated the research aims and objectives. The significance of research was discussed to explain the importance of achieving the research objectives and, therefore, emphasizing the research contributions to the society, government, environment, industry, and academic field.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter presents numerous discussions on the main subject of the literature review. The initial segment offers contextual information on digital twins in the construction sector, encompassing terminology, the idea, and the benefits of digital twins. The subsequent phase involves a comprehensive analysis of relevant literature on organizational attributes and strategies, as these factors are essential to the research. Next, to give a basic understanding of the current state of the digital twin in the AEC industry, the difficulties in utilizing the process within the construction industry are highlighted. Meanwhile, this body of work explores the evaluation of readiness, focusing specifically on the idea, the existing model, and its components.

2.2 Digital twins

2.2.1 Definitions of digital twins

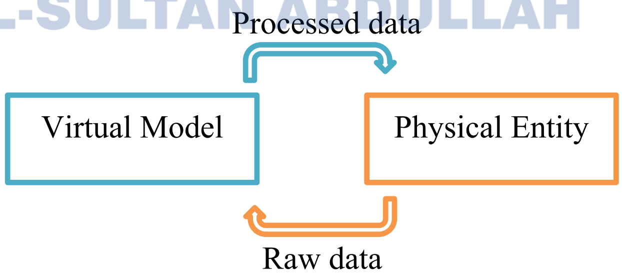

Figure 2.1 Digital twin paradigm.
Source: Agrawal et al., (2022); Grieves, (2015).

There are many definitions of digital twins. Michael Grieves initially introduced the concept of digital twins in 2003, describing them as a digital representation of a physical system. Figure 2.1 illustrates the relationship between the virtual model and physical entity in digital twin production, which was introduced by Michael Grieves.

Therefore, the term "twin" broadly embraces any prototypes that aid in replicating real operating situations (Grieves, 2015). This representation ideally encompasses all necessary information for accomplishing the task and maintains a connection with the corresponding physical system (Agrawal et al., 2022; Grieves & Vickers, 2016). Sandkuhl & Stirna (2020) stated that establishing a digital twin is done by connecting physical devices with their digital representations at their core. According to Chevallier et al., (2020) a digital twin is a collection of data representing a system's condition and evolution over time. This dataset can reflect the system's real-time status or a potential state derived from digital twin data simulations. The integration of these simulated outcomes with feedback allows for the prediction of the system's future state.

Bolton et al., (2018) defined a digital twin as a dynamic and virtual model of a physical entity, using real-time data to enhance understanding, learning, and decision-making. Meanwhile, Barricelli et al., (2019) described it as a physical or virtual entity, such as a machine or computer model, that replicates or 'twins' the existence of an actual object, process, person, or human-related characteristic. Meanwhile, Brilakis et al., (2019) characterized the digital twin as a digital representation of a physically built asset. They note that common to all definitions of a digital twin is the presence of a physical model, a digital model, and a linkage of information between the two. On the other hand, Batty (2018) defined the concept as a real-time, exact mirror image of a physical process, paralleling the physical operation.

However, a digital twin is essentially a virtual representation of a physical entity, closely linked to its physical counterpart, to reflect changes over time accurately. In the Architecture, Engineering and Construction (AEC) industry, the 'physical part' refers to tangible assets like residential and commercial buildings, hospitals, bridges, tunnels, and industrial factories. The 'digital part' is represented by a three-dimensional (3D) model that contains relevant information connected to the physical asset (Shahzad et al., 2022). This connection between the physical and virtual data is vital for advancing the AEC industry's capabilities in constructing, maintaining, and managing construction projects.

Therefore, from the author’s point of view, it can be concluded that digital twins are digital models that integrate data from various sources which include sensors, drones, and building information modelling (BIM), to simulate real-world conditions. It replicates the physical buildings or infrastructure into a virtual replica. Furthermore, with digital twins, stakeholders are enabled to visualize structures in 3D, track any changes over time, help in analyzing potential impacts and promote optimization of building operations and maintenance. Nonetheless, digital twins support decision-making throughout the lifecycle of a building, by providing a dynamic tool for monitoring, management, and forecasting.

2.2.2 Digital twins' concept

The digital twin (DT) concept has progressed since its early adoption in the aerospace sector until today, when it is widely embraced, particularly in the industrial sector, propelled by the Industry 4.0 wave. According to Macchi et al., (2018), the primary uses reported in the literature are (i) the support of studies for improved maintenance and planning, (ii) the digital mirroring of the physical entity, and (iii) the support of the decision-making phase via engineering and statistical analyzes.

According to Grieves (2015), the concept of the digital twin goes beyond the digital product since it is constructed by gathering data from several sources, such as physical, manufacturing, and operational data, together with insights from analytics software. In the past decade, this expression has been firmly associated with the concept of simulation, where the virtual and digital representation of the physical system is utilized to duplicate it for several purposes by synchronizing field-sensed data in real time. Nonetheless, Macchi et al., (2018) highlighted that digital twins enable simulations of a product's whole lifecycle for various reasons, regardless of whether they are based on a semantic data model. Simulations can aid in predicting the future behaviour of an asset, while the semantic data model enables the virtual representation to be continuously updated with real-time data.

2.2.3 Digital twins' benefits

Parmar et al., (2020) highlighted that the deployment of digital twins could result in cost savings by identifying more effective ways to conduct business through simulations of organizational processes. Competitive advantage may be obtained through simulating client purchase behaviour to understand market conditions better. The ability to rapidly model how an organization's performance would respond to a certain choice may increase its agility by using rapid, even automated, data-driven judgements.

Thiyagarajan et al., (2022) stated that embracing the digital twin for changing supply chain management and handling is a crucial investment for businesses. Thiyagarajan et al., (2022) have also emphasized the significance of the digital twin in minimizing supply chain disruptions and developing impending supply chain resilience capabilities. The end-to-end integration of the digital twin's supply chain provides supply chain integrity and real-time data sharing. Digital twin helps organizations optimize supply chain reconfigurations more quickly through real-time communications with supply chain participants.

2.2.4 Study on digital twins readiness assessment

i. Readiness assessment concept:

Digital twin production in the construction industry requires strategic planning and in-depth assessment of multiple aspects. According to Bär et al., (2018), digital transformation necessitates the identification of the current maturity state, the targeted state, and the maturity gaps that must be addressed to reach the desired maturity level. As evaluative criteria for maturity, Frederico et al., (2020) identified human resource management, IT maturity or technological gaps, and organizational procedures as factors to be considered.

In addition, Brinch (2018) noted that enterprises must cultivate capabilities for extracting value from IoT and other supply chain data sources. Thiyagarajan et al., (2022) believed that developing a business case for digital twin production and winning the support of top management is necessary for the inclusion of digital twins. Additionally, accepting the digital twin involves deploying several business systems and supply chain solutions, necessitating significant financing. In the early stages of development. Thiyagarajan et al., (2022) also mentioned that organizations should also determine the digital technologies necessary to build digital twin capabilities and partners. Nevertheless, generating awareness and a solid grasp of digital supply chain technologies is crucial for transformation success.

ii. Readiness assessment theories:

Five theories of readiness were considered, which are illustrated in Table 2.1 in section 2.2.4. Primarily, need pull and technology push models have been suggested to aid in the appropriate selection of technical capabilities as put by Agrawal et al., (2022); Di Stefano et al., (2012); Nemet (2009) and Chau & Tam (2000). The following criteria guided the selection and adaptation of each category:

- The applicability of the category within the setting of the organization.
- The applicability of the category within the context of digital twin productions.

Table 2.1 A compilation of existing theoretical framework for digital twin readiness assessment

Models/ Criteria	Mayring Content Analysis (Abusohyon et al., 2021)	Design Science Research (DSR) / Constructive Research Methodology (Agrawal et al., 2022)	Off-site Construction Digital Twin Maturity Level (OCDTML), (Wei et al., 2022)	Enterprise Modelling and Capability-Driven Development, (EM & CDD), (Sandkuhl & Stirna, 2020)	Maturity Model (CAI OEM), (Medina et al., 2021)
Description and usage	Conduct a systematic process text analysis and interpret texts inside any sort of recorded communication, including interviews, by dividing the text into content-analytical units to create the appropriate categories.	Develops practice-relevant constructs (e.g., conceptual models, procedures, frameworks, or artefacts) while ensuring conceptual rigour.	Designed to train the off-site construction industry on how to handle the digital twin technique for off-site construction. Determine the current level of maturity before establishing a strategy for enhancement. Contains five maturity levels: (Initial, Repeatable, Defined, Managed, and Optimal)	EM - consists of a group of interconnected sub-models, each of which concentrates on a particular viewpoint, such as processes, objectives, ideas, actors, rules, and IS components. CDD - encompasses Capability Design, Context Modelling, Patterns and Variability Modelling, Capability Adjustment Algorithm Specification, and the solution	A novel technique for determining maturity levels. Industry practitioners inside CAI OEMs who are looking to assess their own DTs or develop an implementation plan may find the maturity model useful. This maturity model supports scholarly discussions around contextual DT implementation approaches.

Table 2.1 Continued.

				of business matters.	
Key element and category	1. Identifying DT purpose. 2. Being aware of process. 3. Outsourcing technological part. 4. Implementing technology. 5. Creating DT presentation: 6. Assessing deviation & Improving data workflow.	A five-stage process for the development of the digitalization framework: 1.Identify problem. 2. Define research objectives. 3. Framework design and development. 4. Demonstration and assessment of framework. 5. Test the framework's effectiveness Need pull: Business driver. focuses on the business strategy that drives technology implementation. Technology push: highlights the necessity to adapt organizational strategies to the development of technical capacities.	MATURITY Technology: Hardware Network Software People: Human capability Project team Process: Work process Infrastructure (data storage, data usage and data collection) Site Processes: Data Structure Data Inflow Decision Making Data Outflow	<u>EM&CDD</u>: 1. Modelling and model management 2.Adaptation and modification 3.Continuous lifecycle management <u>CDD</u> application with a piece of a capability model - modelling components for objectives, capabilities, and context.	Analytical capability Model update frequency Data collection frequency Modelling scope Execution of a decision Lifecycle synchronisation Level of DT personalization Impact on business level Operational data accessibility Phase of application
Assessment method	Interview, questionnaire	Ethnographic action research study, literature review, interview, case study	Literature review, questionnaire interview with ACQbuilt	Literature study, descriptive case study	Literature study
Status	A start-up in the maritime industry: Digital-OMT.	Research prototype	Research prototype	Research prototype	Research prototype
Can be used for digital twins?	Yes, however it must be modified before being used to evaluate an organization's digital twin readiness.	Yes, however it must be modified before being used to evaluate an organization's digital twin readiness.	Yes, however it must be modified before being used to evaluate an organization's digital twin readiness.	Yes, however it must be modified before being used to evaluate an organization's digital twin readiness.	Yes, however it must be modified before being used to evaluate an organization's digital twin readiness.

With reference to Table 2.1 in section 2.2.4, i) people, ii) technology, and iii) process are the three (3) primary contributors to the production of digital twins. For the

‘People’ factor, key elements are mentioned by Abusohyon et al., 2021 which are identifying the digital twin purpose, being aware of the process, implementing technology and outsourcing the technological part. Additionally, Wei et al., 2022 also highlighted the importance of human capability and project teams. The key elements for the 'Technology' factor as mentioned by Wei et al., 2022 are hardware, software, and network. Agrawal et al., 2022 also emphasized the technology push where it provides the necessity to adapt organizational strategies to the development of technical capacities. Moreover, Medina et al., 2021 also stated that the maturity model for digital twin personalization is crucial for digital twin productions. Meanwhile, in the 'Process' factor, the key elements are work process, operational data accessibility and infrastructure, which includes data storage, data usage and data collection as stated by Wei et al., 2022. On the other hand, Sandkuhl & Stirna, 2020 highlighted on importance of modelling management, adaptation and modification and continuous lifecycle management. Further assessment and synthesis will be deliberated in Chapter 5 to connect the logic of the gathered data with literature validation and personal interpretation, as well as to prevent duplication of the topic. As a result, the uses of the proposed categories are flexible and reliant on the responses gathered during the interview, Systematic Literature Review (SLR), and questionnaire survey, which constitutes the fundamental contribution of this research.

iii. Organizational capabilities:

Ahuja et al., (2018) defined organizational capabilities as the distinct competencies that an organization possesses, leading to significant business results. According to Smallwood & Ulrich (2004) link these capabilities to the organization's identity and character, which are shaped by its collective abilities, expertise, and knowledge. They also note that investments in employment, training, compensation, communication, and other aspects of human resources contribute to an organization's capabilities. Moreover, organizational capabilities are key intangible assets formed from the combined talents and skills of its people. In addition, Selçuk Çıdık et al., (2017) identified innovative capability as the ability to generate new methods for improvement through proposed solutions. Nevertheless, as stated by Ahuja et al., (2018), the successful implementation of technology within an organization crucially depends on involving actual users. Enhancing the knowledge and skills of these users is vital for an organization to boost its capabilities.

2.2.5 Organizational attributes to produce accurate digital twins

Hodgson (2004) emphasized that organizational attributes influence the actions of organizations by serving as restraints and amplifiers. Subsequently, Hodgson (2004) stated that organizational characteristics are not only by implementing limits in the organizations but also by preserving organizational knowledge. According to Song & Chen (2014), organizational attributes primarily pertain to resource allotment and collaborative actions in organizations. Accordingly, Tian et al., (2010) underlined that enabling technologies must integrate discipline and flexibility effectively. In addition to connecting organizations with technology, organizations must have the flexibility to respond to change. Moreover, Song & Chen (2014) underlined that creative businesses must possess ownership and organizational versatility characteristics to give employees tactical initiatives, ideal frameworks, individual leeway, and collective understanding.

Concerning the digital twin, Sandkuhl & Stirna (2020) highlighted that the digital twin's technological development has gotten a substantial amount of attention, while the organizational and commercial areas still need to receive more. In addition, Wache & Dinter (2020) concluded that the existing articles mainly concentrate on technology positioning and underrepresent the organizational viewpoint crucial for the adaptation of digital twin, which has motivated this research. Consequently, according to Agrawal et al., (2022), resources are required for the technological capabilities to create a digital twin, and the value that a digital twin contributes to an organization would vary in each instance. Therefore, to successfully implement a digital twin, managers and practitioners must:

i. Determine the optimal level of digital twin:

This research can potentially become the construction industry's benchmark for building construction. The digitalization framework enables professionals to systematically assess different levels of digital twins and select the one that offers the most significant benefit given current technological capabilities. It assists them in defining the potential outcomes of digital twins in terms of business value and understanding the technological requirements needed to achieve those outcomes.

ii. Enhance management of stakeholders and create digital strategies:

Achieving the "perfect" digital twin envisioned is not a one-time task. There may be times when the expectations of the business and the capabilities of the technology need to align. Such misalignments frequently result in delayed digital twin deployment, if not total project failure. According to Lu et al., (2020), lack of sufficient involvement from project clientele and professional consultants was a prevalent cause of poor technology investments, highlighting the necessity for strategic collaboration across multiple shareholders for technology deployment to be effective.

iii. Imparting a strategic mentality to the entire organization:

Due to the varied areas of expertise within a corporation, some individuals may be more familiar with the technology than the commercial value, resulting in a misaligned organizational strategy. To minimize missed opportunities, the organizations' leaders of varying ranks must engage in an open and frank discussion about the changing technological landscape and its implications for the firm.

Agrawal et al., (2022) also highlighted the principle of synchronization relating to the need pull and technology push to identify an appropriate technical competence as the digitalization framework's central theme:

i. Need pull perspective:

This is based on the principle that the production of digital twins is driven by the company's needs, in which a company's management aims to achieve a particular value or competitive advantage. In many circumstances, the problems (or need) to be addressed by a digital twin are obvious and function as the determinant for choosing the proper level of digital twin and the technological capabilities necessary to achieve it.

ii. Technology push perspective:

Describes technology as the impetus for the implementation of innovative solutions. Sometimes, a "technology champion" or any other employee fascinated by technological advancements decides to implement a change. This scenario may not be necessitated by a compelling "need" to begin with, and it may be necessary to look for an appropriate use case for technology development.

Alternatively, Weber-Lewerenz (2021) uses a mind map, as shown in Figure 2.2 to represent the outcomes of an overview of the elements essential for shaping a responsible digital transformation with interdependent long-standing impact.

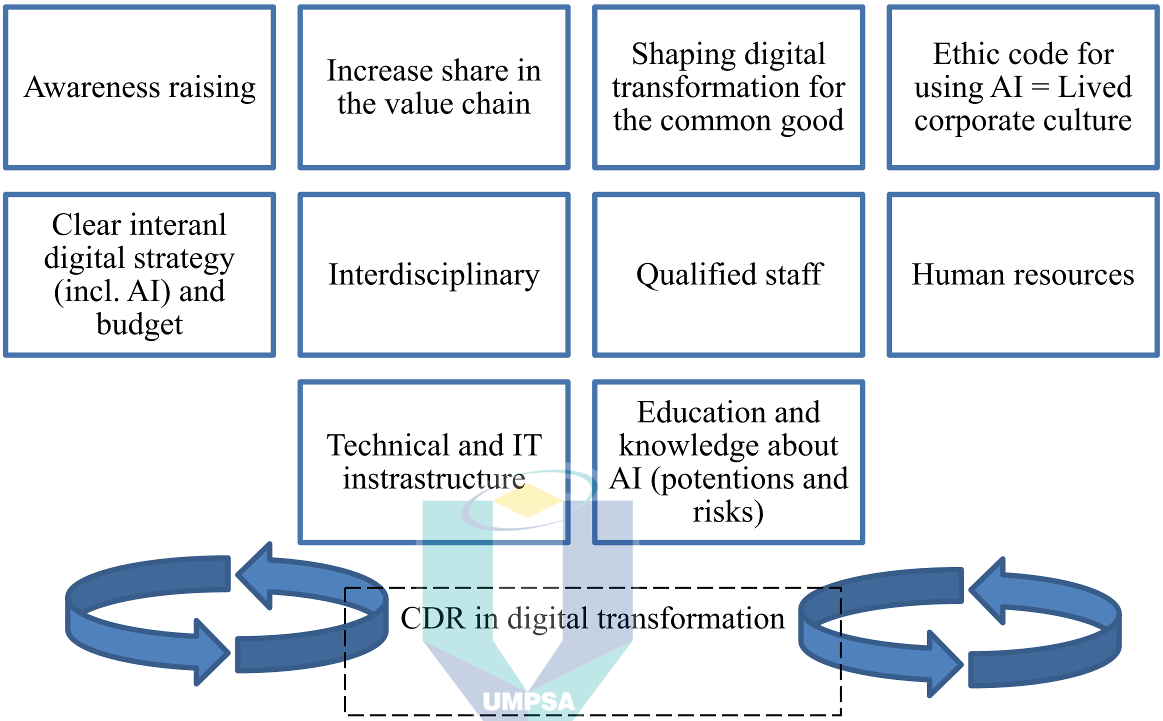

Figure 2.2 Interrelationship among the key elements of Corporate Digital Responsibility (CDR).

Source: Weber-Lewerenz, (2021)

Alternatively, Weber-Lewerenz (2021) also underlined the importance of the following elements for using breakthrough digital technology in the construction industry:

- **i.** Knowledge and skill development, creation of all basic technological needs, interdisciplinarity.
- **ii.** State regulations are crucial for the safety and security of data management.
- **iii.** Technology confidence can only be attained through the ethical consideration of technical approach usage, comprehension of the functions, structure, transparency, and the communication of hazards through authorized control mechanisms and reliable design.
- **iv.** Determine the optimal level of digital twin. Define precise data, process, qualification, quality feature, and interface requirements. This is accomplished by

ensuring the continual planning and implementation of essential digitalization data sets and providing all process participants with access to comprehensive data platforms.

v. Digital transformation demands trust, expertise, and a business culture founded on core values.

2.2.6 Organizational strategies to produce accurate digital twins

According to Weber-Lewerenz (2021), all stakeholders are tasked with successfully driving this process and shaping it proactively with competent personnel, open discourse on new technological options, and an allotment of potential application regions. This will aid the construction sector in rethinking technological advancement and catching up with digitalization sustainably. In the construction business, eliminating this barrier is a top priority. However, there needs to be more acknowledged application disciplines and diversity.

Weber-Lewerenz (2021) also highlighted the following foundational techniques for the utilization of innovative digital technologies:

i. By developing the necessary talents and maximizing their potential, businesses may steer this process to success. First, a thorough understanding of digital technology and procedures must be gained. Predicaments demonstrate yet again that organizations with a strong digital presence are better positioned, nimble, and able to continue operations.

ii. Along with the professional chambers and organizations, the institutions and companies serve as role models, particularly in politics, academic teaching, research, and science. They act as catalysts for the ethical dialogue regarding digitalization technologies used in the construction sector and ensure adherence to ethical standards.

iii. Before organizations can embrace digital responsibility for things that others still need to comprehend or appraise, they must thoroughly understand digital technologies and procedures. Humans must be at the core of technical innovations for sustainable digital transformation to be successful and for value chain shares to expand.

iv. A process of radical rethinking, particularly in SMEs in which are taking responsibility, breaching boundaries, and leadership. According to Construction Industry 4.0, engineers, architects, designers, and artisans serve as makers of living spaces and technical, social, and human transformation.

v. Further interdisciplinary, in-depth research is required.

vi. Simulation models offer decision-making resources for the planning and building processes by enabling forecasts and corporate strategy. Data may be safeguarded in interdisciplinary contexts, and interfaces can be unified by merging all digital devices.

vii. Its goals, opportunities, and hazards, how specific methodologies might allow better or new business models, what decisions and responsibilities must be managed ethically, and how the linkages between research, education, and practice must be modified.

According to Agrawal et al., (2022), the authors emphasized that employing the digitalization framework as a planning tool, especially at the beginning of a project and at critical in-between stages, facilitates efficient communication of the project's goals. Consequently, participants in the project have a shared knowledge of what to expect and how to manage resources. In addition, the digitalization framework serves as a diagnostic tool by discovering and understanding the underlying causes of these misalignments, therefore initiating discussions on the rectifications. The digitalization framework also aids in formulating an enduring vision for the anticipated level of the digital twin and a tactical strategy for obtaining that level from the existing level of the digital twin. Consequently, the plain digitalization framework language form can be beneficial for instilling a strategic attitude throughout the organization and fostering ongoing technological discourses.

2.3 Architecture, Engineering and Construction (AEC) industry

2.3.1 Definition and concept

AEC is the abbreviation for Architecture, Engineering and Construction. Thus, when the AEC industry is mentioned, it encompasses the types of professionals involved who are architects, engineers, draftsmen, surveyors, manufacturers, and others. The AEC industry plays a crucial role in creating vital living spaces for humans, encompassing the construction of cities, buildings, bridges, and underground structures (Zhang et al., 2023).

2.3.2 Digital twins in the AEC industry

Digital twin technology possesses the potential to transform the construction industry. Digital twins enhance monitoring capabilities, allowing for accurate assessment of a building's status, risk forecasting, and refinement of maintenance approaches. Employing digital twin technology can lead to notable advancements in the quality of construction, efficiency in managing supply chains, and safety hazard management (SHM). This improves safety, dependability, and overall efficiency in construction projects (Omrany et al., 2023). Figure 2.3 shows digital twins' areas of applications in the AEC industry.

Data gathered from digital twin models can be utilized for planning and managing assets during emergencies and calamities (Macchi et al., 2018). In short, it can be recapitulated that data from digital twin models assists in conveying challenges and limitations to stakeholders, which include:

i. Forecasting the status of physical assets.
ii. Estimating energy usage while adhering to environmental standards.
iii. Monitoring the structural integrity of infrastructure assets.
iv. Predicting the lifespan of structures.

In addition, Macchi et al., (2018) also mentioned that the integration with artificial intelligence (AI) algorithms and data analytics enhances the models for forecasting future conditions or analyzing past performance assessing the future state of an asset and comparing it with an intended target state.

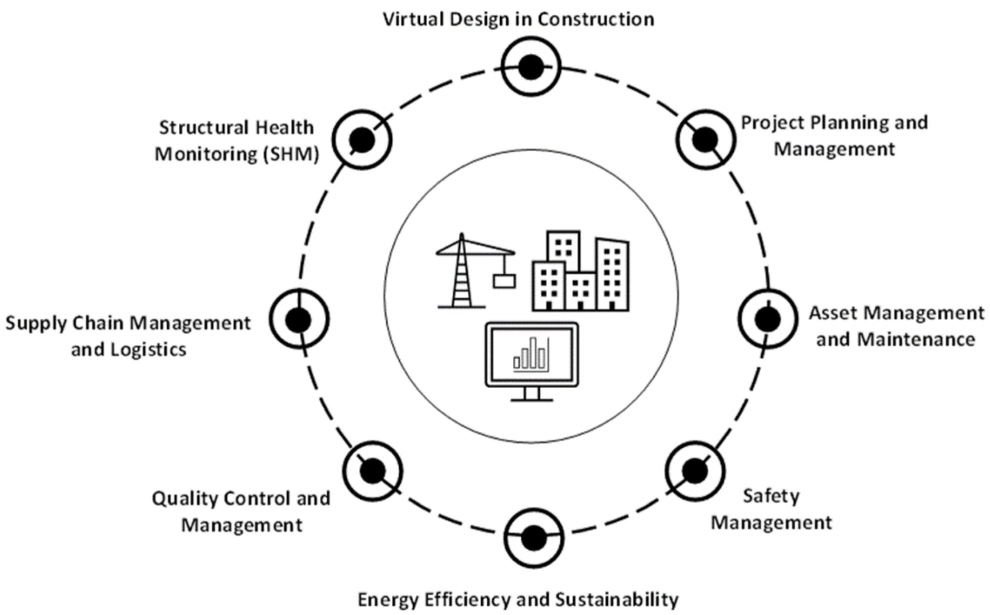

Figure 2.3 Digital twins areas of applications in the AEC industry.
Source: (Omrany et al., 2023)

Besides predictions, digital twin models assist stakeholders in selecting eco-friendly design solutions with low carbon emissions and clean energy usage (Feng et al., 2021). This involves:

v. Enabling rapid production of various design options, considering environmental, cost, and scheduling benefits.

vi. Updates from these models are crucial for real-time monitoring of the construction workforce, particularly in identifying and mitigating risks to worker safety.

vii. Continuous real-time updates are essential for protecting workers and reducing manual interventions in hazardous construction sites.

Nonetheless, Feng et al., (2021) also emphasized that digital twin models facilitate broader involvement in urban planning and design by incorporating public preferences and material usage priorities. These models effectively bridged the gap between people and their urban environments by offering needed flexibility and customization. Digital twin models connect buildings and citizens at the urban level, creating a cohesive federated model that simplifies city development management. Therefore, with a robust data infrastructure supporting digital twins' production in the

AEC industry, digital twins hold significant potential to enhance integrations among diverse stakeholders, thereby leading to improvements in decision-making processes.

2.3.3 AEC industry construction projects lifecycle stages

The AEC industry encompasses all aspects of the planning, design, and building processes for various types of structures. In the AEC industry, the construction project development stages involve several stages before the project reaches its end users. In general, the construction project lifecycle stages consist of five stages, according to Faris et al., (2022) ; RIBA Architecture (2007):

i. Preparation

A construction initiative begins by addressing a necessity - a strategy to enhance productivity or expand public amenities. Various alternatives may be suggested until a viable one is selected. A feasibility analysis is conducted to ascertain if the solution is viable as a project and can be realistically implemented. The project is then assessed based on objectives, budget, schedule, and resources. The client must invest sufficient time in the initial phases to ensure successful project completion and minimize changes during the later design and construction phases (Zou et al., 2007).

ii. Design

Typically, an architect, as a design expert, creates the initial concept designs for the project. Following this, the involvement of specialist engineers is essential to create comprehensive design plans and drawings. The team finalizes the details and secures the client's consent to move forward with the specified details. Subsequently, during the technical design phase, the objective is to enhance and elaborate on the fundamental design proposals from different stakeholders, culminating in preparing documents to guide the construction process (Bennett, 2007). The design phase is complex, making it crucial to include all key stakeholders, like contractors, in a collaborative effort to achieve the project objectives (Bemelmans et al., 2012). Working together in this manner will enhance practical expertise, minimize alterations in design, and facilitate smoother execution of projects.

iii. Pre-construction

This phase is focused on selecting the contractor who will execute the construction work and overseeing the tendering process. Bennett (2007) explained that this process can be undertaken through different approaches, such as prequalification tendering, open tendering, invited tender, and negotiation. At this juncture, numerous construction projects face hurdles, mainly due to the need for standardized practices and well-defined models for contract negotiation in emerging economies (Narayanan & Huemann, 2021). Hence, cooperation between the governing bodies is crucial at this stage to ensure contractors are chosen meticulously. Allocating sufficient time for the tendering phase and providing ample details is essential. To expedite the construction process, clients may reduce the duration of the bidding award phase. However, this abbreviated negotiation period with the contractor may lead to claims, disagreements, delays, and exceeding the budget (Iyer & Jha, 2005).

iv. Construction

The phase of choosing a contractor can extend into the construction phase's mobilization stage. Mobilization typically refers to the activities carried out after the contractor is selected but before actual work begins on the site. Subsequently, the contractor receives all necessary project details, paving the way for the onset of physical construction. At this juncture, it is crucial to ensure all parties involved in construction have the information they need to prevent delays and poor performance. Beyond the primary contractor, appointing other participants like subcontractors, specialists, and consultants is necessary. However, their engagement occurs at various stages, and some may never interact with each other (Winch, 2010). This contributes to the segmented nature of construction projects. Therefore, fostering a collaborative atmosphere among the parties involved is essential to ensure consistent progress and meet the client's requirements (Baiden et al., 2006).

v. Use

This is the final lifecycle stage of a construction project, which encompasses activities following the practical completion of the building. This stage primarily involves the administration of the building contract post-completion, which includes conducting final inspections to ensure that all aspects of the construction meet the required standards and specifications. During the initial occupation period, they play a critical role in assisting building users, providing support and guidance to facilitate a smooth transition into the new environment. This support could range from addressing operational queries to resolving any immediate issues related to the building's functionality. Lastly, an essential component of this stage is reviewing the project's performance in use. This review aims to evaluate how effectively the building serves its intended purpose, assess its operational efficiency, and gather insights for future projects. This reflective process is crucial for continuous improvement in construction practices and project management methodologies (RIBA Architecture, 2007).

As for the Operation and Maintenance Stage outlined by CIDB Malaysia, the focus is on early procurement and management of assets reports, reducing lifecycle costs, eliminating defects, and ensuring fewer, more predictable disruptions in business operations. This stage employs digital facilities management, equipped with comprehensive operation and maintenance information, enabling building operators to reduce operating costs effectively. This approach is part of a broader strategy to enhance efficiency and sustainability in the construction industry, particularly in the context of the Building Information Modelling (BIM) framework.

2.3.4 Digital twins' during the pre-construction stage in the AEC industry

In the AEC industry, the construction industry is characterized by its time-consuming, labour-intensive, and information-intensive nature. The pre-construction stage encompasses strategic project planning, design creation, permit acquisition, and the mobilization of labour and resources required for construction. Bakar & Embi (2016) emphasized the significance of the pre-construction phase in determining the success of a construction project. Effective communication and information exchange among various participants, including architects, engineers, contractors, facility managers, and construction workers, is essential at each project phase. This can be facilitated by employing digital twin technology. Singh et al., (2022) pointed out that digital twins foster a sustainability-focused approach from the design stage. Hence, digital twins can evaluate a structure's carbon footprint and energy usage in advance, enabling these factors to be integrated into its design and construction.

2.3.5 Challenges to produce digital twins in the AEC industry

According to Weber-Lewerenz (2021), the number and complexity of data for businesses are growing. To always have data available, in its most current version, entirely and without data loss, businesses of all sizes must develop standardized data platforms accessible to all stakeholders. Due to their drive to perform efficient operations, save expenditures, remain in business, and increase their competitiveness, most construction organizations are willing to pay attention to digital transformation. Therefore, it would be reasonable to claim that the vocabulary necessary for digital transmission should likewise be more straightforward and less complicated.

In addition, Weber-Lewerenz (2021) highlighted that many interviewed political decision-makers claimed that organizations continue to profit from past success and plan "on sight." They, therefore, feel free to employ digitalization, explore innovative possibilities, or modify their corporate structures. Despite this, a significant number of construction organizations and suppliers are only observers of new technological movements, as opposed to co-designers. It is only possible to overcome scepticism with knowledge. The collaboration amongst industry and small and medium-sized businesses (SMEs) with technological start-ups and establishing regional networks and clusters are regarded as the most significant alternatives, as they have evolved substantially in recent years.

According to expert interviews conducted by Neto et al., (2020), the lack of structured project pathways for digital twin development and cultural and strategical resistance to change are the most significant barriers to digital twin adaptation, therefore implying a dearth of strategic vision among practitioners and organizations. Perno et al., (2022) analyzed more than forty papers on digital twin implementation and cited the challenges of appropriate choices and investments for the technological solutions and the difficulties in developing clear value propositions connected with digital twin solutions as obstacles to its industry development. In contrast, Jahanger et al., (2022) cited the inability of owners and contractors to comprehend the issues and obstacles associated with digital development as one of the key reasons for the delay in implementing digital technology.

Love & Matthews (2019) observed that a lack of information among practitioners and organization management about the capabilities required for a digital twin might lead to false expectations for the technology. Accordingly, Love & Matthews (2019) noted that poor management of resources impedes the realization of the technology's advantage. Furthermore, finally, there is a rejection of digital twins as a marketing gimmick, as described by Wright & Davidson (2020).

2.4 Research gap

Figure 2.4 SLR Literature sample findings

The subsequent body of literature reveals a discernible gap in producing accurate digital twins within the Architecture, Engineering and Construction industry. As shown in Figure 2.4, the SLR literature findings, dated 4 September 2023, resulted in 316 articles, which can be categorized into four main groups according to the Enterprise Architecture Framework: Business, Data, Application, and Technology. Table 2.2 in section 2.4 listed the limitations and prospective future works of previous research.

i. Business

Due to media coverage and conferences, digital twin technology is at the forefront of industry practitioners' minds nowadays. The AEC industry is witnessing a transformative shift driven by advancements in construction sector management (Sepasgozar et al., 2023; Salem & Dragomir, 2022; Weber-Lewerenz, 2021), particularly in the realm of producing accurate digital twins. These digital replicas not only enhance business efficiency (Venkateswaran, 2020) but also facilitate the comprehensive lifecycle management of smart and sustainable infrastructure assets (Hemdan et al., 2023; Broo & Schooling, 2023; Venkateswaran, 2020). Through process mapping (Akinyemi et al., 2021) with digital twins, businesses gain unparalleled insights, enabling data-driven planning and workflow control (Hemdan et al., 2023). This, in turn, opens new adoption and development opportunities (Lünnemann et al., 2023; Waqar et al., 2023; Su et al., 2023 ; Kineber et al., 2023; Ammar et al., 2022; Salem & Dragomir, 2022), positioning organizations at the forefront of innovation in the industry.

ii. Data

In the realm of producing accurate digital twins within the AEC industry, data aspects play a pivotal role. It begins with ongoing digital twin research initiatives (Ozturk, 2021; Fuller et al., 2020) that have developed multi-domain digital representations (Zhang et al., 2021; Ryzhakova et al., 2008). These representations are at the core of effective digital representation management (Akinyemi et al., 2021; Zhang et al., 2021), incorporating vital asset operation monitoring data (Lu et al., 2020). This synergy results in the creation of an integrated digital twin framework (Wei et al., 2022; Pregnolato et al., 2022; Pan & Zhang, 2021), where digital representations seamlessly interact with the physical environment (Zhang et al., 2021). Moreover, integrating digital twin data with IoT and blockchain technologies, referred to as DT-IOT blockchain data integration

(Hemdan et al., 2023), ensures the reliability and security of the data, marking a significant advancement in the industry's data-driven capabilities.

iii. Application

In the AEC industry, the application aspects of producing accurate digital twins are driving innovation and efficiency. These applications encompass a wide range of areas, from off-site construction digital twin models (Wei et al., 2022) to DT-BIM integration solutions (Nguyen & Adhikari, 2023) and BIM-DT design methods (Nguyen & Adhikari, 2023). Practical usage of digital twins spans various domains (Nguyen & Adhikari, 2023; Gürdür Broo et al., 2022; Ammar et al., 2022; Tan & Aziz, 2022; Fuller et al., 2020), with digital twin fundamentals (Su et al., 2023; Ammar et al., 2022; Shahzad et al., 2022; Jones et al., 2020) at the core of their implementation. The concept of physical-virtual architecture (Pregnolato et al., 2022) is becoming a reality, thanks to digital twin mechanisms and their connectivity (Saunila et al., 2022; Zhang et al., 2021), allowing for real-time monitoring (Hemdan et al., 2023), and precise control of physical assets (Hemdan et al., 2023). These applications are transforming the industry's design, construction, and operations approach by harnessing the power of accurate digital twins.

iv. Technology

The technological aspects of producing accurate digital twins are evolving in the AEC industry. This evolution encompasses a broad spectrum of developments, from enhancing the building life cycle through digital twin technology (Gulewicz, 2022; Khajavi et al., 2019), to raising awareness of its potential (Hemdan et al., 2023). The ongoing development of digital twin technologies (Su et al., 2023; Nour El-Din et al., 2022; Deng et al., 2021) and their enabling technologies (Fuller et al., 2020) drive innovation, while the emergence of a digital twin innovative maturity model sets new benchmarks (L. Chen et al., 2021). Collaborations in asset lifecycle technologies (Ammar et al., 2022; Shahzad et al., 2022) are playing a vital role in shaping the future, as seen in the digital twin construction lifecycle framework (Su et al., 2023; Agrawal et al. 2022; Abusohyon et al., 2021). Furthermore, cloud integration (Venkateswaran, 2020) is expanding the reach of digital twins, and the integration of BIM-DT and Big Data

(Torrecilla-García et al., 2022; Ryzhakova et al., 2008) is paving the way for data-driven insights and decision-making in the AEC industry.

In the context of Malaysia's AEC industry, there is a notable research gap in identifying and understanding the organizational attributes and strategies essential for producing accurate digital twins. While global advancements in digital twin technology are well-documented, localized research specific to Malaysia remains limited. With its unique cultural, economic, and geographical background, research is needed to explore effective data integration and management practices tailored to the Malaysian context. Investigating how Malaysian construction practitioners can develop centralized data repositories and establish practical data governance policies is crucial.

Additionally, research on technological adoption and innovations is needed as there is a lack of research on how Malaysian AEC organizations can adopt and integrate advanced technologies such as BIM, IoT, and AI. Studies should focus on the challenges and best practices for implementing these technologies within the unique regulatory and market conditions of Malaysia. Nonetheless, exploring models of innovation tailored to the Malaysian AEC industry, including the development of digital twin frameworks and the potential for cloud integration, can provide valuable insights for enhancing project efficiency and sustainability.

Research should also investigate frameworks for effective collaboration among architects, engineers, and construction practitioners in Malaysia. This includes understanding the cultural and organizational dynamics that influence cross-disciplinary teamwork and identifying strategies to foster a collaborative environment. Effective strategies for engaging stakeholders, including clients, regulatory bodies, and community members, in the development and implementation of digital twins are underexplored in the Malaysian context. Besides that, there is a need for research on organizational strategies for training and developing a skilled workforce capable of utilizing digital twin technologies. This includes identifying specific training programs and professional development initiatives that can address the skills gap in the Malaysian AEC industry.

Addressing these gaps can provide a comprehensive understanding of the organizational attributes and strategies needed to effectively produce digital twins in Malaysia's AEC industry. This will enable Malaysian construction practitioners to leverage digital twin technologies for improved efficiency, sustainability, and innovation in construction projects. Future research should focus on localized case studies, the development of best practices for technology integration, and strategies for fostering interdisciplinary collaboration within the unique context of Malaysia. Through these undertakings, this research propels the discourse ahead

Table 2.2 Limitations and prospective future works of previous research

Digital twin technology	Scope of existing research	Limitation	Future work	References
1. Framework	Characteristics	Complex technology adoption framework	- Empirically and analytically examine real scenarios for convergent technology adoption in various countries.	1,4,7,12,16, 19
	Factors	Consider technical, individual, social, organization and environmental factors	- Data model can be extended to wider application by further studies.	
	Current practice	Limited by the number of off-site construction companies	- Consider other types of construction	
	Advantages	More informative Organization assessment	- Future in-depth strategic analysis of BIM-based digital twin as a decisive factor of decision-making in safety management.	
	Challenges	Lack of skilled workers	- Explore how firms with several Digital Twins utilise the framework and enhance it to consider their connections.	
		Resistance to change	- Explore the cybersecurity issue.	
		Data security issues	- Examine the framework's implementation in a secure manner by considering a security audit for data encryption and user and device identification.	

Table 2.2 Continued.

	Application complexity	- Recommended more complex cases with multiple data streams to test the developed framework.
	Interoperability issues	- More comprehensive insights from construction observations.
	Lack of high-quality standardized information	- Explore the suggested framework in many case studies with varied asset uses and complexities in various disciplines.
	Compatible terminologies with the AEC industry have not been defined in well-established technical documents, nor have the roles of the actors who develop, use, and own them.	
	Development of a DT using existing technical references.	
	The feasibility of adopting an interoperable, standardized DT for construction assets has been substantially diminished.	
	Limited to off-site construction	
Strategies	Utilize convergent technologies	
	Essential to conduct more detailed studies on the application of the ISO 19650	

Table 2.2 Continued.

			series to a DT framework for construction asset.		
2.	**Data integration**	Integration	sample size is a limitation due to the newness of the subject.	- Develop optimized algorithms and architectures that can improve the efficiency and speed of the integration process. Develop more robust security protocols and architectures that can improve the security of the system. - Develop interoperability standards that can enable seamless integration of digital twins with IoT-based blockchain across different platforms. - Explore the potential of integrating digital twins with IoT-based blockchain for real-time monitoring and control of physical systems in various industries. - Develop advanced data analytics and machine learning algorithms that can extract insights and patterns from this data. - Focus on defining further operational thresholds and how data is presented to stakeholders to best support decision-making. - Data related to practice-oriented innovations and industry-initiated improvements to achieve broader and more informed results.	2,10, 25

Table 2.2 Continued.

3.	**Infrastructure**	Challenges	The focus of the interviews was on the vertical section and Digital Twin for infrastructure was not discussed.	- More studies on experiences and learning on digital twin design and development to build common knowledge.	3, 20
		Strategies	A broader sample size of experts with more diverse experience in construction projects.	- Further investigate the challenges and develop prototypes that can help in quantifying the benefits of implementing Digital Twins on a Construction Project.	
4.	**Digital twin adoption**	Awareness	Lack of awareness.	- To include the analysis of specific cases affecting the implementation of digital twins in enterprises.	5,6,8,14,15, 17,18,21, 22, 23, 26
		Challenges	Neglecting the benefits of social, ethical engineering and construction technologies.	- Extension of expected features and capabilities of an ideal next-generation Digital Twin in multi building.	
			Lack of the necessity for systemic cultural change in the digital transformation process.	- The importance of researching data fusion due to the nature of sensitive data used in healthcare.	
			Increasing technical challenges combined with new digital technologies in changing global markets.	- Explore research for smart cities.	
			Academic teaching should adapt to equip teachers with the skills to prepare students for ethics and digital transformation.	- The potential to investigate Digital Twins for traffic management systems and smart city developments.	

Table 2.2 Continued.

	Small sample of respondents	- Prioritise various identities to provide mitigation measures that can assist Malaysia's smart city development and construction sector embrace DTT.
	Limited past research to compare tech trends and familiarity changes over time.	- Continue developing mitigation approaches since Malaysia's smart city sector requires proven methods to grow.
	Lack of exploration on how to deal with the organizational challenges.	- Explore the implementation of the digital twin for a building interior.
	Lack of clear definitions for a Digital Twin.	- Expansion of sensor network to be included with a higher variety to allow for additional applications for the digital twin of a building.
	Some research wrongly identifies Digital Twins as models and shadows.	- A study of system affordability versus its benefits.
	Lack of domain knowledge on successfully scaling up larger Digital Twins.	- Future studies with data from different locations for comprehensive comparisons.
	Lack of effort to explain and measure the advantages of digital twins.	- Focus on establishing an AI-based system to anticipate construction project readiness while considering barriers.
	Lack of accessible and customizable technology.	- Develop future research on models that show how obstacles interact.
	Lack of common data standards and tools.	- Broaden the scope to include multiple countries for improved generalizability of the findings.

Table 2.2 Continued.

	Lack of data security.	- Future technological developments, such as sensors, machine vision, data governance, and modelling.
	Lack of surrounding data protection and ownership	- Focus on improved integration, data analytics, lifecycle management, interoperability, sustainability, energy efficiency, user experience, and smart city integration.
	Lack of workforce upskilling	- Examine principles of user-centric design, user experience, and integration with smart cities to improve teamwork, communication, and project outcomes.
	Cost and trust issues in reducing human involvement on construction.	- Resilient Digital Twins include robustness into the DT framework.
	The possible incompatibilities among its components (technical, managerial or otherwise).	
	Uncertainties about the use of digital technologies and advanced AI for decision-making.	
	Limited consideration on organizational aspects or historical contexts in DT implementation.	

Table 2.2 Continued.

			Limited exploration using PLS-SEM to analyze data. Geographically limited.		
		Strategies	Use general questions about the level of familiarity with digital twin technology.		
5.	**Digital system**	Not stated	Not stated	- Creation of a digital platform for integrated modelling and creating a digital twin of urban development based on BIM technology.	11
6.	**Task completion**	Challenges	Limited usefulness in understanding the delays of task completion.	- Counterbalance current structural forces in similar projects.	13
7.	**Maturity model**	Not stated	Not stated	- Use an expert pool in the evaluation stage.	24
				- Improve this maturity model in cities and learn how to utilise this digital twin maturity tool to optimise municipal services and assess social and economic effects.	

Note:1. (Sepasgozar et al., 2023); 2. (Hemdan et al., 2023); 3. (Broo & Schooling, 2023); 4. (Wei et al., 2022); 5. (Weber-Lewerenz, 2021); 6. (Gulewicz, 2022); 7. (Torrecilla-García et al., 2022); 9. (Pregnolato et al., 2022); ; 10. (Ryzhakova et al., 2008); 11. (Abusohyon et al., 2021); 12. (Akinyemi et al., 2021); 13. (Deng et al., 2021); 14. (Fuller et al., 2020) ; 15. (Pan & Zhang, 2021); 16. (Jones et al., 2020); 17.(Waqar et al., 2023); 18. (Nour El-Din et al., 2022); 19. (Ammar et al., 2022); 20. (Khajavi et al., 2019); 21. (Shahzad et al., 2022); 22. (Salem & Dragomir, 2022); 23. (L. Chen et al., 2021); 24. (Ozturk, 2021); 25. (Kineber et al., 2023); 26. (Nguyen & Adhikari, 2023).

2.5 Research conceptual framework

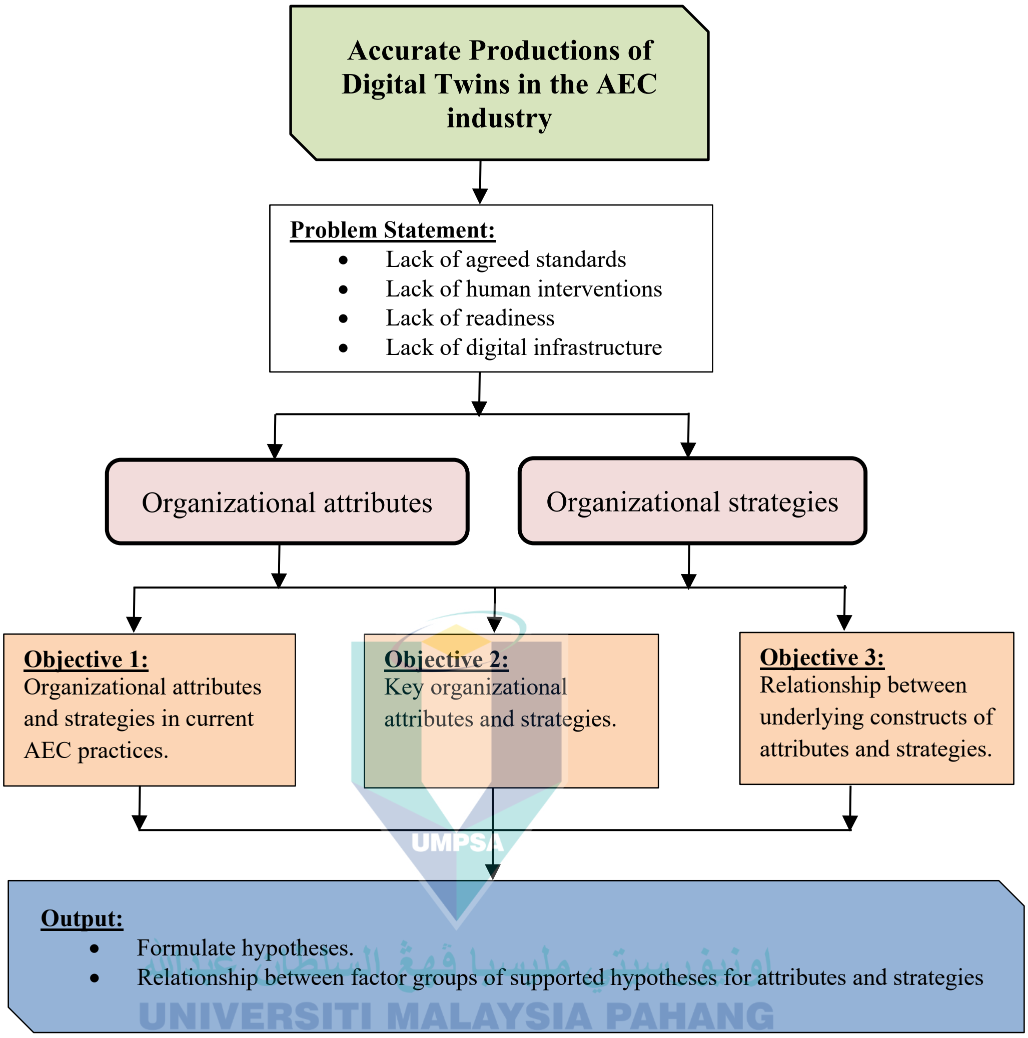

Figure 2.5 Research conceptual framework

The research conceptual framework as shown in Figure 2.5 discussed the relationship between the organizational attributes and strategies to produce accurate digital twins of construction projects successfully, by addressing key challenges such as the lack of agreed standards, human interventions, readiness, and digital infrastructure. It focuses on determining the organizational attributes and strategies by achieving three main objectives: identifying organizational attributes and strategies in current AEC practices. determining key organizational attributes and strategies and analyzing the relationship between underlying constructs of attributes and strategies. The research will result in formulating hypotheses and understanding the relationship between different factors, ultimately in accurate digital twin productions in the AEC industry.

Table 2.3 List of organizational attributes for producing accurate digital twins of construction projects from literature review findings

Organizational attributes for producing accurate digital twins of construction projects		Source
1	Technological capabilities among employees on digital twin.	Agrawal et al. (2022)
2	Strategic mindset among employees on digital twin.	Agrawal et al. (2022); Abusohyon et al. (2021); Shahzad et al (2021)
3	Employee awareness on the business value of digital twin.	Agrawal et al. (2022); Abusohyon et al. (2021)
4	Employee understanding on the value of digital twin data.	Agrawal et al. (2022); Abusohyon et al. (2021)
5	Digital twin technological on infrastructure.	Shahzad et al (2021)
6	Mechanisms for digital twin data operationalization.	Broo and Schooling (2022)
7	Internal strategic digitalization framework on digital twin.	Agrawal et al. (2022)
8	Data compatibility plan for digital twin.	Agrawal et al. (2022); Broo and Schooling (2022); Quichen et al (2019)
9	Shared data environment for digital twin.	Broo and Schooling (2022); Aghimien et al. (2020)
10	On-going improvement processes for digital twin deployment.	Abusohyon et al. (2021)
11	Internal guidelines for developing digital twins.	Shahzad et al (2021); Broo and Schooling (2022)
12	Organizational standardized procedures for developing digital twin.	Agrawal et al. (2022); Broo and Schooling (2022); Quichen et al (2019)
13	Data security procedures on digital twin.	Shahzad et al (2021)
14	Well-defined organizational objective(s) on digital twin.	Abusohyon et al. (2021); Quichen et al (2019)
15	Organizational work culture transformation plan for digital twin.	Shahzad et al (2021); Broo and Schooling (2022)
16	Top-down management involvement in the digital twin concept.	Shahzad et al (2021); Broo and Schooling (2022)

Table 2.4 List of organizational strategies for producing accurate digital twins of construction projects from literature review findings

Strategies for producing accurate digital twins of construction projects		Source
1	Determine the right level of complexity when developing digital twin.	Agrawal et al. (2022)
2	Determine strategies for organizational cultural transformation on digital twin.	Shahzad et al (2021); Broo and Schooling (2022)
3	Determine the organization's transformation goals for digital twin.	Broo and Schooling (2022)
4	Determine the best method to achieve the expected level of data transmission quality for digital twin.	Abusohyon et al. (2021); Shahzad et al (2021)
5	Provide internal training on digital twin.	Abusohyon et al. (2021); Shahzad et al (2021); Broo and Schooling (2022)
6	Provide opportunities for learning and experimentation without restrictions on time or cost.	Broo and Schooling (2022)
7	Provide employees with opportunities to explore digital twin data.	Abusohyon et al. (2021); Shahzad et al (2021); Broo and Schooling (2022)
8	Provide effective tools for communicating information on digital twins.	Shahzad et al (2021)
9	Provide digital twin awareness to all management levels.	Shahzad et al (2021)
10	Increase investments in aligning top employees and digital transformation.	Broo and Schooling (2022)
11	Enhance the organization's attractiveness to attract talented employees.	Broo and Schooling (2022)
12	Enhance the organization's attractiveness to attract digital twin experts.	Broo and Schooling (2022)
13	Develop a strategic vision among all management levels to implement digital twin.	Agrawal et al. (2022)
14	Transform conventional working practices to digitalized working platforms.	Shahzad et al (2021)
15	Implement initiatives to manage cultural risk on digital twin.	Broo and Schooling (2022)
16	Implement digitalization framework as a project planning diagnostic tool throughout the organization.	Agrawal et al. (2022); Abusohyon et al. (2021)
17	Implement a digitalization framework to assist in a long-term vision of achievable levels.	Agrawal et al. (2022)

Table 2.4 Continued.

18	Implement a digitalization framework to assist in a strategic road map.	Agrawal et al. (2022)
19	Implement a comprehensive assessment framework on digital twin.	Wei et al. (2022); Agrawal et al. (2022)
20	Create innovative workspaces using new technologies.	Broo and Schooling (2022)
21	Ensure employees have basic knowledge of digital twin.	Broo and Schooling (2022)
22	Ensure compatibility between new and previous versions of available software related to digital twin.	Abusohyon et al. (2021)
23	Emphasize transparency and accountability among employees on digital twin.	Broo and Schooling (2022)
24	Incorporate existing data to generate information to improve insights for operations management in sustaining infrastructure assets.	Broo and Schooling (2022)
25	Arrange digital experts as external partners.	Abusohyon et al. (2021); Aghimien et al. (2020)

2.6 Summary

In summary, as shown in Tables 2.3 and 2.4 above, it can be encapsulated that organizational attributes act as amplifiers and restraints to the organization. Producing accurate digital twins in the AEC industry primarily pertains to the organization's resource allotment and collaborative actions in providing a strategic mindset among employees on digital twins, digital twin technology infrastructure, organizational work culture transformation plan for digital twins, data security procedures on digital twin, and on-going improvement processes for digital twin deployment. These elements ensure that digital twins are precise, up-to-date, and capable of providing valuable insights for optimizing construction projects.

Organizational strategies, on the other hand, promote cohesion, teamwork, and autonomy. This is achievable proactively with competent personnel, open discourse on new technological options, and an allotment of potential application regions. In producing accurate digital twins in the AEC industry, organizations must determine strategies for organizational cultural transformation on digital twins, providing opportunities for learning and experimentation without restrictions on time or cost, increasing investments in aligning top employees and digital transformation, implementing a comprehensive assessment framework on digital twin, incorporating existing data to generate information to improve insights for operations management in sustaining infrastructure assets and arrange digital experts as external partners. These strategies collectively ensure that digital twins are accurate and beneficial for optimizing construction projects and achieving superior outcomes.

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter examines and discusses the research methods utilized for collecting data. The research methodology included open-ended interviews, systematic literature reviews, a questionnaire survey, and continuous analysis of the collected data. Meticulous data analysis techniques were run, which are the Reliability test (Cronbach Alpha test, Mann Whitney U test and Two Standard deviation test), Normalized Mean Score Ranking, Exploratory Factor Analysis (EFA) and Partial Least-Squares Structural Equation Modeling (PLS-SEM). The subsequent sections elaborate on the processes of collecting data and data analysis.

3.2 Research framework

This research employed a mixed-methods approach, incorporating qualitative and quantitative techniques to deepen understanding and validation. The research methodology in Figure 3.1 outlined how each objective was accomplished within the study. The research comprised three stages: Phase 1 involved collecting qualitative data through open-ended interviews with 20 Building Information Modelling (BIM) professionals, ranging from assistant managers to directors, with knowledge of digital twins together with Systematic Literature Review (SLR) and a pilot study. In Phase 2, quantitative data was gathered through a questionnaire survey administered on the Survey Legend platform, targeting a more comprehensive range of construction professionals identified through LinkedIn. The insights from Phase 2 then informed the data analysis process in Phase 3.

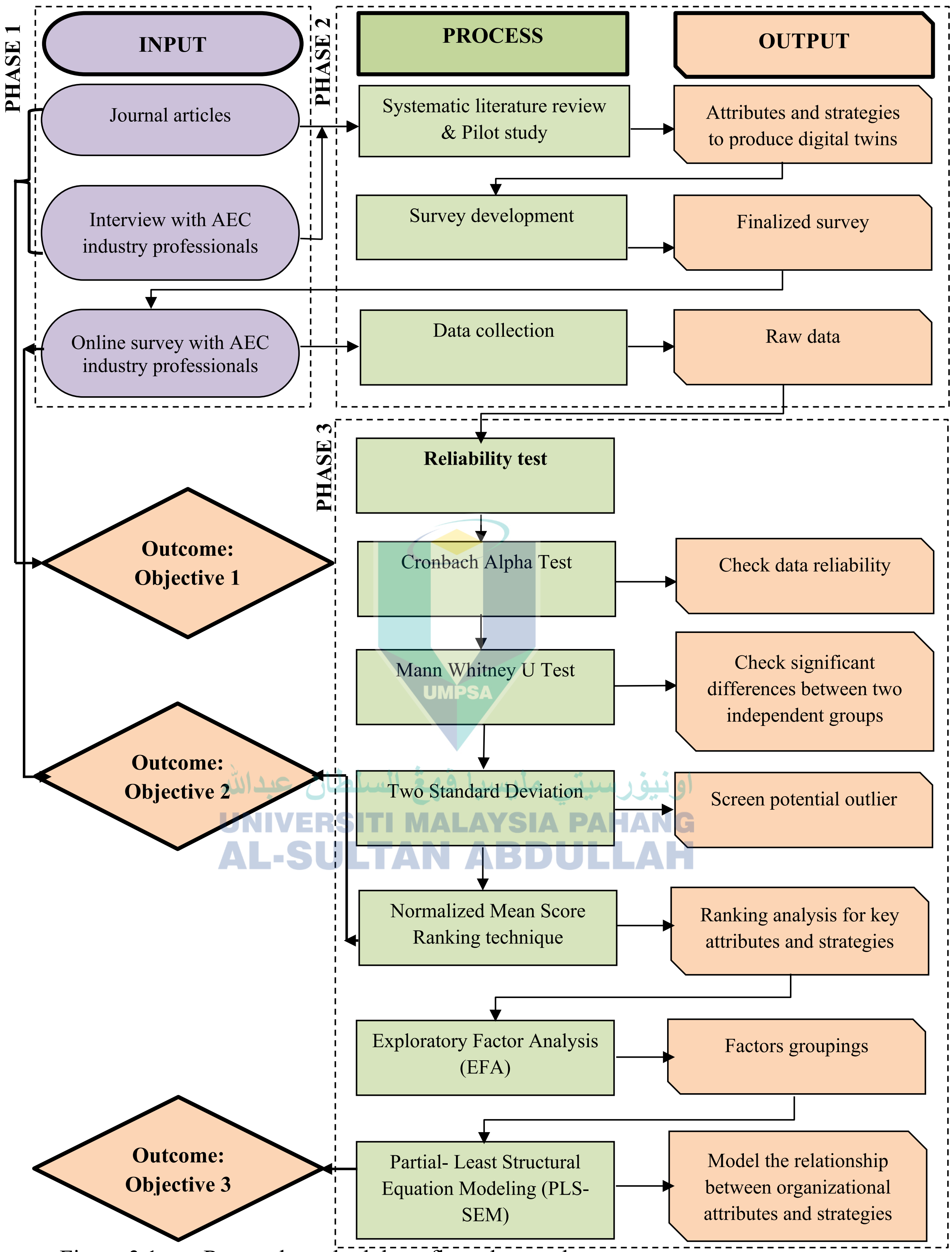

Figure 3.1 Research methodology flow chart and outcome

The first objective (to identify organizational attributes and strategies in current AEC practices to produce accurate digital twins of construction projects) was achieved in Phase 1 via qualitative methods (open-ended interviews) together with SLR and a pilot study using the thematic analysis process. The second objective (to determine key organizational attributes and strategies to produce accurate digital twins of construction projects) was achieved in Phase 2 and Phase 3 via a quantitative method (questionnaire survey) and Normalized Mean Score Ranking technique. The final objective (to analyze the relationship of underlying constructs of organizational attributes and strategies to produce accurate digital twins of construction projects) was achieved in Phase 3 via meticulous data analysis techniques. Reliability analysis (Cronbach Alpha test, Mann Whitney U test and Two Standard Deviation test), Normalized Mean Score Ranking technique, Exploratory Factor Analysis (EFA) and Partial Least-Square Structural Equation Modelling were conducted to achieve objectives 2 and 3.

3.3 Phase 1: Qualitative method

The data collected in Phase 1 were targeted to achieve objective 1, that is, to identify organizational attributes and strategies in current AEC practices to produce accurate digital twin for a building in the AEC industry. The data collected for this phase is initiated through open-ended interviews together with SLR and a pilot study. The data were analyzed using the thematic analysis method.

3.3.1 Sampling size

Baker & Edwards (2012) highlighted that experts in qualitative research argue there is no straightforward response to determining sample size, as a range of epistemological, methodological, and practical factors influences it. Vasileiou et al., (2018) noted that specific numerical recommendations are sometimes provided, typically drawing on the experiential knowledge of specialists in qualitative research.

Hagaman & Wutich (2017) demonstrated that sample sizes of 20 to 40 interviews were necessary to reach data saturation for cross-site meta-themes. In defining and reporting sample size in qualitative information systems research, Marshall et al., (2013) proposed recommending appropriate sample size ranges for a grounded theory which is

20 to 30 interviews, and a single case is 15 to 30 interviews studies. Thus, for this research, 20 target respondents were used to gather information for open-ended interviews, which was an optimal sample size.

3.3.2 Sampling techniques

Based on the referenced Table 3.1, the two (2) most appropriate non-probability sampling methods were used for this research: the Purposive and Snowballing sampling techniques. The purposive technique was selected because specific people need to be consciously selected to provide vital information regarding the production of digital twins in the AEC industry. Besides that, a pilot study was also conducted to validate the data collected from the open-ended interviews and SLR.

Table 3.1 Comparison of different non-probability sampling techniques.

Quota sampling: Quota sampling, defined by Davis (2005); Taherdoost (2016), is a non-random sampling technique that selects participants based on specific traits to match the population's characteristics.	Snowball sampling: Snowball sampling is a non-random sampling method that recruits more cases from a small sample. Brewerton & Millward (2001); Taherdoost (2016) recommend this strategy for closed groups like secret societies and remote professions.
Purposive / Judgement sampling: Maxwell, (2012); Taherdoost (2016) defines purposeful or judgmental sampling as the conscious selection of places, people, or events to offer important information that cannot be obtained through other means. The researcher includes cases or participants in the sample because they deserve to be.	Convenience sampling: Convenience sampling selects convenient individuals. According to Ackoff (1953); Taherdoost (2016), students choose convenience sampling because of its low cost and simplicity. Convenience sampling solves several research issues. Friends and family are easier sample subjects than strangers.

3.3.3 Target population

The respondents in this research ranged from assistant managers to directors, knowledgeable in Building Information Modelling (BIM), with the capacity to understand the operations to produce accurate digital twins. Twenty potential respondents were gathered through LinkedIn, with recommendations from ex-colleagues and friends from the AEC industry. Approaching potential respondents via LinkedIn will be carefully selected based on the individuals' backgrounds in the AEC industry, involvement with BIM, knowledgeable about digital twins' operations, and working experiences for their varied professional experiences and roles to ensure diverse perspectives. Their active participation and decision-making roles in construction projects are crucial, as they significantly influence the success of these projects.

3.3.4 Interview preparation

For the interview preparations, potential respondents' contacts were gathered through phone calls to further confirm interview dates. The interview protocol included an opening script, a procedure for conducting the interview, and the date, time, location, and interviewee's name. Interviews began with demographic questions, followed by questions related to the research. Regarding the means of conducting the interview, it was conducted via telephone calls that were not recorded. The interviewees were contacted beforehand through WhatsApp to confirm their availability, and the interview questions were impromptu, with no questions provided in advance to any targeted responders. If requested, only three primary questions were asked to the intended respondents.

3.3.5 Data collection

Initial primary data collection consisted of an open-ended interview with twenty BIM professionals with digital twin knowledge. These twenty respondents were chosen based on their participation in construction projects, BIM experience, and knowledge of digital twins. This method was used to identify organizational attributes and strategies in current AEC practices to produce accurate digital twins of construction projects. Three questions were raised:

1. What are the attributes needed for an organization to produce accurate digital twins in their practice?
2. What attributes have the most impact on your practice?
3. What are the strategies required to enhance organizational attributes to produce accurate digital twin in building projects?

These questions were intended to identify and acquire information regarding the organizational attributes and strategies to produce accurate digital twins of construction projects in their practises. The open-ended interviews were utilised to elicit as much specific information as possible. Figure 3.2 explains the interview process of the open-ended interviews carried out for this research.

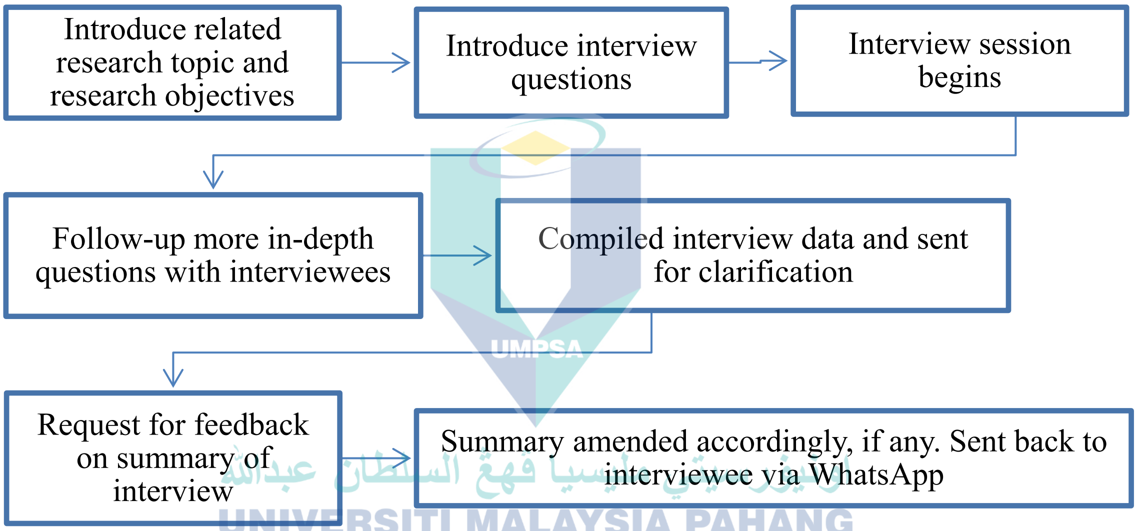

Figure 3.2 Interview session flowchart

The individual interview process commenced with an initial presentation of the research's subject matter and objectives. Interview questions were introduced. The information collected needs to be refined to further understand the interviewee's responses accurately. Thus, follow-up questions were anticipated to have a more in-depth explanation. Following each interview, the gathered information was compiled and sent to the respondents via WhatsApp for clarification. After verifying information from the interviewee, the interview summary is amended if needed before it is sent back to the interviewee. The process continues further by analyzing combination data from SLR and conducting a pilot study.

Systematic literature review (SLR) was conducted to generate a list of potential attributes and strategies by executing a comprehensive literature review. Using the title/abstract/keyword search feature of the Scopus database, a comprehensive search for available construction management papers on digital twins were conducted. This was accomplished using the phrases, TITLE-ABS-KEY ("digital twin" AND "organization*" OR "organisation*" OR "compan*") AND (LIMIT-TO (SRCTYPE, “j”)) AND (LIMIT-TO (LANGUAGE, “English”)), dated 22nd June 2022 resulted with 255 articles.

Researchers often use pilot studies to fine-tune training strategies for the research personnels and assess whether initial findings justify a larger, more comprehensive investigation (Lowe, 2019). In other words, the pilot study is crucial for enhancing the quality and efficiency of the main study (In, 2017). Thus, for this research, a pilot study was conducted to ensure the data collection process was sound. This pilot study was then reviewed by academic experts and professionals within the construction field to eliminate ambiguous content and ensure the appropriate usage of technical terminology. The academic input contributed to the survey's theoretical and empirical validity, while the insights from industry professionals confirmed its practical applicability in real-world scenarios.

3.3.6 Data analysis: Thematic analysis

Qualitative data consists of nonnumerical information such as transcribed interviews, notes, recordings of video and audio, photographs, images, and word-processing documents. As suggested by Seers (2012), the first step is to filter and organize the data by encoding it somehow. A thematic analysis was conducted to examine the interview data for this research, in which bodies of data are categorized according to their themes. These themes aided in understanding and deriving meaning from the data. Figure 3.3 illustrates the actions performed by thematic analysis to analyze the qualitative interview data collected.

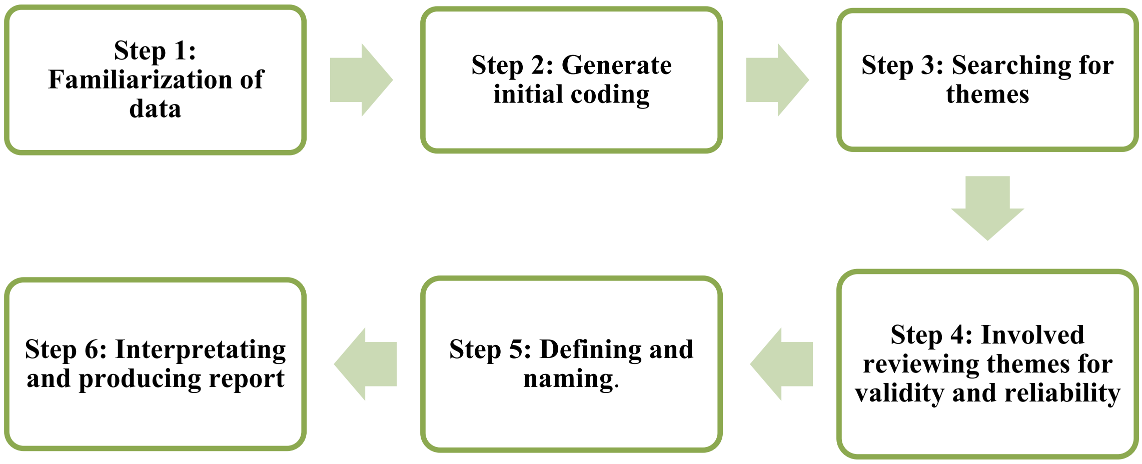

Figure 3.3 6-step guide to good thematic analysis.

Source: (Braun & Clarke, 2006)

Based on Figure 3.3, the first step was to get familiar with the interview data collected by doing multiple readings through the interview transcripts and jotting down initial impressions. The second step was to generate initial coding by collating data that were meaningful and relevant to each code systematically. Next, search for themes by categorizing codes into potential themes. The fourth step was reviewing the themes for validity and reliability by reviewing the themes related to the coded data and the entire dataset. At this stage, a thematic map was generated. The fifth step involved defining and naming themes, where the purpose is to establish the core of each theme. The final step, step six, necessitated interpreting and producing a report for the analysis results.

3.4 Phase 2: Quantitative method

The data collection in Phase 2 was targeted to achieve objective 2, that is, to determine key organizational attributes and strategies to produce accurate digital twins of construction projects through conducting questionnaire survey.

3.4.1 Sampling size

For quantitative data, the sample size will be affected by design decisions that align with the study objectives. According to Delice (2010), the following aspects should be considered when establishing the sample size based on the applicable research method:

i. The sample size shall not be less than 30 if the research has a relational survey design.

ii. The necessary sample size for causal-comparative and experimental research must not exceed 50.

iii. The recommended sample size for survey research is 100 for each major subgroup of the population and 20 to 50 for each minor subgroup.

According to Delice (2010), these recommendations are essential criteria and should be considered inadequate. For instance, if the smallest sub-group comprises 5% of the overall population and a relational survey is to be done, the research should contain at least 30 samples from this sub-group and a total of 600 samples. Debora Indriani et al., (2019) recommended that at least 100 respondents are required to get good data results. Avoidance of data that is either excessively large or too small is necessary. Research that is too small may be inefficient as it cannot produce valuable findings, whereas a study that is too large may need excessive resources (Suresh & Chandrashekara, 2012). Therefore, a minimum sample size of 100 is adequate for statistical data analysis and for generating valid findings in this research.

3.4.2 Sampling techniques

Based on the referenced Table 3.1 in section 3.3.2, the two (2) most appropriate non-probability sampling methods used for this phase are the Purposive and Snowballing sampling techniques. The purposive and snowballing techniques were used in the survey and targeted the respondents' group were consciously selected from different regions in Malaysia consisting of North region (Perlis, Kedah, Pulau Pinang), Central region (Wilayah Persekutuan Kuala Lumpur, Putrajaya, Selangor), South region (Johor, Malacca, Negeri Sembilan), East region (Pahang, Terengganu, Kelantan) and East Malaysia (Sabah Sarawak, Labuan), jobs positions and working experiences due to their predetermined criteria to give pertinent insights on the research-related information.

3.4.3 Target population

In Phase 2, the targeted population was focused on the respondents from the construction industry, who play a huge responsibility in the successful execution of construction projects. With reference to the CIDB Guideline for Small and Medium

Enterprise Developers and Contractors Migration from Conventional Methods to IBS in the Malaysian Construction Industry, the respondents comprise various stakeholders from different organizations ranging from Clients (Government / Private developers), Consultants, Contractors, Suppliers, Manufacturers, and Others. Significantly, this research focuses exclusively on the Malaysian construction industry. Thus, all respondents are actively engaged in construction projects within the vicinity of Malaysia.

The recruitment of respondents for Phase 2 utilized a purposive and snowball sampling technique, which was selected due to its congruence with the study objectives and the necessity to get focused and pertinent insights (Tongco, 2007). The participants were intentionally selected according to predetermined criteria that guaranteed their substantial role in making choices on the deployment of technology within the framework of the construction industry in Malaysia. More precisely, the participants chosen were those who had practical expertise in either carrying out or intending to carry out the use of new building technologies in their projects.

Using purposeful sampling also strengthens the reliability and comprehensiveness of the research. The research guarantees that the conclusions are based on actual realities by deliberately choosing individuals with significant expertise in technology adoption. Using purposeful sampling facilitated the incorporation of perspectives from a diverse range of construction organizations, encompassing both major corporations and small to medium-sized firms. The presence of this variety reflects the wide range of organizational differences in the construction sector. It recognizes that the variables that affect technology adoption might vary depending on each organisation's size, structure, and goals.

The intentional choice of decision-makers from diverse professional backgrounds and organizational sizes enhances a comprehensive comprehension of the issues that influence decisions about technology deployment. The research seeks comprehensive and practical results that promote informed decision-making in the Malaysian construction industry by combining inputs from relevant stakeholders.

3.4.4 Survey development

This research used a non-probability snowball sampling technique to acquire data from difficult-to-reach participants (Chua, 2012). Non-probability sampling is preferable despite a comprehensive sampling frame (Radzi et al., 2022; Patton, 2015). The snowball sampling method begins by recruiting initial respondents who voluntarily participate in the survey and then refer others (Noy, 2008). This technique is widely utilized in construction project management research (Farouk, 2022 ; Radzi et al., 2022).

In Phase 2, the research focused on individuals within the construction industry who bear significant responsibility for ensuring the successful execution of construction projects. These individuals encompass a diverse range of stakeholders representing various types of organizations. A questionnaire survey was employed as a valuable tool to systematically collect relevant data. Questionnaire surveys have been widely used in the field of construction management to solicit expert opinions.

Therefore, a questionnaire survey was developed and utilized to gather data for the research. To construct the questionnaire survey, primary data were gathered through thematic analysis of open-ended interviews, a systematic literature review and a pilot study to determine the variables associated with attributes and strategies required to produce accurate digital twins of construction projects in the AEC industry. A questionnaire survey developed contained 21 organizational attributes and 30 organizational strategies.

3.4.5 Data collection

The survey's cover page included the research objectives and contact information, followed by three sections. The first section, Section A, focused on gathering demographic information from respondents. This was essential to verify the reliability of responses and ensure that participants belonged to the specific target population under investigation (Aithal & Aithal, 2020).

The second section (Section B) of the questionnaire survey consisted of organizational attributes for producing accurate digital twins of construction projects. On a five-point Likert scale, respondents will be asked to assess the significance of each method (1 = not critical, 2 = slightly critical, 3 = moderately critical, 4 = critical, and 5 = very critical). According to Zhang et al., (2011), the Likert scale's popularity originates from its capacity to produce precise results. Meanwhile, the third section (Section C) included a list of the organizational strategies for producing accurate digital twins of construction projects. Respondents were asked to rank the significance of each variable using a Likert scale. At the completion of the questionnaire survey, respondents were given the option to describe and evaluate any additional organizational attributes or strategies deemed crucial to produce accurate digital twins of construction projects.

The process of collecting data has evolved due to technological advancements and a broad spectrum of internet usage. With the advanced technology today, data or information can be dispersed faster. For organizations, professionals, and those networking online, sending surveys via emails and other platforms like LinkedIn is becoming very common these days. For this research, a questionnaire survey was created using the cloud-based Survey Legend platform. Survey Legend produces mobile-friendly surveys, manages questionnaire surveys online efficiently, customizes questions and monitors responses using this platform. Additionally, it also allows users to share surveys effectively through hosted links and other social media platforms.

The data-collecting process was carefully organized to guarantee efficient and thorough involvement of the respondents. The data collection commenced on 31st March 2023 and ended on 2nd June 2023. This allowed sufficient time for the intended respondents to receive, analyse, and reply to the surveys. The time was carefully chosen to achieve a compromise between receiving sufficient replies and minimizing respondent weariness.

3.5 Phase 3: Analyzing survey data

IBM's Statistic Package for the Social Sciences (SPSS) version 28.0 (Armonk, NY: IBM) will be utilized to conduct reliability analysis, whereas Smart PLS 3 (Oststeinbek, German: SmartPLS) will be used to statistically evaluate the hypotheses based on structural equation modelling utilizing the partial least squares (PLS) method as outlined by Ringle et al., (2014).

3.5.1 Reliability analysis

Before detailed analysis is conducted, the data reliability was checked to ensure the responses obtained are reliable and valid. Version 23.0 of IBM's Statistical Package for the Social Sciences (SPSS) was utilized to conduct a reliability analysis.

3.5.1.1 Cronbach alpha test

The Cronbach's alpha reliability test was conducted to check that the components have been classified accurately. The reliability of the data obtained from a scale or questionnaire, which might be in a multiple-point or contradictory format, was assessed using the Cronbach alpha coefficient, which ranges from 0 to 1. According to Nunnally & Bernstein (2010), the minimal value for Cronbach's alpha coefficients is 0.60. According to Santos et al., (1999), a score closer to 1 indicates a higher level of reliability in the data.

3.5.1.2 Mann-Whitney U test

For this research, the Mann-Whitney U test was conducted to identify potential differences in the evaluation between distinct, independent groups of those familiar and unfamiliar with digital twins. This research's null hypothesis (H0) stated that "there is no significant ranking difference between the two independent groups." (Hinton et al., 2004). A significance level below 0.05 ($p = 0.05$) leads to the rejection of the null hypothesis.

3.5.1.3 Two Standard Deviations (SD) technique

The two-standard deviation (SD) technique was utilized to identify potential outliers that could substantially affect the results. This method involves calculating means, standard deviations, and two SD intervals for organizational attributes and digital twin production strategies. *Outliers* are attributes and strategies that fall outside the minimum and maximum range.

3.5.2 Criticality analysis

To achieve the intended objective 2 of this research, data from the questionnaire survey was analyzed using the Normalized Mean Score ranking technique to determine the key organizational attributes and strategies.

3.5.2.1 Normalized Mean Score Ranking technique

This research utilized the normalization method because it provides a more accurate interpretation of the data. The min-max normalization method was evaluated, and the dataset will range from 0 to 1. According to Osei-Kyei & Chan (2017), only elements with a normalized value ≥ 0.50 were the most significant. The approach of normalization was derived by Chan et al., (2014).

The method of ranking using mean score was used to rank the organizational attributes and strategies required to produce accurate digital twins in the AEC industry. This technique is commonly applied to analyze survey data, as Chan et al., (2011) described. Scale ranking analysis was employed to determine rankings, and SPSS 28.0 was utilized to calculate the mean, standard deviation, and number from survey responses. According to Chen & Chen (2007), things were ranked based on their mean score values. If two things have identical mean score values during the ranking procedure, the smallest Standard Deviation (SD) item is ranked highest. Then, the selection of the items will be determined by the normalization value (NV), where the NV score must be more than 0.5 for an item to be deemed the best in a particular category.

Mean score ranking and normalization were used to determine the relative classification of variables. Normalization provides accurate data interpretation, making it the method of choice for identifying important characteristics and strategies in this research. Radzi et al., (2022); Lee et al., (2015) have previously used this technique to identify important factors. The method converts the minimum mean value to a normalized value of 0 and the maximum mean value to a normalized value of 1. The mean values of other intervals were converted to decimal NV ranging between 0 and 1. Significant variables are those that achieve normalized values of at least 0.50. The formula used to compute the normalized values is shown in Equation 1.1 in section 3.5.2.1. When multiple variables have identical mean scores, the standard deviation ranks them. The minimal standard deviation (SD) characteristics are rated highest.

$$Normalized\ value = \frac{Mean - Minimum\ mean\ value}{Maximum\ mean\ value - Minimum\ mean\ value} \qquad 0.1$$

3.5.3 Relationship analysis

To achieve the intended objective 3 of this research, data was analyzed using the Exploratory factor analysis (EFA) and Partial least-squares structural equation modelling (PLS-SEM) to analyze the relationship of underlying constructs of organizational attributes and strategies to produce accurate digital twins of construction projects.

3.5.3.1 Exploratory factor analysis (EFA)

Exploratory Factor Analysis (EFA) was used to identify the key variables related to organizational attributes and strategies to produce accurate digital twins. According to (Norušis, 2008), EFA allows the consolidation and reduction of several interrelated factors into a smaller and more meaningful collection of constructs. The two preferred types of factor analysis are exploratory factor analysis and confirmatory factor analysis. The purpose of EFA is to discover the constructs that drive a series of responses. In contrast, confirmatory component analysis examines if a given collection of hypothesized constructs influences responses in the hypothesized manner. The sample size for EFA will be calculated by the sample size to several variables ratio. According to Gorsuch (1983) the minimum acceptable ratio value is 5.00. Using the Kaiser-Meyer-Olkin (KMO) and Bartlett's tests for sphericity, the suitability of the attributes and strategies data for EFA will be determined. For this study, a KMO value of 8.0 will be chosen referring to the latest research done by (Pallant, 2020).

According to Hair et al., (2008), the significant factor loading for an approximately 100-person sample is 0.60. An average value above 0.6 is acceptable for samples less than 100, an average value between 0.5 and 0.6 is acceptable for sample sizes between 100 and 200 (MacCallum et al., 1999). As a result, a factor loading threshold of 0.50 was utilized to eliminate weak indicators of common components. EFA was done using Principal Axis Factoring because these exploratory approaches statistically analyze the correlations between the instrument items and domains to elucidate the unknown underlying factorial structure (dimensions) of the construct of interest (Tavakol & Wetzel, 2020).

3.5.3.2 Partial Least-Squares Structural Equation Modelling (PLS-SEM)

Partial least-squares structural equation modelling (PLS-SEM) was employed to examine the hypotheses. Using SEM, observed variables were assessed directly, whilst latent variables can be extracted from observed variables. Measurement models and structural models are the components of a structural equation model. A measurement model depicts the relationship between every observable variable and its corresponding latent variable. A structural model depicts the relationships between latent variables. Covariance-based SEM (CB–SEM) and PLS-SEM are the two types of SEM. According to Hair et al., (2014), PLS-SEM is more effective than CB–SEM at handling non-normal data and small-scale sample sizes. Subsequently Joreskog & Wold (1982), suggested that it is equally useful to conduct exploratory research using incompletely established theoretical models.

Munianday et al., (2022) stated that PLS-SEM generates a collection of measurement and structural models. Firstly, the measurement model's validity will be examined using extracted average variance (AVE), variable loadings and composite reliability. According to Hair et al., (2011), the internal consistency reliability will be evaluated using composite reliability and Cronbach's alpha, both of which must be greater than 0.70. Additionally, the indicator's dependability is assessed using variable loadings on the relevant construct, which must be at least 0.40.

Then, Hair et al., (2011) stated that convergent validity is assessed using the AVE, and its value must be more than 0.5. Evaluation of discriminant validity comes next. Hulland (1999) outlined discriminant validity as the degree to which one construct varies from other constructs. For an acceptable discriminant validity, Fornell & Larcker (1981) suggested that the square root of AVE for each construct should be greater than the correlations between any combination of any two constructs in the model. The significance and relevance of the structural model's relationships was used to determine the structural model's validity. Meanwhile, the appropriateness of the Heterotrait-Monotrait (HTMT) ratio is a subject of debate. Several works Henseler et al., (2015); Hair et al., (2011) indicate that values below 0.9 are preferable. It is generally recommended that the HTMT ratio should not surpass 1.00. The assessment of the structural model's validity involves an evaluation of the importance and relevance of the links within the model (Henseler et al., 2015).

a. Convergent validity

Convergent validity pertains to the degree of correlation between the new scale, other variables, and other measures that assess the same construct. The concept should have positive correlations with related factors and should not exhibit correlations with dissimilar, unrelated variables (Krabbe, 2016). Loadings of variables on AVE values should surpass the minimum threshold of 0.4 and 0.5, while Cronbach's alpha values should surpass the minimum threshold of 0.7. In this research, assessing the dependability and accuracy of the measurement models is essential. The construction of dependable measurement models is a necessary condition for conducting structural model testing.

b. Discriminant validity

Discriminant validity is established by empirical data indicating that measurements of dimensions that are not expected to have a strong relationship with each other are indeed not strongly associated. In practical terms, the discriminant validity coefficients should be significantly smaller in size compared to the coefficients for convergent validity (Hubley, 2021). In this research, the square-rooted AVE values for the constructs were considered for discriminant validity evaluation. The readings from the Fornell-Larcker criterion, Heterotrait-Monotrait ratio (HTMT) – Matrix values and Cross-loadings analysis results were also considered.

3.6 Summary

The purpose of the methodology chapter is to delineate how the research objectives were achieved, and the methods employed, including open-ended interviews, systematic literature reviews, pilot study and questionnaire surveys. It also encompasses a research framework outlining the key steps in fulfilling the research aims and objectives. The questionnaire survey was developed based on insights gathered from open-ended interviews, a thorough systematic literature review (SLR), and a pilot study to validate the questionnaire. The target respondents were selected from a diverse group of construction professionals ranging from Building Information Modelling (BIM) assistant managers to organizational leaders with knowledge of digital twin production. This research primarily utilized purposive sampling and snowball sampling techniques for respondents' selection. In this research, Reliability Analysis (Cronbach Alpha test, Mann Whitney- U test and Two Standard Deviation technique), Normalized Mean Score Ranking technique (NV), Exploratory Factor Analysis (EFA), and PLS-SEM were applied to discover the organizational attributes and strategies to produce accurate digital twins and to unlock the inter-relationship between the organizational attributes and strategies.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

This section discusses the results obtained from the interview data, systematic literature review, and questionnaire survey. The results yielded 21 organizational attributes and 30 organizational strategies in Phase 1, 11 key organizational attributes and 20 key organizational strategies in Phase2 and six hypotheses were formulated with two classified factor groups for organizational attributes (organizational digital twin capabilities and technological capabilities requirements) and three groups for organizational strategies (organizational competitiveness and investments, organizational workforce management and training, and organizational management capabilities). Moreover, only three hypotheses were finally supported in Phase 3.

4.2 Phase 1: Qualitative method

The data collection in Phase 1 aims to achieve objective 1, that is, to formulate a theory to identify organizational attributes and strategies to produce accurate digital twin of construction projects in the AEC industry.

4.2.1 Respondents' profile

The open-ended interview was structured to gather specific details extensively. As illustrated in Table 4.1, the research involved 20 BIM experts knowledgeable in digital twins, ranging from BIM assistant managers to organization directors. These participants were selected for their ability to provide the needed information and their diverse professional backgrounds and work experiences. After each interview, a summary was sent to the respective respondents for confirmation, ensuring the accuracy and validity of the information collected.

Table 4.1 Respondents list

Respondent	Gender	Age	Work experience	Position
R1	M	36	4	Architectural Senior Lecturer, Certified BIM personnel
R2	M	30	10	Head of BIM Department
R3	M	34	5	Built Environment Sector Lead
R4	M	29	4	BIM Section Head
R5	M	41	5	BIM Assistant Manager
R6	M	44	4	Senior BIM Manager
R7	M	37	14	Chief Operating Officer
R8	M	33	8	Senior BIM Engineer
R9	M	45	11	Director
R10	M	30	6	Principal Business Expert
R11	M	37	11	Consultant
R12	M	40	6	Director
R13	M	33	11	Director
R14	M	37	15	Senior Civil Engineer
R15	M	44	10	Civil Engineer
R16	F	42	10	BIM Development Senior Manager
R17	M	28	12	Associate
R18	M	47	12	Special Director
R19	M	33	2	Senior Executive BIM
R20	M	40	8	Director

4.3 Results of interview data

4.3.1 Organizational attributes to produce digital twins

This research presents findings from interviews with 20 Malaysian BIM professionals knowledgeable about digital twins. The study aimed to identify essential attributes for organizations to develop a digital twin in the AEC industry. The results shown in Figure 4.1 had categorized three main themes: "Process", "People", and "Technology". These main themes are further organized into six subthemes: "Software", "Hardware", "Work Process", "Experts", "Project Team", and "Mindset Readiness". The report delves into these themes and subthemes in greater detail in subsequent sections.

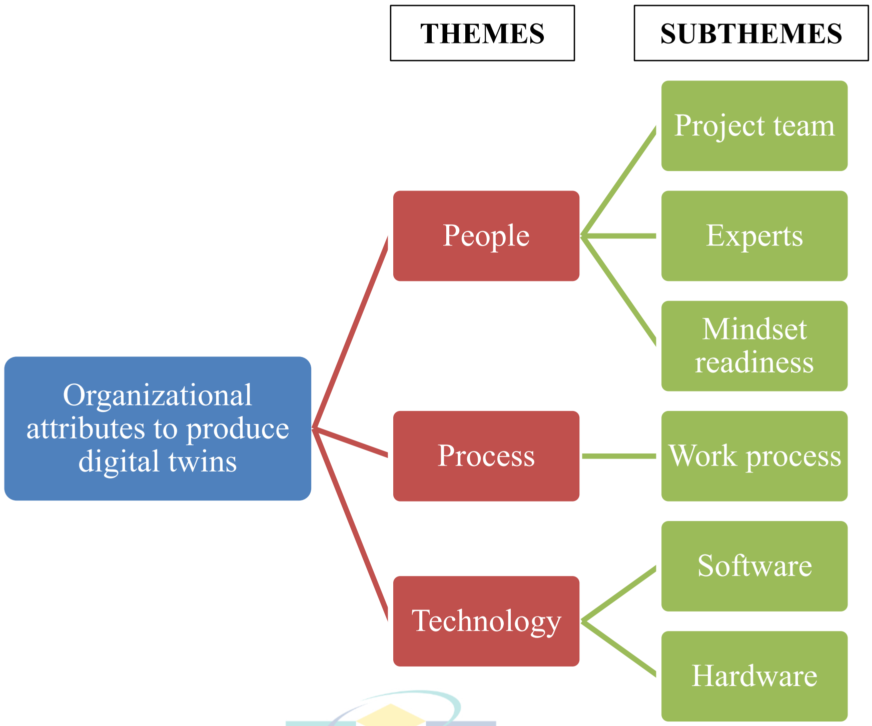

Figure 4.1 Organizational attributes to produce digital twins

4.3.1.1 People

"People" play a crucial role in adopting digital twin technology in the AEC industry. This involves how an organization adapts and influences the future use of digital twins. Challenges include resistance to change in current technology practices and a need for knowledge in embracing new methods. Key attributes related to the "People" aspect are (i) Project Team, (ii) Experts, and (iii) Mindset Readiness, which are essential for the successful implementation of digital twins in the industry.

i. Project team

Project teams play a vital role in managing the workflow of every project from start to finish. Their responsibilities include efficient communication within the team, coordination of tasks, understanding and following a clear project structure, and guiding the project's direction. Additionally, the maturity of the supply chain among stakeholders and consultant teams is critical to embracing new methodologies in practice. The insights and details from the interviews that highlight this necessity are summarized in Table 4.2 in section 4.3.1.3.

ii. Experts

For the successful implementation of new technologies like digital twins, it is crucial to have experts with specialized knowledge. These skilled professionals are essential for efficiently preparing and integrating digital twins within an organization. Their expertise significantly enhances the efficiency of the work process. The insights and details from the interviews that highlight this necessity are summarized in Table 4.2 in section 4.3.1.3.

iii. Mindset readiness

The hesitation in Malaysia to adopt digital twins arises from a general unpreparedness in the construction industry to embrace system changes. Additionally, there needs to be more awareness about the benefits digital twins can offer. The insights and details from the interviews that highlight this necessity are summarized in Table 4.2 in section 4.3.1.3.

4.3.1.2 Process

A streamlined construction process leads to improved workflow and outputs, yet it requires complex procedures to achieve results. Innovativeness and a thorough understanding of concepts and theories are also crucial for enhancing output quality. Within this context, an attribute identified is the "Work Process", which is integral to the efficiency of the construction process.

i. Work process

The work process entails a well-defined roadmap and strategic thought to enable construction teams to implement digital twins in their organizations effectively. An efficient work process starts at an early stage, emphasizing the need for proper asset information requirements. The insights and details from the interviews that highlight this necessity are summarized in Table 4.2 in section 4.3.1.3.

4.3.1.3 Technology

A skilled team and adequate information alone can only execute work effectively with technology. Technology is critical in ensuring tasks are completed as required, with optimal use saving time. Two key technological attributes are identified in this context: (i) Software, which provides the necessary applications and platforms, and (ii) Hardware, the physical tools and equipment essential for the process.

i. Software

Software, defined as the programs and operating data computers use, is intrinsically linked to hardware. In the realm of digitalization, particularly for preparing digital twins, both software and hardware are essential. However, a cost implication is associated with utilizing high-quality software to develop digital twins. The insights and details from the interviews that highlight this necessity are summarized in Table 4.2 in section 4.3.1.3.

ii. Hardware

Hardware refers to the physical equipment necessary to operate the software. Appropriate hardware, such as high-performance computers and reliable laptops, is crucial for creating digital twins. The ease of digital twin development is significantly enhanced when there is strong compatibility between the software and hardware used. The insights and details from the interviews that highlight this necessity are summarized in Table 4.2 in section 4.3.1.3.

Table 4.2 Respondents' statements on organizational attributes to produce digital twins

Attributes	Respondent's statements
Project team	Supply chain maturity in adopting new approaches in practice, the willingness of multidisciplinary stakeholders within a project team to adopt new technology." (R1) "Proper project briefs, project goals." (R5)
Experts	"Need proper qualifications for 3D modelers, coordinators, and managers." (R5) "Technical skill workers - It will make the job easier because of the knowledge they have to understand the purpose of BIM." (R6)

Table 4.2 Continued.

Work process	"People and technology are related to each other. The work process is bridging between people and technology." (R15) "Guidelines are driven by BIM manager. Not necessarily in a detailed format, as long as a road map can be generated, and projects can be executed." (R17)
Mindset readiness	Mindset readiness "Lack of knowledge to adopt a new practice. Especially by client and project stakeholders. Client plays a huge role to spearhead change." (R1) "Lack of awareness and knowledge." (R2)
Software	"Tools - software and hardware. Cost factor. Relates to return of investment to the company." (R11) "Tools - hardware and software. For better connectivity of workflow." (R7)
Hardware	"Hardware is related to providing high spec computers that require a good ICT network that acts as a server because digital twin uses a lot of wireless sensors." (R15) "Tools - hardware and software. Good specs, tiptop." (R9)

4.3.2 Organizational strategies to produce digital twins

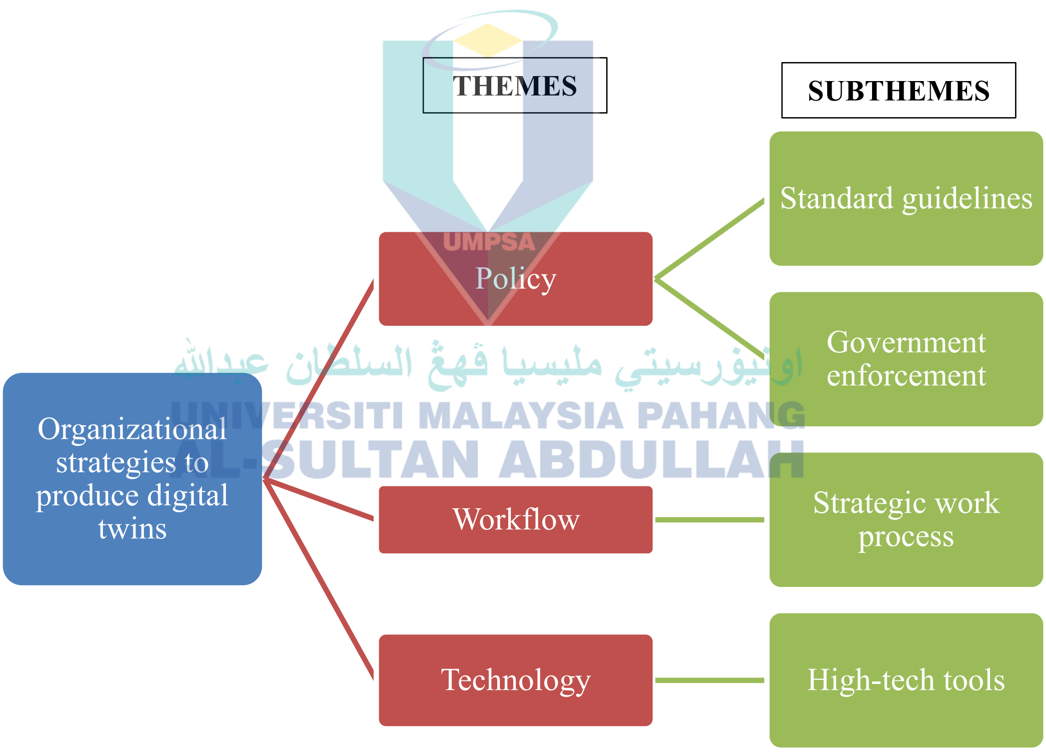

Figure 4.2 Organizational strategies to produce digital twins

Figure 4.2 provides a concise overview of the themes and subthemes related to strategies to enable an organization to attain the attributes associated with developing a digital twin. A survey of twenty participants identified four distinct subthemes that represent the strategies employed. These subthemes are labelled as follows: "Standard

Guidelines," "Government Enforcement," "Strategic Work Processes," and "High-tech Tools." Furthermore, these four subthemes can be categorized into three overarching themes, namely "Policy," "Workflow," and "Technology”. The detailed themes and subthemes are further deliberated in the following subsections.

4.3.2.1 Policy

A policy serves as a guiding principle for actions taken by organizations or individuals. In the Malaysian construction industry context, a policy is instrumental in facilitating the transition from traditional practices to adopting digital twins. Two critical strategies related to policy have been pinpointed: (i) Standard Guidelines and (ii) Government Enforcement, which both play significant roles in steering this change.

i. Standard guidelines

The standard guidelines vary across different organizations and individuals, leading to a need for a unified direction for stakeholders. Therefore, there is a need for a universally applicable standard tailored to the country's specific needs and context. The insights and details from the interviews that highlight this necessity are summarized in Table 4.5 in section 4.3.2.3.

ii. Government enforcement

In Malaysia, the government is a pivotal force in the construction sector, playing a key role in advancing the implementation of digital twins across organizations. Government enforcement is influential in ensuring that organizations or individuals adhere to set standards, as it aligns with the national direction. This enforcement is crucial for successfully integrating digital twins into the industry. The insights and details from the interviews that highlight this necessity are summarized in Table 4.5 in section 4.3.2.3.

4.3.2.2 Workflow

A workflow entails a strategic approach to work processes, encompassing thorough planning, specific action plans, and a carefully thought-out roadmap. This strategy is essential for ensuring a smooth work process with minimal disruptions. In this context, the critical strategic element linked to workflow is identified as (i) Strategic Work Process, which focuses on effectively organizing and guiding work activities.

i. Strategic work process

A strategic work process is designed to assist organizational leaders in making decisions that align with their objectives. It is vital to strategize from the onset, defining clear goals and plans for the upcoming years to ensure targeted achievements are met. The insights and details from the interviews that highlight this necessity are summarized in Table 4.5 in section 4.3.2.3.

4.3.2.3 Technology

People and technology are interdependent, with technology continually evolving over time. The technology must be sufficiently advanced to meet its requirements to prepare a digital twin successfully. Consequently, technology must be regularly updated to stay effective. In this context, an essential strategic aspect linked to technology is using (i) High-tech Tools, emphasizing the need for modern and sophisticated equipment to support digital twin initiatives.

i. High-tech tools

High-tech tools represent the most advanced technology currently available in the market. These cutting-edge tools are essential for the creation and production of digital twins. The insights and details from the interviews that highlight this necessity are summarized in Table 4.5 in section 4.3.2.3.

Table 4.3 Respondents’ statements on organizational strategies to produce digital twins

Strategies	Respondent’s statements
Standard guidelines	“Different companies produce different plans and guidelines.” (R2)
	“Need proper guidelines.” (R9) “Guidelines and standards - depending on the organization which guidelines to follow, whether to develop own company’s guidelines or adopt guidelines available in the market. e.g., To follow JKR standards or international standards using ISO.” (R17)

Table 4.3 Continued.

Government enforcement	"Effective Enforcement by government or client to adopt digital twin." (R1) "Enforcement by regulatory bodies - It relates to the national directions." (R10) "Policy - Government to start to implement. People will start to look into it once initiated by the government. The top to bottom of the organization also needs to start to look into it because it is related." (R13)
Strategic work process	"To develop something, you need to make some investment. And you need to strategize the workflow." (R13) "At least, for a start, kick start with a small project like a small room or a single unit bungalow. This is to test out the expertise needed, roadmap and guidelines required that works and workable." (R17) "Road map - Road map is directly related to an action plan. It involves strategizing on plans and on what is to be achieved. E.g., Plan for the next two years, three years, and five years. KPI to be achieved. Strategized early." (R15)
High-tech tools	"We need to use technology to help us make better decisions." (R12) "Technology - ICT, software, and hardware. Everything needs to be updated accordingly." (R14) "Utilize the latest technology, robots, artificial intelligence, virtual reality, and drone technology. The building process will be better but with a cost. The value of the building must match the investment. E.g., Now, in Malaysia, we applied the stamping approach. Typical condominiums must have car parks, malls, and housing units at the top." (R12)

Table 4.4 Link between interview respondents and the identified organizational attributes to produce digital twin.

Attributes	Respondent 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	
1. Technology																					
Data environment			√	√	√	√							√	√		√	√				8
Digital technology	√	√	√	√		√	√	√	√	√		√	√	√	√						13
Software				√	√	√	√	√	√					√	√	√	√	√			11
Hardware	√				√	√	√	√	√						√	√	√	√	√	√	12
Digital security			√			√	√														3
2. Fundings																					
Financial capability	√				√			√	√						√						5
Government funding	√					√						√		√	√						5
Investments	√			√				√					√		√	√	√				7
3. Policy																					
Government enforcement	√				√				√				√		√		√				6
Standard submission guidelines		√	√			√	√		√	√			√			√	√				9
State authority enforcement									√		√	√									3
Organization policy						√	√			√			√				√	√			6
Standard operating procedure							√										√	√			3

Table 4.4 Continued.

Contracts				√												√					2
4. Process																					
Work process		√	√		√	√	√						√		√	√	√	√		√	11
Quality working system																√				√	2
Research and development				√								√	√				√				4
5. People																					
Organization leadership	√		√		√		√	√		√			√					√			8
Project team	√	√	√	√	√	√	√	√	√	√			√		√		√	√		√	15
Specialized personnel										√								√		√	3
Upskilling staffs	√					√		√					√		√	√	√	√	√		9
Experts	√	√	√	√	√	√	√	√	√	√			√		√	√	√	√		√	16
Mindset readiness	√	√	√	√			√	√	√								√	√	√		10
Work culture transformation	√		√			√	√														4
Information awareness	√	√	√		√							√	√			√		√			8

Table 4.5 Link between interview respondents and the identified organizational strategies to produce digital twin.

Strategies	Respondent																				
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	
1. Policy																					
Standard guidelines		√	√	√		√		√	√	√	√	√		√	√		√	√	√		14
Organization policy	√						√			√	√										4
Government enforcement	√	√	√			√			√	√			√	√				√	√		10
2. People																					
Supply chain maturity	√		√				√	√		√			√								6
Work culture mentality						√	√			√	√	√	√								6
Experts					√			√	√		√				√	√	√			√	8
Training programs				√	√									√				√			4
Graduates hands-on training		√		√	√														√		4
Organization leadership							√			√				√			√				4
Education system		√	√	√	√				√										√		6
Awareness initiatives			√	√	√								√	√				√	√		7
Research and Development				√						√		√	√				√				5
3. Financial																					
Government funding							√					√									2
Tools subsidies					√	√		√		√											4
Financial support					√		√	√			√	√									5
Contractual fees	√							√											√		3

Table 4.5 Continued.

4. Workflow																			
Quality management														√					1
Asset information system																		√	1
Strategic work process	√										√		√		√		√	√	6
5. Technology																			
Digital data platform					√		√	√		√		√							5
Hi-tech Tools		√	√		√	√				√		√	√					√	8
Digital currency										√									1
Technology impacts					√				√	√			√				√		5
Smart contracts										√									1

4.4 Phase 2: Quantitative method

The data collection in Phase 2 was targeted to achieve objectives 2 and 3, that is, to determine key organizational attributes and strategies to produce accurate digital twins of construction projects and to analyze the relationship of underlying constructs of organizational attributes and strategies to produce accurate digital twins of construction projects. The questionnaire survey was developed based on the interview data, systematic literature review and pilot study conducted in Phase 1, which produced a list of 21 organizational attributes and 30 organizational strategies. The listed variables were used to run the survey using the Survey Legend platform to gain responses and feedback.

4.4.1 Data collection

The target population comprises AEC industry professionals with knowledge of the production of digital twins. Tables 4.6 and 4.7 show the list of organizational attributes and strategies for producing accurate digital twins of construction projects.

Table 4.6 List of organizational attributes for producing accurate digital twins of construction projects

Codes	Organizational attributes for producing accurate digital twins of construction projects	Source
ADT1	Technological capabilities among employees on digital twin.	Agrawal et al. (2022)
ADT2	Strategic mindset among employees on digital twin.	Agrawal et al. (2022); Abusohyon et al. (2021); Shahzad et al (2021); *Interview*
ADT3	Coordination among employees on digital twin.	Interview
ADT4	Employee awareness on the business value of digital twin.	Agrawal et al. (2022); Abusohyon et al. (2021); *Interview*
ADT5	Employee understanding on the value of digital twin data.	Agrawal et al. (2022); Abusohyon et al. (2021); *Interview*
ADT6	Digital twin technological on infrastructure.	Shahzad et al (2021); *Interview*
ADT7	Mechanisms for digital twin data operationalization.	Broo and Schooling (2022)
ADT8	Internal strategic digitalization framework on digital twin.	Agrawal et al. (2022)
ADT9	Data compatibility plan for digital twin.	Agrawal et al. (2022); Broo and Schooling (2022); Quichen et al (2019); I*nterview*
ADT10	Shared data environment for digital twin.	Broo and Schooling (2022); Aghimien et al. (2020); *Interview*
ADT11	On-going improvement processes for digital twin deployment.	Abusohyon et al. (2021); *Interview*

Table 4.6 Continued.

ADT12	Internal guidelines for developing digital twins.	Shahzad et al (2021); Broo and Schooling (2022); *Interview*
ADT13	Organizational standardized procedures for developing digital twin.	Agrawal et al. (2022); Broo and Schooling (2022); Quichen et al (2019); *Interview*
ADT14	Data security procedures on digital twin.	Shahzad et al (2021); *Interview*
ADT15	Organizational strategic plan on digital twin.	Interview
ADT16	Strategic working processes on digital twin.	Interview
ADT17	Well-defined organizational objective(s) on digital twin.	Abusohyon et al. (2021); Quichen et al (2019); *Interview*
ADT18	Organizational work culture transformation plan for digital twin.	Shahzad et al (2021); Broo and Schooling (2022); *Interview*
ADT19	Top-down management involvement in the digital twin concept.	Shahzad et al (2021); Broo and Schooling (2022); *Interview*
ADT20	Financial capability of the organization for developing digital twin.	Interview
ADT21	Organizational business development approach in relation to digital twin.	Pilot study

Table 4.7 List of organizational strategies for producing accurate digital twins of construction projects

Codes	**Strategies for producing accurate digital twins of construction projects**	**Source**
SDT1	Determine the right level of complexity when developing digital twin.	Agrawal et al. (2022); *Interview*
SDT2	Determine strategies for organizational cultural transformation on digital twin.	Shahzad et al (2021); Broo and Schooling (2022); *Interview*
SDT3	Determine the organization's transformation goals for digital twin.	Broo and Schooling (2022); *Interview*
SDT4	Determine the best method to achieve the expected level of data transmission quality for digital twin.	Abusohyon et al. (2021); Shahzad et al (2021); *Interview*
SDT5	Provide external training on digital twin.	Interview
SDT6	Provide internal training on digital twin.	Abusohyon et al. (2021); Shahzad et al (2021); Broo and Schooling (2022); *Interview*
SDT7	Provide opportunities for learning and experimentation without restrictions on time or cost.	Broo and Schooling (2022); *Interview*
SDT8	Provide employees with opportunities to explore digital twin data.	Abusohyon et al. (2021); Shahzad et al (2021); Broo and Schooling (2022); *Interview*
SDT9	Provide effective tools for communicating information on digital twins.	Shahzad et al (2021); *Interview*
SDT10	Provide digital twin awareness to all management levels.	Shahzad et al (2021); *Interview*
SDT11	Increase investments in aligning top employees and digital transformation.	Broo and Schooling (2022)
SDT12	Enhance the organization's attractiveness to attract talented employees.	Broo and Schooling (2022)

Table 4.7 Continued.

SDT13	Enhance the organization's attractiveness to attract digital twin experts.	Broo and Schooling (2022)
SDT14	Recognize the necessity of having digital twins as part of the business.	Interview
SDT15	Use digital currency as the organization's payment method.	Interview
SDT16	Develop a strategic vision among all management levels to implement digital twin.	Agrawal et al. (2022); *Interview*
SDT17	Transform conventional working practices to digitalized working platforms.	Shahzad et al (2021)
SDT18	Implement initiatives to manage cultural risk on digital twin.	Broo and Schooling (2022)
SDT19	Implement digitalization framework as a project planning diagnostic tool throughout the organization.	Agrawal et al. (2022); Abusohyon et al. (2021)
SDT20	Implement a digitalization framework to assist in a long-term vision of achievable levels.	Agrawal et al. (2022)
SDT21	Implement a digitalization framework to assist in a strategic road map.	Agrawal et al. (2022)
SDT22	Implement a comprehensive assessment framework on digital twin.	Wei et al. (2022); Agrawal et al. (2022); *Interview*
SDT23	Create innovative workspaces using new technologies.	Broo and Schooling (2022)
SDT24	Ensure employees have basic knowledge of digital twin.	Broo and Schooling (2022)
SDT25	Ensure compatibility between new and previous versions of available software related to digital twin.	Abusohyon et al. (2021)
SDT26	Emphasize transparency and accountability among employees on digital twin.	Broo and Schooling (2022); *Interview*
SDT27	Incorporate existing data to generate information to improve insights for operations management in sustaining infrastructure assets.	Broo and Schooling (2022)
SDT28	Arrange digital experts as external partners.	Abusohyon et al. (2021); Aghimien et al. (2020)
SDT29	Build up a good organizational financial support system on digital twin.	Interview
SDT30	Investment in creating custom technology to suit local market needs.	Pilot study

4.4.2 Respondents profile

129 valid responses were successfully obtained. Based on Table 4.8, the respondents encompass various organizations that are classified into six distinct categories: 1) Clients (Government / Private developers), 2) Consultants, 3) Contractors, 4) Suppliers, 5) Manufacturers, and 6) Others. From 129 respondents resulted into 18.6% represent clients, 44.2% are consultants, 29.5% constitute contractors, 0.8% stand as suppliers, 3.9% are manufacturers, and 3.1% fall into the 'Others' category. Regarding professional tenure, 31.8% of respondents possess over a decade of work experience, while 23.3% have accrued 6 to 9 years, 29.5% hold 2 to 5 years, and 15.5% have less

than 2 years of experience. Geographic workplace location shows that Central region has the highest percentage of 44.2% compared to East Coast region of only 10.2%. This robust distribution assures the respondents' competence in providing credible insights for the survey. Table 4.8 shows the details of respondents' profile from survey data.

Table 4.8 Respondents' profiles from survey data

Profiles	**Categories**	**Number of respondents**	**Percentage (%)**
Types of organization	Client (Government/Private Developer)	24	18.6
	Consultant	57	44.2
	Contractor	38	29.5
	Supplier	1	0.8
	Manufacturer	5	3.9
	Others	4	3.1
Types of profession	Architect	23	17.8
	Civil and Structural Engineer	36	27.9
	MEP Engineer	16	12.4
	Contractor	5	3.9
	Others	6	4.7
	BIM professionals	31	24.0
	Research contractor	1	0.8
	Project manager	3	2.3
	Structural designer	1	0.8
	CMMS engineer	1	0.8
	Project engineer	1	0.8
	Quantity surveyor	3	2.3
	Contract manager	1	0.8
	Land survey engineering	1	0.8
Current workplace location	North region	17	13.2
	South region	21	16.3
	East Coast region	14	10.9
	Sabah & Sarawak	20	15.5
	Central region	57	44.2
Years of experience in construction industry	Less than 2 years	20	15.5
	2 to 5 years	38	29.5
	6 to 9 years	30	23.3
	More than 10 years	41	31.8
Working experience related to digital twin or BIM	Less than 2 years	61	47.3
	2 to 5 years	50	38.8
	6 to 10 years	16	12.4
	More than 10 years	2	1.6
Types of construction sector involved. *Multiple answers	Non - residential (eg. Hotel, shop houses, business complex, office)	68	
	Residential (eg. Terrace, bungalow, flat, condominium)	73	
	Social amenities (eg. Hospital, youth centre, community centre)	48	

Table 4.8 Continued.

	Infrastructure (eg. Airport, railway or train station, bus station)	62	
	Others	10	
Heard of digital twin	No	85	65.9
	Yes	44	34.1

4.5 Phase 3: Analysis and results

4.5.1 Realibility analysis

Version 23.0 of IBM's Statistical Package for the Social Sciences (SPSS) was utilized to conduct a reliability analysis. Ringle et al., (2014) conducted exploratory factor analysis and statistically evaluated the hypotheses using structural equation modelling with the partial least squares (PLS) approach and SmartPLS3 (Oststeinbek, Germany: SmartPLS).

4.5.1.1 Cronbach alpha test

The alphas range from 0 to 1, with values between 0.7 and 0.8 indicating acceptable internal consistency (Pallant, 2020). Cronbach's alpha values were 0.975 for respondents knowledgeable about digital twins and 0.986 for respondents unfamiliar with the concept in this research. These high values demonstrate outstanding reliability at a 5% significance level, making the collected samples suitable for further analysis.

4.5.1.2 Mann-Whitney U test

This research's null hypothesis (H0) states that "there is no significant ranking difference between the two independent groups." (Hinton et al., 2004). A significance level below 0.05 (p: 0.05) leads to the rejection of the null hypothesis. The Mann-Whitney test generally produces p-values greater than 0.05, except for "ADT10" (p-value: 0.023) and "ADT14" (p-value: 0.037). This indicates minimal to no significant differences between the two respondent groups regarding familiarity with digital twins. Therefore, there are no statistically significant differences between respondents who have and have not heard of digital twins.

4.5.1.3 Two standard deviations (SD) technique

This method involves calculating means, standard deviations, and two SD intervals for organizational attributes and digital twin production strategies. *Outliers* are attributes and strategies that fall outside the minimum and maximum range. Consequently, "ADT8" was identified as an outlier among attributes, and "SDT15" was identified as an outlier among strategies (King et al., 2022; Radzi et al., 2021). Thus, the outliers were removed from the list of variables.

4.5.2 Criticality analysis

In identifying key organizational attributes and strategies to produce accurate digital twins, Normalized Mean score ranking technique was conducted to achieve it. Variables were ranked with accordingly from highest to lowest NV value.

4.5.2.1 Normalized mean score ranking technique

In this context, the method normalizes the minimum mean value to 0 and the maximum mean value to 1. Attributes and strategies with normalized values of at least 0.50 are designated as significant to produce accurate digital twins. This method ranked key attributes and strategies with identical mean scores according to their standard deviations, with smaller standard deviations ranking higher. According to the results shown in Table 4.9 and Table 4.10, there are 11 key attributes and 20 key strategies for producing accurate digital twins.

In summary, based on Table 4.9 and Table 4.10, the listed key attributes for organizational attributes were ADT3, ADT10, ADT13, ADT20, ADT12, ADT18, ADT19, ADT17, ADT15, ADT9 and ADT11. ADT3 ranked the highest, with NV= 1.00, while ADT 9, with NV=0.50, ranked the lowest due to a larger SD value compared to ADT11. This showed that coordination among employees on digital twins is a top priority in producing digital twins. For organizational strategies, the listed key strategies were SDT4, SDT11, SDT12, SDT10, SDT25, SDT13, SDT24, SDT5, SDT9, SDT8, SDT1, SDT26, SDT14, SDT6, SDT27, SDT20, SDT22, SDT29, SDT2 and SDT7. SDT4 ranked the highest with NV=1.00, while SDT 7, with NV=0.514, ranked the lowest with a larger SD value compared to SDT2. This indicated that determining the best method to achieve the expected level of data transmission quality for digital twins is a vital strategy for producing digital twins in the AEC industry.

Table 4.9 The normalized value for organizational attributes for producing accurate digital twins of construction projects

Code	Organizational attributes to produce digital twin	Mean	SD	NV	Rank
ADT3	Coordination among employees on digital twin.	4.0233	1.11429	1.000	1
ADT10	Shared data environment for digital twin.	4.0155	1.03066	0.964	2
ADT13	Organizational standardized procedures for developing digital twin.	4.0078	1.06613	0.929	3
ADT20	Financial capability of the organization for developing digital twin.	3.9535	1.15150	0.679	4
ADT12	Internal guidelines for developing digital twins.	3.9457	1.01789	0.643	5
ADT18	Organizational work culture transformation plan for digital twin.	3.9457	1.02553	0.643	6
ADT19	Top-down management involvement in the digital twin concept.	3.9457	1.04066	0.643	7
ADT17	Well-defined organizational objective(s) on digital twin.	3.9225	1.04293	0.536	8
ADT15	Organizational strategic plan on digital twin.	3.9147	1.05350	0.500	9
ADT11	On-going improvement processes for digital twin deployment.	3.9147	1.03101	0.500	10
ADT9	Data compatibility plan for digital twin.	3.9147	1.08276	0.500	11
ADT4	Employee awareness on the business value of digital twin.	3.9070	1.16218	0.464	12
ADT16	Strategic working processes on digital twin.	3.8682	1.05608	0.286	13
ADT14	Data security procedures on digital twin.	3.8605	1.06613	0.250	14
ADT21	Organizational business development approach in relation to digital twin.	3.8527	1.13262	0.214	15
ADT5	Employee understanding on the value of digital twin data.	3.8372	1.18447	0.143	16
ADT1	Technological capabilities among employees on digital twin.	3.8295	1.06891	0.107	17
ADT2	Strategic mindset among employees on digital twin.	3.8217	1.07855	0.071	18
ADT6	Digital twin technological on infrastructure.	3.8140	1.16436	0.036	19
ADT7	Mechanisms for digital twin data operationalization.	3.8062	1.06123	0.000	20

Table 4.10 The normalized value for organizational strategies for producing accurate digital twins of construction projects

Code	Organizational strategies to produce digital twin	Mean	SD	NV	Rank
SDT4	Determine the best method to achieve the expected level of data transmission quality for digital twin.	4.1240	0.87507	1.000	1
SDT11	Increase investments in aligning top employees and digital transformation.	4.1163	0.96524	0.973	2
SDT12	Enhance the organization's attractiveness to attract talented employees.	4.1085	0.90347	0.946	3
SDT10	Provide digital twin awareness to all management levels.	4.1085	1.05505	0.946	4
SDT25	Ensure compatibility between new and previous versions of available software related to digital twin.	4.0930	0.90521	0.892	5
SDT13	Enhance the organization's attractiveness to attract digital twin experts.	4.0853	0.94399	0.865	6
SDT24	Ensure employees have basic knowledge of digital twin.	4.0853	1.00802	0.865	7
SDT5	Provide external training on digital twin.	4.0698	1.03219	0.811	8
SDT9	Provide effective tools for communicating information on digital twins.	4.0620	0.99020	0.784	9
SDT8	Provide employees with opportunities to explore digital twin data.	4.0543	1.06294	0.757	10
SDT1	Determine the right level of complexity when developing digital twin.	4.0465	0.92585	0.730	11
SDT26	Emphasize transparency and accountability among employees on digital twin.	4.0388	0.98745	0.703	12
SDT14	Recognize the necessity of having digital twins as part of the business.	4.0310	0.95964	0.676	13
SDT6	Provide internal training on digital twin.	4.0233	1.10018	0.649	14
SDT27	Incorporate existing data to generate information to improve insights for operations management in sustaining infrastructure assets.	4.0233	0.92251	0.649	15
SDT20	Implement a digitalization framework to assist in a long-term vision of achievable levels.	4.0078	0.94783	0.595	16
SDT22	Implement a comprehensive assessment framework on digital twin.	3.9922	0.92277	0.541	17

Table 4.10 Continued.

SDT29	Build up a good organizational financial support system on digital twin.	3.9922	0.96417	0.541	18
SDT2	Determine strategies for organizational cultural transformation on digital twin.	3.9845	0.89254	0.514	19
SDT7	Provide opportunities for learning and experimentation without restrictions on time or cost.	3.9845	1.07518	0.514	20
SDT17	Transform conventional working practices to digitalized working platforms.	3.9767	0.96392	0.486	21
SDT23	Create innovative workspaces using new technologies.	3.9612	0.90487	0.432	22
SDT3	Determine the organization's transformation goals for digital twin.	3.9457	0.98671	0.378	23
SDT19	Implement digitalization framework as a project planning diagnostic tool throughout the organization.	3.9380	0.93334	0.351	24
SDT16	Develop a strategic vision among all management levels to implement digital twin.	3.9380	0.95812	0.351	25
SDT30	Investment in creating custom technology to suit local market needs.	3.9302	0.92014	0.324	26
SDT21	Implement a digitalization framework to assist in a strategic road map.	3.8915	0.92060	0.189	27
SDT18	Implement initiatives to manage cultural risk on digital twin.	3.8760	0.94379	0.135	28
SDT28	Arrange digital experts as external partners.	3.8372	1.00616	0.000	29

4.5.3 Relationship analysis

The relationship analysis was conducted using Exploratory factor analysis (EFA) to determine the factor groups of attributes and strategies, and Partial least-squares Equation Modeling (PLS-SEM) to model the relationship between organizational attributes and strategies.

4.5.3.1 Exploratory factor analysis (EFA)

The minimum ratio recommended by Gorsuch (1983) was 5.00. Therefore, the sample size-to-variable ratios for organizational attributes data are 11.73 and for organizational strategies data they are 6.45. Thus, the sample size for this research was confirmed as adequate.

Using the Kaiser-Meyer-Olkin (KMO) test and Bartlett's test of sphericity, the applicability of the strategies data and capacity attributes data for EFA was assessed. The KMO values of 0.959 (attributes) and 0.949 (strategies) in this study exceeded the minimal admissible threshold of 0.80, indicating that the data are suitable for analysis (Pallant, 2020). Bartlett's test of sphericity yielded results of 2706.92 for attributes and 4049.74 for strategies, each with a significance value of 0.000, indicating the significance of the correlation matrix at p:0.05 and ruling out the possibility that it is an identity matrix. Therefore, the data are appropriate for factor analysis. Principal Axis Factoring was conducted to run EFA. Tables 4.11 and 4.12 show the exploratory factor analysis results for organizational attributes and strategies for producing accurate digital twins of construction projects.

In summary, the results of the exploratory factor analysis showed that the organizational attributes were divided into two-factor groups while three-factor groups were divided for organizational strategies. For organizational attributes, factor group 1 consisted of ADT10, ADT11, ADT12, ADT13, ADT14, ADT15, ADT16, ADT17, ADT18, ADT19, ADT20 and ADT21. Meanwhile, for factor group 2, there were ADT1, ADT2, ADT3, ADT4, ADT5, ADT6, ADT7, and ADT9. For organizational strategies, factor group 1 consisted of SDT11, SDT12, SDT13, SDT16, SDT17, SDT19, SDT20, SDT21, SDT23, SDT27, SDT28 and SDT30. For factor group 2 were SDT5, SDT6, SDT7, SDT8, SDT9, SDT10, SDT14, SDT24, SDT25, SDT26 and SDT29. Moreover, factor group 3 ranged from SDT1, SDT2, SDT3, SDT4, SDT18 and SDT22.

Table 4.11 Exploratory factor analysis results for organizational attributes for producing accurate digital twins of construction projects.

Codes	**Organizational attributes for producing accurate digital twins of construction projects**	**Factor** 1	2
ADT10	Shared data environment for digital twin.	0.637	-
ADT11	On-going improvement processes for digital twin deployment.	0.687	-
ADT12	Internal guidelines for developing digital twins.	0.707	-
ADT13	Organizational standardized procedures for developing digital twin.	0.644	-
ADT14	Data security procedures on digital twin.	0.707	-
ADT15	Organizational strategic plan on digital twin.	0.792	-

Table 4.11 Continued.

ADT16	Strategic working processes on digital twin.	0.767	-
ADT17	Well-defined organizational objective(s) on digital twin.	0.713	-
ADT18	Organizational work culture transformation plan for digital twin.	0.669	-
ADT19	Top-down management involvement in the digital twin concept.	0.744	-
ADT20	Financial capability of the organization for developing digital twin.	0.678	-
ADT21	Organizational business development approach in relation to digital twin.	0.728	-
ADT1	Technological capabilities among employees on digital twin.	-	0.730
ADT2	Strategic mindset among employees on digital twin.	-	0.800
ADT3	Coordination among employees on digital twin.	-	0.728
ADT4	Employee awareness on the business value of digital twin.	-	0.656
ADT5	Employee understanding on the value of digital twin data.	-	0.653
ADT6	Digital twin technological on infrastructure.	-	0.800
ADT7	Mechanisms for digital twin data operationalization.	-	0.751
ADT9	Data compatibility plan for digital twin.	-	0.592
Eigenvalue		13.673	1.067
Variance (%)		66.927	3.949
Cumulative variance (%)		66.927	70.875

Note: Extraction method: principal axis factoring; Rotation method: Varimax with Kaiser Normalization.

Table 4.12 Exploratory factor analysis results for organizational strategies for producing accurate digital twins of construction projects.

Codes	**Strategies for producing accurate digital twins of construction projects**	**Factor**		
		1	2	3
SDT 11	Increase investments in aligning top employees and digital transformation.	0.633	-	-
SDT 12	Enhance the organization's attractiveness to attract talented employees.	0.657	-	-
SDT 13	Enhance the organization's attractiveness to attract digital twin experts.	0.689	-	-
SDT 16	Develop a strategic vision among all management levels to implement digital twin.	0.667	-	-
SDT 17	Transform conventional working practices to digitalized working platforms.	0.657	-	-
SDT 19	Implement digitalization framework as a project planning diagnostic tool throughout the organization.	0.741	-	-
SDT 20	Implement a digitalization framework to assist in a long-term vision of achievable levels.	0.686	-	-
SDT 21	Implement a digitalization framework to assist in a strategic road map.	0.687	-	-
SDT 23	Create innovative workspaces using new technologies.	0.551	-	-
SDT 27	Incorporate existing data to generate information to improve insights for operations management in sustaining infrastructure assets.	0.595	-	-
SDT 28	Arrange digital experts as external partners.	0.587	-	-
SDT 30	Investment in creating custom technology to suit local market needs.	0.581	-	-

Table 4.12 Continued.

SDT 5	Provide external training on digital twin.	-	0.665	-
SDT 6	Provide internal training on digital twin.	-	0.640	-
SDT 7	Provide opportunities for learning and experimentation without restrictions on time or cost.	-	0.663	-
SDT 8	Provide employees with opportunities to explore digital twin data.	-	0.685	-
SDT 9	Provide effective tools for communicating information on digital twins.	-	0.627	-
SDT 10	Provide digital twin awareness to all management levels.	-	0.628	-
SDT 14	Recognize the necessity of having digital twins as part of the business.	-	0.540	-
SDT 24	Ensure employees have basic knowledge of digital twin.	-	0.525	-
SDT 25	Ensure compatibility between new and previous versions of available software related to digital twin.	-	0.495	-
SDT 26	Emphasize transparency and accountability among employees on digital twin.	-	0.528	-
SDT 29	Build up a good organizational financial support system on digital twin.	-	0.533	-
SDT1	Determine the right level of complexity when developing digital twin.	-	-	0.697
SDT 2	Determine strategies for organizational cultural transformation on digital twin.	-	-	0.736
SDT 3	Determine the organization's transformation goals for digital twin.	-	-	0.658
SDT 4	Determine the best method to achieve the expected level of data transmission quality for digital twin.	-	-	0.752
SDT 18	Implement initiatives to manage cultural risk on digital twin.	-	-	0.635
SDT 22	Implement a comprehensive assessment framework on digital twin.	-	-	0.581
Eigenvalue		18.819	1.326	1.118
Variance (%)		63.881	3.524	2.843
Cumulative variance (%)		63.881	67.405	70.248

Note: Extraction method: principal axis factoring; Rotation method: Varimax with Kaiser Normalization.

4.5.3.2 Hypotheses structural model

Using the EFA process outlined in the preceding section, the subsequent six hypotheses were formulated to explore the interrelationships between factors related to attributes and strategies:

i. Hypothesis H1: Organizational digital twin capabilities (ATC1) positively affect organizational competitiveness and investments (STC1).

ii. Hypothesis H2: Organizational digital twin capabilities (ATC1) positively affect organizational workforce management and training (STC2).

iii. Hypothesis H3: Organizational digital twin capabilities (ATC1) positively affect organizational management capabilities (STC3).

iv. Hypothesis H4: Technological capabilities requirements (ATC2) positively affect organizational competitiveness and investments (STC1).

v. Hypothesis H5: Technological capabilities requirements (ATC2) positively affect organizational workforce management and training (STC2).

vi. Hypothesis H6: Technological capabilities requirements (ATC2) positively affect organizational management capabilities (STC3).

4.5.3.3 Partial Least-Squares Structural Equation Modeling (PLS-SEM)

The proposed hypotheses were evaluated using Structural Equation Modelling (SEM) (Objective 3). Partial Least Squares Structural Equation Modelling (PLS-SEM) is a statistical technique that generates a set of measurements and structural models. The assessment of internal consistency reliability is conducted using composite reliability and Cronbach's alpha, whereby optimal values are expected to surpass the threshold of 0.7 (Hair et al., 2011). Indicator reliability is assessed by examining variable loadings on the relevant concept, aiming for a minimum value of 0.4 (Hair et al., 2011). A minimum acceptable AVE value for evaluating convergent validity is 0.5 or above. The subsequent analysis pertains to the assessment of discriminant validity (Hair et al., 2011).

Additionally, the loading of a measuring item on its corresponding construct should be higher than its cross-loadings. The appropriateness of the Heterotrait-Monotrait (HTMT) ratio is debatable. Several works (Henseler et al., 2015; Hair et al., 2011) indicate that values below 0.9 are preferable. According to Henseler et al., (2015), it is generally recommended that the HTMT ratio should not surpass 1.00. The assessment of the structural model's validity involves an evaluation of the importance and relevance of the links within the model. Table 4.13 and Figure 4.3 show the measurement model evaluation results for all the constructs.

Table 4.13 Measurement model evaluation.

Constructs	Indicators	Loadings	AVE	CR	CA
Organizational digital twin capabilities			0.718	0.968	0.964
	ADT10	0.836	-	-	-
	ADT11	0.861	-	-	-
	ADT12	0.847	-	-	-
	ADT13	0.828	-	-	-
	ADT14	0.803	-	-	-
	ADT15	0.891	-	-	-
	ADT16	0.909	-	-	-
	ADT17	0.870	-	-	-
	ADT18	0.807	-	-	-
	ADT19	0.835	-	-	-
	ADT20	0.818	-	-	-
	ADT21	0.855	-	-	-
Technological capabilities requirements			0.749	0.960	0.952
	ADT1	0.859	-	-	-
	ADT2	0.890	-	-	-
	ADT3	0.858	-	-	-
	ADT4	0.834	-	-	-
	ADT5	0.840	-	-	-
	ADT6	0.898	-	-	-
	ADT7	0.912	-	-	-
	ADT9	0.827	-	-	-
Organizational competitiveness and investments			0.695	0.965	0.960
	SDT11	0.825	-	-	-
	SDT12	0.827	-	-	-
	SDT13	0.855	-	-	-
	SDT16	0.869	-	-	-
	SDT17	0.852	-	-	-
	SDT19	0.876	-	-	-
	SDT20	0.856	-	-	-
	SDT21	0.872	-	-	-
	SDT23	0.822	-	-	-
	SDT27	0.824	-	-	-
	SDT28	0.720	-	-	-
	SDT30	0.794	-	-	-
Organizational workforce management and training			0.712	0.964	0.959
	SDT10	0.856	-	-	-
	SDT14	0.863	-	-	-
	SDT24	0.829	-	-	-
	SDT25	0.841	-	-	-
	SDT26	0.855	-	-	-
	SDT29	0.815	-	-	-
	SDT5	0.803	-	-	-
	SDT6	0.847	-	-	-
	SDT7	0.801	-	-	-
	SDT8	0.887	-	-	-
	SDT9	0.879	-	-	-
Organizational management capabilities			0.763	0.951	0.938
	SDT1	0.825	-	-	-
	SDT18	0.874	-	-	-
	SDT2	0.907	-	-	-
	SDT22	0.879	-	-	-
	SDT3	0.881	-	-	-
	SDT4	0.873	-	-	-

Note: AVE: Average variance extracted, CR: composite reliability; CA: Cronbach’s alpha.

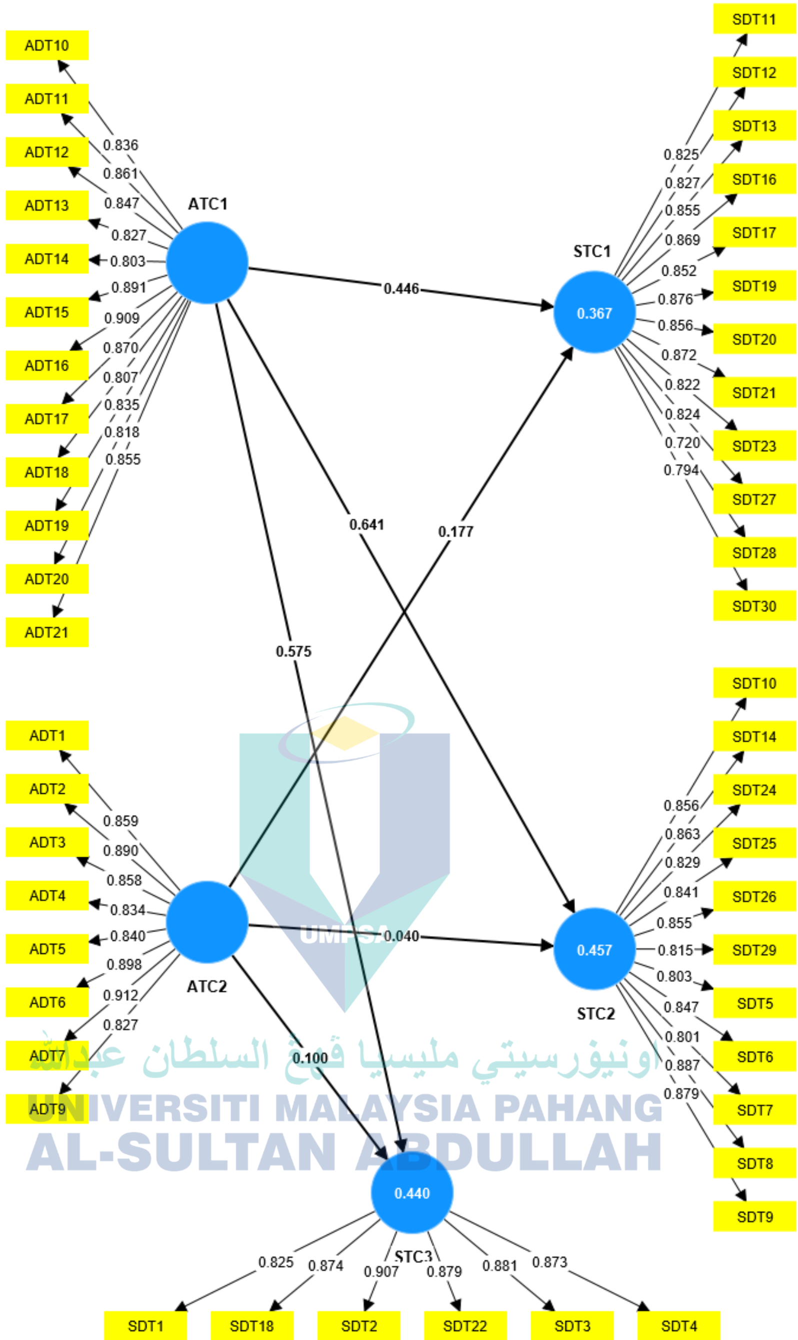

Figure 4.3 Measurement model evaluation

a. Convergent validity

Based on the findings reported in Table 4.13 and Figure 4.3 in section 4.5.3.3, it can be observed that the loading of all variables and AVE values surpassed the suggested thresholds of 0.4 and 0.5. These results indicate satisfactory convergent validity for the indicators and constructs under investigation (Hair et al., 2011). Furthermore, it should be noted that the calculated composite reliability values and Cronbach's alpha values for all constructs surpass the minimum threshold of 0.7, as established by Hair et al., (2011). This suggests that the internal consistency and reliability of the measures are reasonable.

b. Discriminant validity

The results show the square-rooted AVE values for the constructs, which indicates a satisfactory level of discriminant validity for most latent constructs, except for ATC1. According to the Fornell-Larcker criteria in Table 4.14, the observed value of construct ATC1 (0.847) exhibited a lesser magnitude than the correlation coefficient between ATC1 and ATC2 (0.873). Furthermore, by employing the Heterotrait-Monotrait ratio (HTMT) – Matrix shown in Table 4.15, it was presented that the values for ATC1-ATC2 (0.911), STC1-STC2 (0.911), and STC2-STC3 (0.902) were all below the threshold of 1.0, therefore satisfying the criterion established by Henseler et al., (2015). Furthermore, a discriminant validity assessment was conducted through a cross-loadings analysis, as shown in Table 4.16. The variables had a stronger association with the construct they were intended to assess, as opposed to other constructs within the model. This finding suggests that the constructs possess discriminant validity.

Table 4.14 Fornell-Larcker criterion

Constructs	Organizational digital twin capabilities	Technological capabilities requirements	Organizational competitiveness and investments	Organizational workforce management and training	Organizational management capabilities
Organizational digital twin capabilities	0.847	-	-	-	-
Technological capabilities requirements	0.873	0.865	-	-	-
Organizational competitiveness and investments	0.599	0.565	0.834	-	-
Organizational workforce management and training	0.676	0.596	0.876	0.844	-

Table 4.14 Continued.

Organizational management capabilities	0.661	0.605	0.823	0.860	0.874

Table 4.15 Heterotrait-Monotrait ratio (HTMT) - Matrix

Constructs	**Organizational digital twin capabilities**	**Technological capabilities requirements**	**Organizational competitiveness and investments**	**Organizational workforce management and training**	**Organizational management capabilities**
Organizational digital twin capabilities.	-	-	-	-	-
Technological capabilities requirements.	0.911	-	-	-	-
Organizational competitiveness and investments.	0.613	0.580	-	-	-
Organizational workforce management and training.	0.694	0.617	0.911	-	-
Organizational management capabilities	0.689	0.634	0.859	0.902	-

Table 4.16 Cross-loadings

Code	**Organizational digital twin capabilities**	**Technological capabilities requirements**	**Organizational competitiveness and investments**	**Organizational workforce management and training**	**Organizational management capabilities**
ADT1	0.714	0.859	0.480	0.498	0.506
ADT2	0.729	0.890	0.537	0.554	0.521
ADT3	0.726	0.858	0.472	0.527	0.540
ADT4	0.731	0.834	0.437	0.449	0.445
ADT5	0.749	0.840	0.489	0.497	0.496
ADT6	0.736	0.898	0.507	0.527	0.527
ADT7	0.801	0.912	0.547	0.568	0.596
ADT9	0.802	0.827	0.409	0.478	0.484

Table 4.16 Continued.

ADT10	0.836	0.794	0.417	0.495	0.471
ADT11	0.861	0.775	0.518	0.576	0.533
ADT12	0.847	0.719	0.476	0.573	0.519
ADT13	0.827	0.761	0.406	0.475	0.519
ADT14	0.803	0.658	0.389	0.447	0.525
ADT15	0.891	0.743	0.548	0.607	0.631
ADT16	0.909	0.796	0.592	0.671	0.647
ADT17	0.870	0.761	0.555	0.628	0.620
ADT18	0.807	0.680	0.530	0.608	0.534
ADT19	0.835	0.664	0.496	0.569	0.552
ADT20	0.818	0.707	0.502	0.557	0.524
ADT21	0.855	0.733	0.594	0.604	0.605
SDT1	0.495	0.485	0.622	0.665	0.825
SDT2	0.588	0.532	0.712	0.744	0.907
SDT3	0.594	0.510	0.724	0.764	0.881
SDT4	0.567	0.485	0.639	0.723	0.873
SDT5	0.549	0.473	0.705	0.803	0.653
SDT6	0.544	0.448	0.701	0.847	0.682
SDT7	0.492	0.398	0.654	0.801	0.628
SDT8	0.563	0.485	0.736	0.887	0.759
SDT9	0.619	0.524	0.755	0.879	0.762
SDT10	0.593	0.504	0.722	0.856	0.741
SDT11	0.470	0.381	0.825	0.757	0.616
SDT12	0.440	0.492	0.827	0.732	0.634
SDT13	0.504	0.534	0.855	0.735	0.678
SDT14	0.567	0.520	0.800	0.863	0.742
SDT16	0.575	0.547	0.869	0.755	0.751
SDT17	0.542	0.530	0.852	0.743	0.742
SDT18	0.596	0.583	0.787	0.774	0.874
SDT19	0.493	0.511	0.876	0.712	0.728
SDT20	0.517	0.504	0.856	0.719	0.718
SDT21	0.528	0.415	0.872	0.753	0.734
SDT22	0.617	0.525	0.809	0.825	0.879
SDT23	0.539	0.460	0.822	0.777	0.720
SDT24	0.506	0.541	0.714	0.829	0.735
SDT25	0.576	0.529	0.793	0.841	0.765
SDT26	0.632	0.568	0.755	0.855	0.760
SDT27	0.479	0.469	0.824	0.729	0.691
SDT28	0.389	0.311	0.720	0.608	0.539
SDT29	0.604	0.495	0.776	0.815	0.727
SDT30	0.480	0.409	0.794	0.739	0.633

4.5.4 Structural Model Evaluation

Following the method outlined by Hair et al., (2011), 5,000 bootstrap samples were employed. The bootstrapping method was used to determine the significance of path coefficients and evaluate the hypotheses. The essential t-value for a two-tailed test was 1.96 (significance level: 0.05). Table 4.17 confirmed that all hypotheses have path coefficients that are positive and significant at the 0.05 level. The results in Table 4.17 show that hypotheses 4, 5, and 6 are unsupported. In contrast, hypotheses 1, 2, and 3 are supported and therefore substantiated.

Table 4.17 Structural model evaluation

Hypothesis	Path	t-value	P-values	Decision
H1	Organizational digital twin capabilities → Organizational competitiveness and investments	2.614	0.009	Supported
H2	Organizational digital twin capabilities → Organizational workforce management and training	4.622	0.000	Supported
H3	Organizational digital twin capabilities → Organizational management capabilities	4.008	0.000	Supported
H4	Technological capabilities requirements → Organizational capabilities management	0.965	0.335	Not supported
H5	Technological capabilities requirements → Organizational competitiveness and investments	0.239	0.811	Not supported
H6	Technological capabilities requirements → Organizational workforce management and training	0.654	0.513	Not supported

4.6 Discussion

Phase 1 of the research underscores essential organizational attributes needed for producing digital twins in buildings within the AEC industry. Organizational attributes identified are People, Process, and Technology. The research emphasizes the influence of project teams on the entire workflow of a project, noting the importance of effective communication, task coordination, and a thorough understanding of the project's framework and direction. Besides that, experts are essential in enhancing the efficiency of the work process for digital twin preparation, as they possess the necessary knowledge and information. However, a significant challenge is the need for more readiness to embrace digital twins. This reluctance, particularly among construction industry personnel, stems from resistance to systemic changes, complicating the adoption process due to hesitancy from industry leaders. An effective construction process involving strategically planned workflows and guidance for teams to proficiently develop digital twins within their firms is crucial. Technology, comprising necessary software and compatible hardware, plays a vital role in meeting project requirements.

Meanwhile, in the realm of producing accurate digital twins for construction projects, three pivotal organizational strategies stand out which are Policy, Workflow, and Technology. Policy forms the backbone of this triad, establishing the guidelines and standards that ensure consistency and compliance throughout the digital twin production process. Establishing and enforcing policies with standardized guidelines, especially with government support, is key to facilitating the adoption of digital twins across various organizations. Besides, a workflow with strategic planning aids in reaching goals and streamlining procedures. This includes the meticulous planning, execution, and coordination of various tasks and stages in the project lifecycle, ensuring that every aspect of the physical construction is mirrored precisely in the digital twin. The relationship between technology and human input is crucial. Up-to-date, high-tech tools are indispensable, as modern technology significantly reduces the time required to create a digital twin by optimizing processes.

For Phase 2, key organizational attributes must be closely supported to produce accurate digital twins in construction projects. Employee coordination ensures unified digital twin creation, which is crucial for accuracy. A shared data environment guarantees data consistency, impacting the precision of digital twins. Standardized procedures across the organization ensure uniformity in development, enhancing accuracy. Adequate financial capability allows for sophisticated technology, influencing model precision. Internal guidelines maintain high standards in development, while a culture embracing digital innovation is fundamental for creating detailed twins. Top-down management involvement provides essential support, focusing organizational efforts on accuracy. Clear organizational objectives for digital twins and a strategic plan ensure a long-term commitment to precision. Continuous improvement processes update and refine digital twins, and a data compatibility plan ensures precise and harmonious data inputs. These elements are crucial for aligning organizational efforts towards creating accurate and reliable digital twins in construction projects.

Meanwhile, to produce accurate digital twins for construction projects effectively, key organizational strategies should focus on enhancing data transmission quality for reliability, increasing investment in skilled employees and digital transformation to drive innovation, and attracting talent, especially digital twin professionals. Raising digital twin awareness across all management levels ensures strategic alignment while ensuring software compatibility and providing comprehensive internal and external training enhances skill development. Encouraging employees to explore digital twin data and maintaining transparency and accountability are vital for precision. Balancing the complexity of digital twins, integrating them into business strategy, and leveraging existing data for insights are crucial for operational accuracy. Implementing digitalization and assessment frameworks, coupled with strong financial support and strategies for cultural transformation, fosters an environment conducive to creating accurate, reliable digital twins. Unrestricted opportunities for learning and experimentation further enhance the development of effective digital twins, aligning with the organization's strategic goals in construction project management.

Furthermore, for Phase 3, it can be concluded that:

i. Relationship between "Organizational Digital Twin Capabilities" and "Organizational Competitiveness and Investments".

The path coefficient value of 2.614% demonstrates that organizational digital twin capabilities positively and substantially affect organizational competitiveness and investments. The H1 hypothesis is therefore supported. According to Thiyagarajan et al., (2022), the acceptability of the digital twin necessitates deploying multiple business systems and supply chain solutions, which require significant funding. This demonstrates that investments in aligning top employees and developing technology tailored to the requirements of the local market are required to create compelling digital twin capabilities within an organization. However, organizations must also identify the digital technologies required to develop digital twin capabilities and partners. Therefore, generating awareness and obtaining a firm understanding of digital supply chain technologies are crucial to the success of the transformation. This must be counterbalanced by establishing an effective organizational financial support structure for digital twin production. (Weber-Lewerenz, 2021)

However, AEC industry professionals need more structured project pathways for digital twin development, and cultural and strategical resistance to change are the most significant obstacles to digital twin adaptation, indicating a need for a more strategic vision among practitioners and organizations (Neto et al., 2020). Ultimately, the obstacles to digital twin productions will likely be overcome by an organization's digital twin capabilities, adaptability to change and possessing shared common values and goals. Implementing organizational measures, such as enhancing the organization's attractiveness to attract talented employees, enhancing the organization's attractiveness to attract digital twin experts, and creating innovative workspaces utilizing new technologies, which will impact the digital twin capabilities of the organization, is a crucial improvement strategy.

ii. Relationship between "Organizational Digital Twin Capabilities" and "Organizational Workforce Management and Training."

The study findings indicate that organizational digital twin capabilities positively and substantially affect organizational workforce management and training. The path coefficient value of 4,622 indicates that organizational digital twin capabilities have the strongest association with the hypotheses regarding the organizational workforce management and training construct. Moreover, an organization's investments in employment, training, compensation, communication, and other human resource sectors increase its capabilities (Smallwood & Ulrich, 2004). In conclusion, Hypothesis H2 is supported.

Top-down management participation in the digital twin concept facilitates this process by encouraging, committing, supporting, and empowering employees. This research concurs with Thiyagarajan et al., (2022), who believed that developing a business case to produce digital twins and gaining the support of senior management is necessary for the incorporation of digital twins. who believed that developing a business case to produce digital twins and gaining the support of senior management is necessary for the incorporation of digital twins. In addition, the findings of this research concur with Weber-Lewerenz's assertion that all stakeholders are responsible for ensuring the success of this process and shaping it proactively with competent personnel, an open dialogue on new technological options, and an allocation of potential application regions (Weber-Lewerenz, 2021).

With a solid financial support system, internal and external training for learning and experimentation can be provided without cost or time constraints. In addition, this study concurs with Smallwood & Ulrich (2004), who asserted that organizational capabilities are significant intangible assets resulting from the talents and skills of an organization's personnel. Therefore, with appropriate training, employees have a foundational understanding of digital twins and the means to explore them. As it relates to organizational integrity, it is essential to emphasize the importance of transparency and employee accountability regarding the digital twin. Consequently, this must be updated with the compatibility of available software related to digital twins and practical tools for communicating information on digital twins. These are important technical aspects to be considered as essential organizational digital twin capabilities strongly related to workforce management and training.

iii. Relationship between "Organizational Digital Twin Capabilities" and "Organizational Management Capabilities."

The path coefficient value of 4.088 supports the conclusion that organizational digital twin capabilities positively and substantially affect organizational management capabilities. In conclusion, Hypothesis H3 is supported. The capability of an organization is also connected to its identity and personality, which are defined by the organization's accumulated skills, abilities, and knowledge (Smallwood & Ulrich, 2004). When creating digital twins, it is essential to determine the ideal level of maturity and complexity (Bär et al., 2018). Human resource management, IT maturity or technological gaps, and organizational procedures are significant organizational management capabilities that may influence the organizational digital twin capabilities (Frederico et al., 2020). This will determine the optimal organizational cultural transformation strategies to produce digital twins. Implementing initiatives that may aid in managing cultural risk and generating a comprehensive assessment framework for digital twin productions, which will influence the digital twin capabilities of the organization, is, therefore, a crucial advancement strategy.

4.7 Summary

The chapter was intended to exhibit the results of the data analysis and how the research objectives were achieved accordingly. For objective 1, the data was collected from the interview data, SLR data and pilot, which resulted in 21 organizational attributes and 30 organizational strategies. The result was later used to develop a questionnaire survey to achieve objective 2, using the Survey Legend platform and LinkedIn website to collect respondents. Once data was collected, a reliability test was conducted to check the data's reliability. Moreover, Normalized Mean Score Ranking technique resulted in 11 key organizational attributes and 20 key organizational strategies. As for objective 3, PLS-SEM was run and resulted in three supported hypotheses, which show the relationships between the three supported constructs (organizational digital twins' capabilities positively affect the needs of organizational workforce management and training, organizational competitiveness and investments, and organizational management capabilities). Thus, the relationships were analyzed, and the objective was achieved.

CHAPTER 5

CONCLUSION

5.1 Introduction

This chapter discusses the summary of aims and objectives' outcomes, limitations and suggestions of research, research contributions to the body of knowledge and the AEC industry, how the contributions impact the Quintuple Helix, and finally, the research recommendations to the AEC industry and future research.

5.2 Summary of aims and objectives' outcomes

The primary aim of this research was to analyze the relationship between the organizational attributes and strategies for producing accurate digital twins in the AEC industry in Malaysia. This aim was successfully achieved with the three objectives, resulting in an empirically supported knowledge of the key attributes and strategies influencing accurate digital twins' production in the Malaysian AEC industry. This research significantly advances a technologically sophisticated setting through a multifaceted interplay of identification, analysis, verification, and practical validation.

5.2.1 Objective 1: To identify the organizational attributes and strategies in current AEC practices to produce accurate digital twins of construction projects.

Objective 1 methodically identified the organizational attributes and strategies in current AEC practices to produce accurate digital twins of construction projects. Through professional interviews (qualitative method), comprehensive Systematic Literature Review (SLR) and a pilot study, this objective has successfully identified 21 organizational attributes and 30 organizational strategies that can be used to produce accurate digital twins of construction projects. These attributes and strategies have jointly established the fundamental basis for achieving accurate digital twins within the AEC industry.

5.2.2 Objective 2: To determine key organizational attributes and strategies to produce accurate digital twins of construction projects.

The second objective was accomplished during Phase 2 using the quantitative approach. Expanding on the extensive compilation of organizational attributes and strategies revealed in the first objective, this research sought to ascertain the crucial organizational attributes and strategies. Two Standard Deviation (SD) technique was conducted to remove any possible outliers from Objective 1. Thus, it resulted in 20 organizational attributes and 29 organizational strategies. Next, 11 key organizational attributes and 20 key organizational strategies were identified using a rigorous Normalized Mean Score Ranking technique. The analytical procedure resulted in identifying a subset of key attributes and strategies shown to have the most significant impact on producing accurate digital twins. This selection not only narrowed down the focus to the main variables but also emphasized the importance of significant attributes and strategies that substantially influence the production of accurate digital twins in the Malaysian AEC Industry.

5.2.3 Objective 3: To analyze the relationship of underlying constructs of organizational attributes and strategies to produce accurate digital twins of construction projects.

The third objective involved a comprehensive analytical process to analyze the relationship of underlying constructs of organizational attributes and strategies at the foundation to produce accurate digital twins of building projects. The journey started by employing Exploratory Factor Analysis (EFA). By condensing the 20 organizational attributes and 29 organizational strategies into a more compact and comprehensible dataset, this procedure generated three underlying factors: organizational competitiveness and investments, organizational workforce management and training, and organizational management capabilities were extracted for organizational strategies from the EFA results, which cling to a strict factor loading threshold of 0.5.

The two fundamental underlying factors for organizational attributes were organizational digital twin capabilities and technological capabilities requirements. The fundamental elements that complexly interact to produce accurate digital twins in the

Malaysian construction industry are supported by these underlying factors, obtained through a careful interaction of EFA and rigorous validation. The research then employed the advanced Partial Least Square Structural Equation Modelling (PLS-SEM) technique. The findings resulted in strong evidence in favour of three hypotheses, proving beyond a shadow of a doubt that organizational workforce management and training, organizational competitiveness and investments, and organizational management capabilities significantly benefit from organizational digital twins' capabilities to produce accurate digital twins in the Malaysian AEC industry.

5.3 Limitations of research and suggestions

As with any research endeavour, there are inherent limitations to consider in this study. The primary aim of this research was to model the relationship between the organizational attributes and strategies for producing accurate digital twins within the context of construction projects in Malaysia. Consequently, it is important to recognize that the applicability of the research's findings to construction projects in other countries or continents may be restricted. Due to potential variations in work culture, geographic conditions, and other influencing factors, the generalizability of the research's findings beyond the Malaysian construction industry and the data collected within that context may be limited.

Additionally, there are limitations related to the study's sampling and timeframe. The sample size in this research is relatively small, which restricts the extent to which the findings can be generalized. A limited number of organizations participating in the research can reduce the generalizability of findings and hinder the ability to draw robust conclusions. Furthermore, the research's time constraints were another limitation. It was conducted as a snapshot in time, which hinders the ability to capture the evolving nature of technology adoption processes. Future research could benefit from adopting a longitudinal approach to understand better how these processes change over time.

In summary, while this research offers valuable insights into the relationship between organizational attributes and strategies to produce accurate digital twins in the Malaysian construction industry, it is essential to acknowledge these limitations when interpreting the results. Addressing these limitations through further research endeavours will contribute to building upon the findings of this research.

5.4 Research contributions

The research contributions are highlighted in this section. This part is subdivided into two subsections, emphasising the research contributions in theoretical and practical domains.

5.4.1 Theoretical contribution (academic)

This research's theoretical contribution pertains to its addition to the extant literature concerning the production of digital twins within the AEC industry. It provides a thorough grasp of the organizational components that contribute to digital twin capabilities and the important variables that determine organizational attributes and strategies for attaining them. As a result, scholars and researchers may apply this idea to create theoretical frameworks for creating digital twins of AEC industry organizations. This research will help academics assess their research on the advantages and uses of digital twins for organizations, the organizational aspects of producing digital twins for building construction practices, and the technological capabilities and advantages of creating them more effectively. Additionally, this research will help increase awareness among academics to better create models and procedures for building practices by examining the relationship between organizational qualities and strategies developed.

5.4.2 Practical contribution (industry)

This research is poised to become a benchmark reference for construction professionals in strategizing, evaluating, and understanding the integration of digital twins in their operations. It is essential for effective technological implementation across various stakeholders and promotes a strategic mindset along the supply chain. According to Turner et al., (2021), productivity in construction significantly impacts economic growth and living standards. Thus, this research also supports adopting digital technologies to enhance operational efficiency and productivity.

5.4.3 Managerial contribution (organizations)

This research provides strategic plans for enhancing organizational digital twins' capabilities to produce digital twins accurately. To strengthen their digital twin capabilities, organizations should focus on the most important variables and acquire an in-depth insight into the attributes and strategies influencing digital twin capabilities. Organizations may also leverage the key attributes and strategies highlighted in this research to enhance their digital twins' competencies.

5.4.4 Methodological contribution (academic)

This research provides a straightforward method of collecting data and analyzing data. This research implemented and used the current methodologies available to gain practical outputs from collected data, thus leading to a clear, valid result that supports the research objectives. Additionally, the same methodologies can be applied to similar research related to project management or in search of attributes and strategies for other technological advancements.

5.4.5 Empirical contribution (academic)

This research findings show that the supported hypotheses involved the relationship between "organizational digital twins' capabilities" that positively affect the need for "organizational workforce management and training", "organizational competitiveness and investments", and "organizational management capabilities". With these hypotheses results, this research suggested opportunities for future research areas of development.

5.5 Impact on Quintuple Helix

i. Government:

Boosting digitalization and advanced technology by optimizing the value of the construction industry's transformation towards digitalization necessitates robust governance to achieve greater productivity and efficiency. This governance involves new, improved policies and procedures, which must be responsive in delivering the 12MP and CIDB Construction 4.0 Strategic Plan.

ii. Industry:

A practical evaluation tool is essential for recognizing the organizational attributes required to produce digital twins. This supports construction stakeholders in generating accurate digital twins, which, in turn, can promote the involvement and coordination of all participants in the construction industry, leading to the maximization of benefits when transitioning from traditional methods to advanced technological approaches.

iii. Academic:

This research may provide a streamlined model of organizational attributes and strategies of digital twins to drive research toward the Construction 4.0 strategic plan for the built environment. It may help to ensure significant potential and benefits in transforming the construction industry through a collaborative research effort involving industry, academia, and the government.

iv. Society:

Human capital is a fundamental enabler of economic growth and socio-economic progress. This research may help to develop future talents and experts in line with the Twelfth Malaysia Plan: Developing future-ready talent, Priority Area B, whereby developing future-ready talents is crucial to cultivate talent that is prepared for the future to fulfil the ever-evolving skill requirements of business and to embrace the rapid evolution of technology.

v. Environment:

This research may increase productivity, operational efficiency, supply chain, delivery improvements, waste reduction, and expenses in the Malaysian construction industry. This conforms with the 12MP, which focuses on promoting sustainability using green technologies, sustainable consumption and production practices, and a national approach to promoting green growth.

5.6 Research recommendations

5.6.1 Recommendations to the AEC industry

Future endeavours within the AEC industry should prioritize the provision of practical guidance tailored to producing accurate digital twins in construction projects. This guidance should be rooted in the identified relationship between organizational attributes and strategies, serving as a structured framework to inform decision-making processes within organizations. Moreover, fostering a culture of collaboration among industry practitioners, researchers, and experts is crucial. Such collaborative efforts can lead to a more comprehensive understanding of how organizational attributes and strategies impact the successful development and utilization of digital twins in construction. Additionally, researchers and industry stakeholders should explore the feasibility of conducting in-depth case studies or on-site observations. These practical research methods can yield invaluable real-world insights that resonate with the identified organizational attributes and strategies. By doing so, the industry can enhance its practices, resulting in more efficient and effective digital twin implementations that contribute to improved outcomes in the built environment.

5.6.2 Recommendations to the future research

Future research undertakings within the AEC industry should aspire to take the comprehension of digital twin productions to even greater depths, building upon the solid foundation established by this research. This entails a commitment to exploring the intricate complexities and multifaceted aspects underpinning the digital twins' production process within the industry. To achieve this, researchers should prioritize conducting empirical case studies and on-site observations, deploying methodologies that yield tangible evidence and contextual richness. These in-depth examinations of real-world scenarios and practical implementations will provide invaluable insights into the relationship between organizational attributes and strategies, grounding academic findings in the practical realities of the AEC industry. Moreover, expanding the participant pool is pivotal to the research's effectiveness. By casting a wider net and encompassing a more extensive and diversified spectrum of industry stakeholders, including professionals, organizations, and experts, future research can generate a more comprehensive, representative, and nuanced perspective of the AEC industry's digital twin landscape. Through these concerted efforts, future research will contribute significantly to the ongoing refinement of digital twin practices, empowering decision-makers with actionable insights and catalyzing innovation across the entire AEC industry.

5.7 Summary

The purpose of this chapter was to highlight the research's contributions, findings, and limitations and provide suggestions for future searches. This guarantees that the research questions are addressed, the study objectives are fulfilled, and the gap identified in Chapter 2 is finally filled. More pertinent to the present is this research. Nevertheless, considering the perpetual evolution of technology and the resulting emergence of novel challenges, additional research is necessary to ascertain the most effective resolutions for these issues.

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APPENDICES

Appendix A: Scopus search engine

TITLE-ABS-KEY ("digital twin" AND "organisation*" OR "organisation*" OR "compan*") AND (LIMIT-TO (SRCTYPE , "j")) AND (LIMIT-TO (LANGUAGE , "English"))

Appendix B: Normalized value equation

$$Normalized\ value = \frac{Mean - Minimum\ mean\ value}{Maximum\ mean\ value - Minimum\ mean\ value}$$

Appendix C: Pilot study for generating questionnaire survey

Universiti Malaysia PAHANG

<u>Section A: Respondent's Demographic Profile</u>
Instruction: Please provide the following information.

1. Gender:
   A. Male
   B. Female

2. Age:
   A. < 25 years old
   B. 26-30 years old
   C. 31-35 years old
   D. 36-40 years old
   E. > 40 years old

3. Highest academic qualification:
   A. SPM
   B. TVET
   C. Diploma
   C. Degree
   D. Master
   E. PhD

4. Your type of organization:
   A. Government
   B. Developer (Private)
   C. Consultant
   D. Contractor
   D. Other: _________________ (please specify)

5. Your professional background:
   A. Client
   B. Project Manager
   C. Architect
   D. Engineer
   E. Contractor
   F. BIM Consultant
   G. Other: _________________ (please specify)

6. Working experiences in the construction industry:
   A. Less than 2 years
   B. 2-5 years
   C. 6-9 years
   D. > 10 years

7. Sector of the built environment your company is involved in:

   Please (√) which is relevant
   __ Building Construction
   __ Infrastructure
   __ Engineering
   __ Property Development
   __ Other: _________________ (please specify)

8. Does your company has experience using digital twin?
   A. Yes
   B. No

<u>Reviewer:</u>
The above questions in section A are clear (**Yes**/No)
Other comments:
____
____
____
____

Pilot Study_ybunjaridh_MAP22001

Section B: Key Organizational Attributes to Produce Digital Twin

Instruction: Please rate the criticality of an organization in having the following attributes to produce accurate digital twins.

1	2	3	4	5
Not Critical	Slightly Critical	Moderately Critical	Critical	Very Critical

Reviewer:
The instruction for section B is clear (**Yes**/No)

No	**Organizational attributes to produce digital twin**	Reviewer's comments on variables if any
1	Technological capabilities among employees on digital twin.	
2	Strategic mindset among employees on digital twin.	
3	Coordination among employees on digital twin.	
4	Employee awareness on the business value of digital twin.	
5	Employee understanding on the value of digital twin data.	
6	Digital twin technological on infrastructure.	
7	Mechanisms for digital twin data operationalization.	
8	Internal strategic digitalization framework on digital twin.	
9	Data compatibility plan for digital twin.	
10	Shared data environment for digital twin.	
11	On-going improvement processes for digital twin deployment.	
12	Internal guidelines for developing digital twins.	
13	Organizational standardized procedures for developing digital twin.	
14	Data security procedures on digital twin.	
15	Organizational strategic plan on digital twin.	
16	Strategic working processes on digital twin.	
17	Well-defined organizational objective(s) on digital twin.	
18	Organizational work culture transformation plan for digital twin.	
19	Top-down management involvement in the digital twin concept.	
20	Financial capability of the organization for developing digital twin.	
21	Organizational business development approach in relation to digital twin.	

Reviewer:
The variables in section B above are clear (**Yes**/No)
Other comments:
____
____
____

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Section C: Strategies to Achieve Attributes to Produce Digital Twin

Instruction: Please rate the criticality of an organization in having the following strategies to achieve attributes for producing accurate digital twins.

1	2	3	4	5
Not Critical	Slightly Critical	Moderately Critical	Critical	Very Critical

Reviewer:

The instruction for section C is clear (**Yes**/No)

No	Organizational strategies to produce digital twin	Reviewer's comments on variables if any
1	Determine the right level of complexity when developing digital twin.	
2	Determine strategies for organizational cultural transformation on digital twin.	
3	Determine the organization's transformation goals for digital twin.	
4	Determine the best method to achieve the expected level of data transmission quality for digital twin.	
5	Provide external training on digital twin.	
6	Provide internal training on digital twin.	
7	Provide opportunities for learning and experimentation without restrictions on time or cost.	
8	Provide employees with opportunities to explore digital twin data.	
9	Provide effective tools for communicating information on digital twins.	
10	Provide digital twin awareness to all management levels.	
11	Increase investments in aligning top employees and digital transformation.	
12	Enhance the organization's attractiveness to attract talented employees.	
13	Enhance the organization's attractiveness to attract digital twin experts.	
14	Recognize the necessity of having digital twins as part of the business.	
15	Use digital currency as the organization's payment method.	
16	Develop a strategic vision among all management levels to implement digital twin.	
17	Transform conventional working practices to digitalized working platforms.	
18	Implement initiatives to manage cultural risk on digital twin.	
19	Implement digitalization framework as a project planning diagnostic tool throughout the organization.	
20	Implement a digitalization framework to assist in a long-term vision of achievable levels.	

21	Implement a digitalization framework to assist in a strategic road map.	
22	Implement a comprehensive assessment framework on digital twin.	
23	Create innovative workspaces using new technologies.	
24	Ensure employees have basic knowledge of digital twin.	
25	Ensure compatibility between new and previous versions of available software related to digital twin.	
26	Emphasize transparency and accountability among employees on digital twin.	
27	Incorporate existing data to generate information to improve insights for operations management in sustaining infrastructure assets.	
28	Arrange digital experts as external partners.	
29	Build up a good organizational financial support system on digital twin.	
30	Investment in creating custom technology to suit local market needs	

Reviewer:
The variables in section C above are clear (**Yes**/No)
Other comments:
____
____
____

Section D:
Instruction: Please indicate and rate any additional *attributes or strategies* that are considered critical produce digital twins in Malaysia.
Reviewer:
The instruction for section D is clear (**Yes**/No)

1	2	3	4	5
Not Critical	Slightly Critical	Moderately Critical	Critical	Very Critical

No	**Attributes to produce digital twin**	**Criticalities**				
1		1	2	3	4	5
2		1	2	3	4	5
3		1	2	3	4	5

No	**Strategies to achieve attributes for producing digital twin**	**Criticalities**				
1		1	2	3	4	5
2		1	2	3	4	5

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