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Technological Drivers and Barriers for Digital Twin Adoption in the Malaysian Construction Industry

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ABSTRACT

Digital twin (DT) technology can potentially boost project performance and decision-making across various industries, including construction. However, the Malaysian construction sector encounters various barriers to its implementation. This paper aims to explore the barriers and drivers associated with the adoption of digital twin technology in Malaysia's construction industry. Specifically, it aims to identify obstacles to adoption and propose technological drivers that could facilitate its integration into construction practices. A total of 23 journal articles were meticulously reviewed using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement. In addition, data from 97 responses collected from G7 construction professionals were analysed using the Statistical Package for Social Sciences (SPSS). The study uncovers various barriers hindering the adoption of digital twin technology in the Malaysian construction industry. These barriers include financial uncertainties, technological complexity, lack of standardisation, cyber security concerns and issues related to intellectual property rights. Furthermore, barriers arise from the novelty of the technology, the diversity of source systems, and interoperability issues. Moreover, the study categorizes the identified drivers into distinct categories and sub-themes, focusing on principles, production, operational performance and preservation. The findings indicate that overcoming these barriers and utilising the identified factors could accelerate the implementation of digital twin technology in the Malaysian construction industry. This study adds to the existing knowledge base and provides insights to encourage the spread of digital twin technology in Malaysia.

1. Introduction
1.1 Research Background

Like any other sector, the construction industry is undergoing a gradual transformation to embrace new technologies. This has given rise to an emerging shift in the construction industry known as Construction 4.0 (C4.0). The concept of C4.0 has been described in various ways depending on the context of the region or organisation discussing it. Broadly, C4.0 encompasses the

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digitalisation of construction and the built environment. For example, some agree that Construction 4. 0 pertains to new technologies that significantly enhance the performance of projects (Regional Conference on Industrial Development 2019). Others view it as a use of Industry 4.0 technologies and processes that have been adapted for the construction industry [26].

Interestingly, C4.0 concept is interpreted differently by various countries and regions. In Europe, it aligns with the European Union's Digital Single Market strategy. For instance, the UK employs Building Information Modelling (BIM) and digital technologies to improve cooperation and productivity among construction project team [40]. The emphasis is placed on the utilisation of complex data analysis and BIM to optimise the processes of project management and collaboration. However, in the United States, C4.0 is frequently associated with such innovative industries as robotics, artificial intelligence, and the Internet of Things (IoT). Government agencies and research institutions like the National Institute of Standards and Technology (NIST) are working on frameworks to incorporate these technologies in construction practices with the purpose of enhancing efficiency as well as safety [21].

In Asia, countries like Japan and South Korea are leading in adopting robotics and automation in construction. Japan has integrated robotics as a solution to labour shortages and as a means of improving efficiency, focusing on new generation robotics and intelligent construction methods. Moreover, Singapore's Smart Nation initiative integrates IoT with construction processes to enhance efficiency and sustainability (Smart Nation Singapore 2024).

In contrast, in most of the African nations, the perception of C4.0 is still evolving as the advantages of digital technologies are gradually being recognised. However, factors such as lack of technology and conventional practices limit the use of digital technologies. Efforts are being made to eliminate these barriers by promoting innovation and education in technology [21].

Therefore, the differences in the definitions of C4.0 affect expectations, implementation plans and perceived advantages. In regions with conservative cultures, C4.0 is expected to bring improvements without disrupting existing processes. Developed nations anticipate rapid changes and growth in efficiency and environmental performance. Implementation strategies also vary; depending on a country's focus area, there may be more training in digital modeling if BIM is prioritised, or greater investment in automation technologies and workforce retraining in the case of robotics [1, 21, 33].

The perceived benefits of C4.0 differ according to the definitions in local areas. Developed countries may aim to raise productivity and cut costs, while developing countries may strive to generate employment, build skills and better physical facilities. Definitions that emphasise sustainability led to expectations of environmental gains, such as the minimisation of waste and energy conservation, while regions that prioritise development expect immediate economic gains. In conclusion, there is no common understanding of what C4. 0 entails, resulting in mixed levels of expectations, implementation strategies and perceived benefits influenced by regional factors and technological development [21].

Adding to this complexity, a country's prosperity is determined by its economic development with all the segments including the primary, secondary, tertiary and quaternary segments, contributing to a stable economy [46, 38]. The construction industry is fundamental to the development of any nation's economy, as it shapes contributions of all sectors at every level [50]. Overall, there is about $10 trillion in construction-related spending globally each year, equivalent to 13 percent of GDP [12]. The construction sector plays a significant role in the contributing to national GDP; hence, there is a need to develop this sector. It has been found that any change in the construction sector is likely to affect all related sectors [47]. The construction sector plays a significant role in contributing to national economy; thus, its impact on a country's economy is characterised by forward and backward linkages with other sectors. All these linkages are contingent on performance; therefore, a shift in any of the sectors will have a substantial impact on the country's economy. Consequently, the construction sector's responsibility for the socio-economic development of any country is undebatable [50].

In the global context, construction labour productivity has been rising at a slow rate of 1% % per year over the last twenty years. This rate is much lower than the reported average of 2.8% of general global economy growth and 3.6% of manufacturing industry. An analysis of overall productivity growth in various countries shows that not more than a quarter of construction companies have met performance indicators comparable to those of the general economy in which they operate. Many fledgling enterprises suffer from incredibly low productivity levels, leading to situations where many construction projects are either delayed or experience cost overrun. Understanding the significance of these statistics, a recent McKinsey & Company (2020) reveals that the gap in digitisation between industries is vast and continues to expand, as shown in Figure 1.

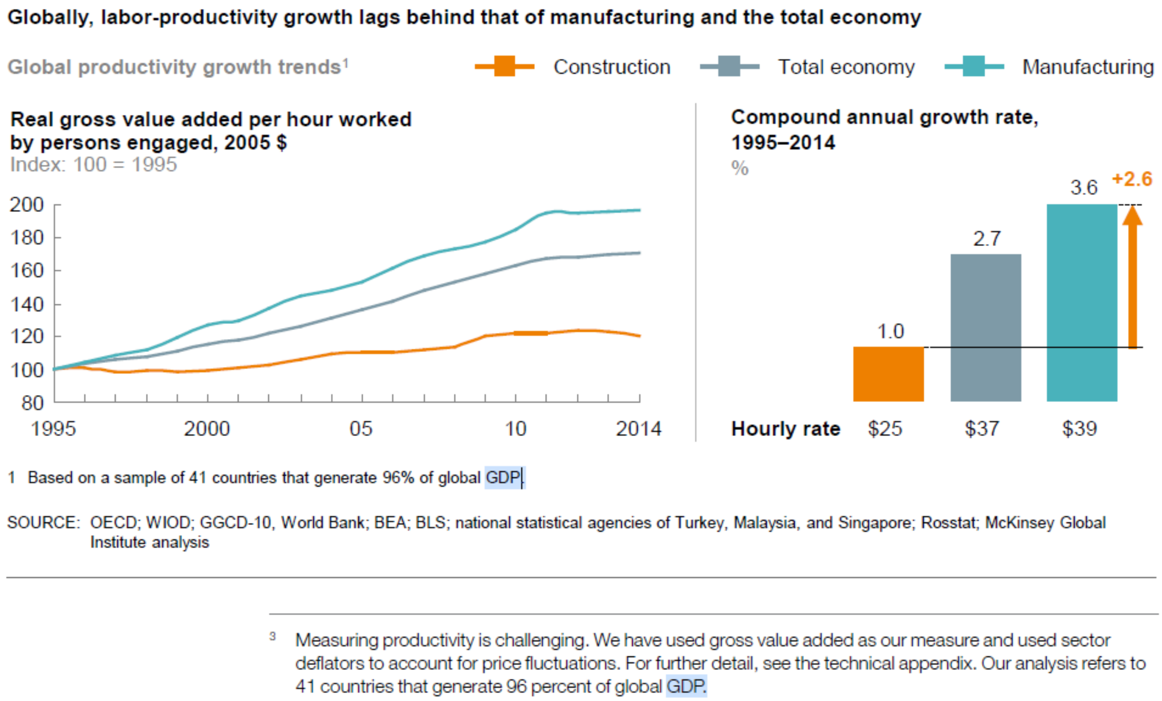

Fig. 1. Global Productivity Growth Trends in Manufacturing, Construction Sector and the Total Economy [12]

Given the current barriers confronting the industry, including its poor productivity, the construction sector faces immense pressure to complete projects within specified deadlines and budgets while satisfying client requirements. Due to these barriers, organisations and leaders must acknowledge the significance of understanding technological barriers and drivers in the context of emerging countries, particularly Malaysia [5]. In light of this, the increased emphasis on data presents opportunities to integrate digital technology and advanced automation into construction projects, streamlining the construction process and making it more efficient, effective and productive [12, 10].

Bridging the digital divide gap has not become easier, particularly in the aftermath of the COVID-19 outbreak. This has further emphasised the critical role of Construction 4.0 in embracing technological advancement to revolutionise the industry towards greater digitisation, raising productivity level to attain global competitiveness and making a significant contribution to the country's economic status [45]. In the era of Construction 4.0, there is no doubt that Building Information Modelling (BIM) is the centrepiece of digital transformation in the built environment.

BIM has become a widely accepted and standardised practice in many developed countries. Its popularity has surged in recent years due to its broad acceptance and promising benefits, allowing for better collaboration, coordination and information management throughout the building lifecycle [22]. However, while BIM uptake is a positive step towards digitisation, much more is needed to significantly enhance overall productivity within the industry [17].

A recent development called Digital Twin (DT) has elevated BIM processes to a completely new level, offering enhanced sustainability and competitive advantages [54]. As noted by Deng *et al.,* [16], researchers widely acknowledge the combination of IoT and BIM as a driving force behind the development of the digital twin concept in Construction 4.0. Simply put, a digital twin is a virtual counterpart that mimics a physical object or system in real time, allowing for testing and evaluating its performance and effectiveness. The main objective is to establish a compatible connection between the physical world and a digital platform, enabling smooth oversight and supervision throughout the entire duration of a project [16]. The digital twin framework also leverages various data sources, such as historical data and simulation results, to maximise asset performance and prolong its lifespan. Continuous monitoring and diagnostic processes can help achieve this goal, allowing for preventive measures to reduce the chances of failures, breakdowns, and unwanted risks.

Nevertheless, the utilisation of digital twin technology in the built environment is currently in its early stages of progress [16, 23]. While the concept of utilising digital replicas for buildings has been around for some time, it is only in recent years that technological advancements have enabled the creation of incredibly precise and intricate digital twins of buildings. Previous studies have not fully tapped into the vast potential of the digital twin concept, as highlighted by Istanullu *et al.,* [23]. Thus, it is crucial to develop a thorough understanding of the fundamental principles and practical applications of digital twin technology within the construction sector.

In summary, from this study, we can see how construction professionals perceive barriers to and drivers for digital twin adoption. As a guideline, it could benefit industry practitioners by providing insights into the fundamental concepts and advantages of digital twin technology. Finally, it is anticipated that the findings could help advance the National Construction 4.0 Strategic Plan (2021-2025), thereby promoting and expediting the progression and implementation of digital twinning among construction practitioners in Malaysia. Regarding the organisations examined in our study, they can use the present results to evaluate their readiness to adopt digital twins, helping to promote change and enhance industry efficiency through the incorporation of digital twin concepts into their practices.

2. Background

2.1 Barriers of Digital Twin Adoption in Construction Industry

2.1.1 Complexity of digital twin technology

The utilisation of digital twin in the construction industry has faced barriers due to its high level of sophistication. Users' perceptions regarding the ease of incorporating this technology are crucial factors influencing its adoption [53]. To maximise the efficiency of digital twin technology, it is important to first understand its complexities. Digital twin technology integrates a combination of analytics, visual representation and advanced technologies such as machine learning and AI to understand and utilize the full potential of digital twin [52]. It can be challenging to implement digital twin technology in the construction industry. Developing and maintaining a digital twin is a significant endeavour that demands a deep understanding of technical complexities. Representing large, complex and dynamic physical systems in a modelling environment adds an extra layer of complexity; furthermore, the principles surrounding the creation of a digital twin model and the constantly changing nature of the built environment present additional barriers to implementing technology in this particular industry.

2.1.2 Lack of standardization

Standardisation poses a significant barrier to the widespread adoption of digital twin technology in construction industry. With the immaturity of the domain and ongoing progress in this technology, common standards or methodologies are missing for creation, execution, ownership as well as preservation of digital twins [55]. Exchanging data between different digital twins becomes challenging, hindering their integration into existing systems and processes [51].

In addition, the lack of consensus on the definition and key characteristics or capabilities of a digital twin presents another barrier [55]. This can lead to misinterpretations and uncertainties on all sides of the discussion, complicating judgments about what constitutes a digital twin that qualifies for best-case scenarios or as a standardized and fully functional digital twin [52]. Therefore, to facilitate the interoperability of digital twin workflow, it is essential to first establish general syntactic and semantic formats. Therefore, the design of algorithms and protocols fulfil for future research initiatives for this purpose appears to be a formidable challenge [51].

2.1.3 Cyber security and intellectual property rights

This absence of regulations and laws also establishes a considerable barrier to digital transformation in the built environment. For firms to develop their strategies effectively and channel these into a proper structural configuration, they require clear governmental guidelines [7]. Moreover, it is important to highlight that the effectiveness of digital twin technology hinges on the secure transmission of a wide range of data, including highly confidential, sensitive and private project information [42]. In the absence of well-defined laws and regulations to safeguard this data, there is a potential risk of data breaches, hacking, or other cyber threats [63].

Furthermore, the creation of a digital twin necessitates the utilisation of exclusive data and models. In the absence of legislation, there may be conflicts regarding property rights and legal issues related to digital twin technology [7, 55, 25]. For digital transformation to be truly successful and thus drive growth in investment from buyers looking at these products as solution elements or components of their vision—standard bodies and laws should be established supporting such initiatives. These guidelines will help eliminate uncertainties by ensuring that all legal, ethical and other considerations are adequately addressed [18].

2.1.4 Financial uncertainties

Moving forward, the financial factor is undoubtedly a major barrier, alongside technological barriers, to the widespread adoption of digital twin technology in the construction sector. Developing and deploying a digital twin can require significant financial investment and allocation of resources. The initial investment needed can vary depending on the project's scope, complexity, and the methods, tools, techniques, and technologies used for its development [13]. Additionally, there may be further expenses associated with the maintenance of the digital twin over time. This includes the continuous collection and management of data, as well as the necessary updates to the digital twin model and any related software and hardware to ensure they remain current and operational [36].

Moreover, the potential uncertainty surrounding the return on investment (ROI) for digital twin technology can pose a challenge to its widespread adoption. The advantages of digital twin can also differ based on the particular project or application, making it difficult to generalize the return on investment across various contexts especially for smaller enterprises or those operating with constrained resources [52, 2]. Consequently, over time, there will be a lack of momentum for technological progress in the construction sector.

2.1.5 Novelty of technology

Given the novelty of the concept, there remains a dearth of comprehensive understanding and definitive evidence regarding the potential benefits that digital twin technology can offer to individuals, businesses, or industries [25]. Additionally, limited knowledge and experience in both technical and practical aspects also impede the advancement of digital twin adoption. Furthermore, it is worth noting that case studies showcasing successful practices in the implementation of digital twin technology in construction projects or providing accurate cost estimates for such implementations are limited [59]. It is worth mentioning that these technologies are still in the early stages of development, which could potentially hinder the progress of the digital twin adoption. Efforts should be made to enhance the effectiveness of digital twin technology by improving the necessary infrastructure, including data storage and sensors.

2.1.6 Diversity in source system and interoperability issue

Furthermore, collecting data with multiple devices in diverse formats can cause fragmentation and heterogeneity of information, making it difficult to ensure interoperability. For instance, data that needs to be assimilated across multiple source systems within the digital twin can prove challenging since such data comes in different formats, protocols and platforms. As a result, the aggregation and synchronisation of data can become increasingly complex. Additionally, to the incorporation with new systems like BIM and other applications may present difficulties due to compatibility issues [15]. This, in turn, may result in the creation data silos, limiting digital twins on broader project management and making the implementation of digital twin technology more difficult [49].

2.2 Drivers of Digital Twin Adoption in Construction Industry

2.2.1 Principle-based drivers

The primary driver behind the adoption of digital twin technology in the construction industry is the necessity to visualise project data in real-time. This capability allows for better decision-making and improved project management. Multiple studies have emphasised the significance of this aspect as a cause of the technological barriers encountered by the construction sector in embracing new technology [29, 42, 48]. However, even though technologies such as BIM are already available, they are characterised by their reliance on static data, which limits access to real-time data is limited. By utilising real-time data visualization, digital twin technology can provide a range of possible data-driven inputs for decision-making related to energy distribution and other demands, forecasting potential savings, and identifying opportunities for reducing building emissions, as noted by Agostinelli *et al.,* [3].

To illustrate, advances in the creation of IoT devices, sensors, and artificial intelligence algorithms have simplified the collection and streaming of real-time data to a digital platform. This allows stakeholders to monitor a project site's current status, perform analyses, and engage in a feedback loop throughout the construction process [6, 48]. Additionally, hypothetical analyses with digital twin technology aspects draws out better risk and decision-making through an analysis powered by unexpected situations, system reactions, and subsequent innovative methods that neutralise unforeseen negative impacts. The use of digital twin in the construction projects allows individuals to "harmlessly" test scenarios without compromising the integrity of the actual physical asset [42].

2.2.2 Production-oriented drivers

This subsection focuses on how efficiency and cost-effectiveness in construction processes can improve with the digital application of this technology. Previous research has indicated that water utility replicas can also reduce energy bills by up to 30% and lower carbon emissions as well. Additionally, they can increase productivity and reduce maintenance costs [35]. The synchronisation and integration of physical and virtual assets through digital twin technology create a collaborative environment for stakeholders to provide feedback and promote innovative solutions through high levels of communication among team members [48]. It was also a suggested solution by Liu *et al.,* [31] in discussion handling safety concerns during lifting fabricated buildings. It allows users to visualise dynamic information interactively and easily connect virtual and real worlds during the hoisting process. This indicates that building practices and safety management could be improved through the use of digital twins [31].

2.2.3 Operational performance drivers

Next, a link is established between the construction project and its users, which improves operational performance and is considered one of the most important factors in digital twin adoption. By using digital twin technology, different environmental factors can be tracked, including relative humidity, lux and decibel levels, and both room and outdoor temperatures inside buildings [41]. This contributes to creating a better the environment. For example, Lin and Cheung [65] conducted a study that employed digital twin as an advanced monitoring and control system for an underground parking garage environment. The study demonstrated that a digital twin is an effective and efficient way to manage and monitor environmental parameters.

Digital twin can also greatly help in tracking and managing different parts their lifecycle. This is particularly beneficial in complex projects involving numerous materials, equipment and people. Consequently, the digital twin has emerged as the primary tool for real-time tracking by integrating various data sources. This integration facilitates the identification and monitoring of different elements [6]. Furthermore, digital twins help people involved in the building make predictions, visualise potential scenarios, and plan effectively by combining algorithms with data from various stakeholders and sources. Any faulty system can be found ahead of time thanks to smart data analysis, thereby facilitating preventative maintenance and enhancing the project's operational efficiency [48].

2.2.4 Preservation-driven factors

This aspect focuses on the importance of preserving construction assets for long-term sustainability. Heritage buildings play a vital role in the construction industry, significantly contributing to the development of sustainable communities [41]. Compared to new constructions, heritage buildings bring about superior environmental and economic advantages by being repurposed. Additionally, they add unique charm to urban areas, thereby enhancing the overall revitalisation of buildings. It is worth noting that the adoption of digital twin technology has the potential to safeguard the cultural importance of heritage assets by facilitating their reuse.

Research by Göçer *et al.,* [19] has also shown that digital twins serve as rewarding tools for the government to preserve and conserve existing building. The data collected provides a more comprehensive view of the actual requirements needed for renovation and conservation projects related to specific buildings. Moreover, the use of digital twin technology is expected to create an accurate and up-to-date project data in a digitised format. This enables the stakeholders to validate their efforts, make better decisions, and build robust project databases that are precise. These databases, as discussed by Ammar *et al.,* [6] provide valuable insights for decision-making on sustainability of buildings. These further highlights how digital twins are particularly relevant and helpful in ensuring whether these buildings endure over time or not. The drivers for Digital Twin adoption in the Malaysian construction industry, as discussed above, have been categorised into four groups, as shown in Figure 2.

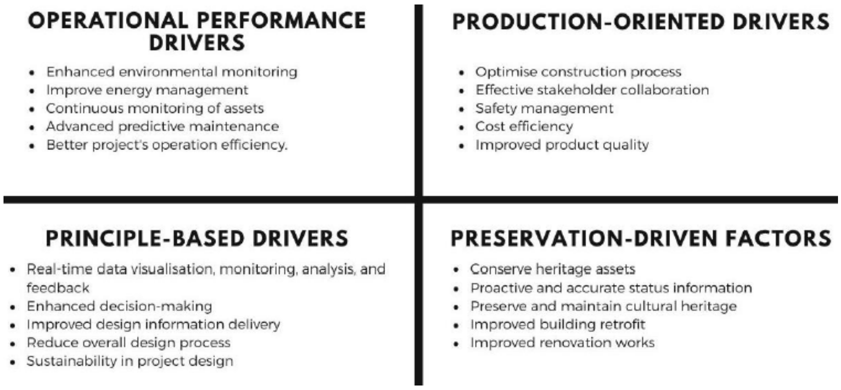

Fig. 2. Towards digital twin adoption in Malaysian construction industry

2.3 Research Gap & Positioning This Study

The rising issues in the Malaysian construction sector, such as low productivity, project delays, and minimal contributions to GDP, have resulted from a lack of interest in innovation and technology. Although several initiatives have been made to mandate the construction industry to digitalise, this development has been significantly slower compared to leading nations [39, 30]. Moreover, studies on digital twin technology in the construction sector of developing nations, including Malaysia, are practically non-existent. Previous investigations have indicated a substantial research gap in this field. There has been insufficient research and development on this subject, specifically regarding the application of Industry 4.0 by Ammar *et al.,* [6] and Madubuike *et al.,* [32]. Despite its significance in sectors such as manufacturing, the use of digital twins in the construction industry remains unexplored.

A major barrier is the limited technological infrastructure. Developing nations frequently lack the essential digital infrastructure required to facilitate the integration of advanced technologies such as digital twins. These limitations encompass inadequate internet access, insufficient capacity for data storage and processing, and a deficiency in integrated digital systems throughout the entire construction process [9]. Furthermore, there exists a significant skills gap. Construction personnel in Malaysia often lack the necessary skills and competence to proficiently employ digital twin technologies. This lack of necessary skills is exacerbated by the general scarcity of specialised training programmes and educational resources that focus on developing construction technologies [56].

Limited financial resources also have a substantial impact on impeding the implementation of digital twin technologies. The significant upfront costs linked to the adoption of digital twins, such as acquiring software, setting up hardware, and maintaining it over time, can be a barrier for numerous construction companies in developing nations. These companies often operate with little financial resources and may prioritise immediate operational requirements over long-term technology investments [62].

Despite these barriers, the advantages of digital twin technology in the construction industry are significant. An example of the utilising digital twin technology to enhance project monitoring and management is the Pan Borneo Highway project in Malaysia. This application has resulted in increased efficiency and minimised project delays [28]. Nevertheless, the broader use of this technology is hindered by a lack of clarity and understanding of its principles among industry professionals.

This study aims to fill these knowledge gaps by conducting a comprehensive analysis of the barriers and drivers that influence the use of digital twin technology in the construction sector of Malaysia. This research seeks to clarify the particular barriers and benefits related to the application of digital twin technology by gathering perspectives from construction professionals. Additionally, the results of the study will enhance the National Construction 4.0 Strategic Plan (2021-2025) by providing real information and practical recommendations to facilitate the digitalisation of Malaysia's construction industry. The insights gathered will assist policymakers, industry stakeholders, and practitioners in formulating targeted strategies to overcome existing barriers and harness digital twin technology for improved productivity, sustainability and innovation. This research fills a significant knowledge gap and offers a roadmap for successfully integrating digital twin technology into the construction industries of developing nations, promoting their growth and advancement.

3. Methodology

3.1 Survey Development

A questionnaire survey is a method systematically of gathering random data. It has frequently been utilised to acquire expert opinions in the field of construction management. Thus, a questionnaire survey was developed and used in this study to collect data.

To begin with, this study employs a systematic literature review (SLR) approach to conduct a thorough review of the existing literature, generating a list of potential strategies and capability factors. The first step of the SLR was to conduct a comprehensive search on existing Digital Twin in construction publications using the 'title/abstract/keyword' feature in the Scopus, Web of Science and Science Direct database. The search terms used were (digital twin" OR "digital replica" OR "digital counterpart" OR "virtual replica" OR "virtual twin") AND ("adopt*" OR "accept*" OR "implement*" OR "application" OR "usage") AND ("construction" OR "built environment" OR "construction industry" OR "building industry" OR "building sector"). The literature searches specifically include publications from the years 2013 to 2023 to exclude any outdated material. The selection criteria for literature search, including publication year, literature categories, and language, were meticulously evaluated to acquire dependable data and ensure the quality of the study.

The search with the specific keywords in databases returned a total of 1,362 articles, of which 189 were duplicates that needed to be removed, leaving 1,173 articles. The next step involved screening the articles according to the selection criteria stated below, resulting in only 331 articles remaining. Lastly, the remaining papers were screened, and 308 papers were excluded due to irrelevance to the research question or inaccessibility to full text articles. Ultimately, 23 papers were determined to be valid for further analysis. Figure 3 below illustrates the articles selected for the SLR through the PRISMA method.

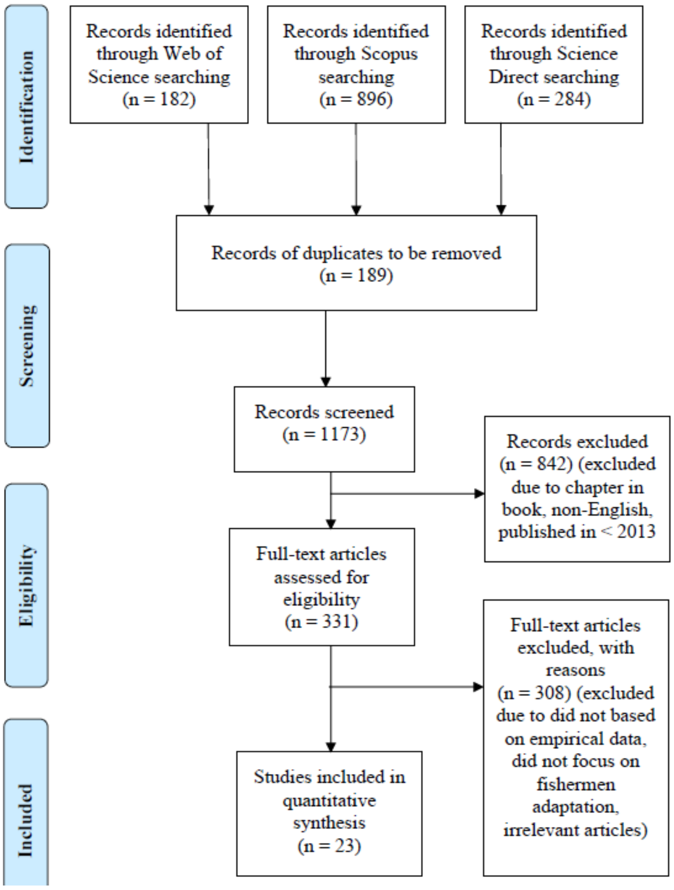

Fig. 3. The systematic literature review procedure (PRISMA framework) [44]

The study objectives and contact information were shown on the survey's front page, which was divided into four sections. To evaluate the reliability of the respondents' answers, the first section included questions about the respondents' organisations and their backgrounds. To ensure the credibility of the findings, the first section consisted of questions regarding the respondent's organizations and their experience. The second section focused on questions related to the implementation of digital twin technology in local constructions, ensuring the reliability of the respondent's responses. In the third section, respondents were asked about the frequency of barriers necessary for applying digital twin technology in the construction industry, followed by the question: 'How critical are the identified barriers? This was measured using a five-point Likert scale ranging from 1, 'not critical,' 2, 'less critical,' 3, 'neutral,' 4, 'critical,' to 5, 'extremely crucial'. As mentioned earlier, in the fourth section, the drivers identified through the literature review were numbered and rated using a five-point Likert scale based on how critical the drivers were in determining the adoption of digital twin technology in the Malaysian construction industry [27].

3.2 Data Collection

The target population includes all construction professionals employed by Malaysian construction companies that have obtained CIDB Grade 7 certification. The research will utilise purposive sampling to examine Malaysian construction companies that are registered with the

Construction Industry Development Board (CIDB). To gather valuable insights and achieve high-quality results, the survey will focus on construction professionals employed in Grade 7 firms. Additionally, the study will centre on Kuala Lumpur, the capital city of Malaysia, renowned for its extensive construction development. According to Showkat *et al.,* [57], this particular sampling method has proven to be highly effective and accurate. It carefully selects respondents from a group of experts in construction practices, ensuring the relevance of the data collected.

Realising that it would be quite tasking to administer the survey to the entire population of contractors in Grade 7, this research will need to make some adjustments to pull a sample size. A search was conducted on May 27, 2023, in CIMS, identifying these construction companies in Kuala Lumpur that fall under the G7 category, totalling 1,753. The respondents were identified in each of the firms involved; these individuals were professionals with prior knowledge of the application of digital twin technology. These initial respondents were later asked to propose other individuals with industrial or academic experience in the field. To improve the chances of completing the survey, follow-up messages were sent out a week later targeting those who did not respond to the first attempt. As a result, 97 valid responses were obtained for the current study.

Tables 1 and 2 below present the respondent profile of these 97 practitioners, with a specific focus on their industry experience and familiarity with digital twin technology. The survey participants have varying levels of experience in the AEC industry. The majority, 77%, have 0-5 years of experience, while a smaller percentage, 14.8%, have 6-10 years of experience. Only 5.7% have 11-15 years of experience, and a mere 0.9% have more than 15 years of experience. These findings demonstrate a decent level of knowledge and experience in the construction industry.

Table 1
Respondent Profile

Variables	Categories	Frequencies	Percentage (%)
Gender	Male	41	34.3
	Female	56	65.7
Profession	Architect	38	3.9
	Engineer	30	33.5
	Quantity Surveyor	14	44.3
	Contractor	9	5.7
	Others	6	12.6
Years of Experience	0 ~ 5 years	51	77.0
	6 ~ 10 years	15	14.8
	11 ~ 15 years	13	5.7
	16 ~ 20 years	12	0.9
	20 years and above	6	1.7

Table 2
Knowledge of Digital Twin

Do you know about Digital Twin?				
		Frequency	Percent	Cumulative Percent
Valid	Yes	54	55.7	55.7
	No	43	44.3	100.0
	Total	97	100.0	

4. Result

The exploratory factor analysis was carried out using the Statistic Package for the Social Sciences (SPSS) version 23.0 (Armonk, NY: IBM) for analysis process for this study.

4.1 Measurement Model Evaluation
4.1.1 Convergent validity

Establishing good measurement models is a prerequisite for testing the structural model. Therefore, the reliability and validity of the measurement models should be assessed. In term of reliability testing, the results in Table 3 show that the Cronbach's α coefficient exceeds the threshold of 0.7, indicating all variables have excellent internal consistency with a coherent relationship among 54 responses to the questions. Thus, the questionnaire is considered highly acceptable and reliable.

Table 3
Reliability statistics

Reliability Statistics	
Cronbach's Alpha	N of Items
0.896	26

With regard to the validity test, the Composite Reliability (CR) values range from 0.791 to 0.913, indicating that these values of CR are at acceptable levels. On the other hand, the values of Average Variance Extracted (AVE) range from 0.436 to 0.679, also falling within the acceptable range. Additionally, the values of factor loadings from the findings are above the threshold of 0.6. In summary, all constructs are acceptable, denoting the convergent validity of the factors measured, as shown in Table 4.

Table 4
Convergent Validity of the Variable

Variables	Item	Factor Loadings	*p*	Cronbach's α	Composite Reliability (CR)	Average Variance Extracted (AVE)
Barriers [B]	B1	0.512	**			
	B2	0.879	**			
	B3	0.780	**	0.707	0.872	0.538
	B4	0.804	**			
	B5	0.738	**			
	B6	0.629	**			
Principle-Based Drivers [PB]	PB1	0.856	**			
	PB2	0.713	**			
	PB3	0.719	**	0.708	0.892	0.626
	PB4	0.768	**			
	PB5	0.884	**			
Production-Oriented Drivers [PO]	PO1	0.788	**			
	PO2	0.744	**			
	PO3	0.545	**	0.664	0.791	0.436
	PO4	0.573	**			
	PO5	0.615	**			
Operational Performance Drivers [OP]	OP1	0.721	**			
	OP2	0.715	**			
	OP3	0.732	**	0.797	0.863	0.558
	OP4	0.785	**			
	OP5	0.778	**			
Preservation-Driven Factors [PD]	PD1	0.802	**			
	PD2	0.788	**			
	PD3	0.746	**	0.761	0.913	0.679
	PD4	0.847	**			
	PD5	0.926	**			

According to the findings in Table 4, the loadings of all variables and AVE values surpassed the suggested thresholds of 0.4 and 0.5, respectively, except for Production Oriented Drivers, which had a loading of approximately 0.436. The indicators and constructs demonstrate a satisfactory level of convergent validity, as noted by Hair *et al.,* [20]. Furthermore, the estimated composite reliability values and Cronbach's alpha values for all constructs exceeded the necessary threshold of 0.7, suggesting satisfactory internal consistency and reliability. However, the Production Oriented Drivers construct had a Cronbach's alpha value of 0.664, falling slightly below the desired level [20].

4.1.2 Discriminant validity

Furthermore, this study examined discriminant validity. The findings, which consist of the correlation matrix and the square roots of the Average Variance Extracted (AVE), can be found in Table 5. The outcomes in Table 5 show that the square roots of the AVE values are higher than the correlation coefficients in their particular columns. These findings show solid discriminant validity for the variables in this study.

Table 5
Discriminant validity of the variable

	PB	PO	OP	PD	B
PB	0.791				
PO	0.673	0.660			
OP	0.631	0.591	0.747		
PD	0.638	0.483	0.555	0.824	
B	0.566	0.383	0.258	0.191	0.734
Notes:	The underlined numbers represent the square roots of average variance extracted; The other numbers denote the correlation coefficient of the factors				

5. Discussions

5.1 Barriers that Impede Malaysian Construction Professionals from Adopting Digital Twin Technology

The study reveals that financial concerns are the most significant barrier, compared to other technological barriers, for construction professionals in using digital twins, as illustrated in Table 6 below. This is mainly because digital twin technology is a new concept in the construction industry. Implementing digital twins necessitates a substantial initial investment in technology, software, hardware, and skilled personnel [61]. In addition, there are ongoing expenses related to data storage, software updates, and maintenance. The full potential of implementing this technology in terms of financial viability is still to be fully understood.

Being a relatively new concept in the built environment, the intricacy of digital twin technology poses challenges to its widespread adoption [58]. The complexity of this situation presents difficulties for individuals and companies, making it the next highly ranked barrier. In this context, the government needs to provide training programmers and educational resources to construction professionals to help them expand their knowledge and improve their skills. Furthermore, the absence of standardised data formats and protocols can lead to unnecessary conflicts and restrict the potential advantages of digital twin technology. Thus, industry stakeholders and technology providers must work together to establish industry-wide standards [9].

Additionally, the findings suggest that barriers such as cybersecurity and intellectual property rights, as well as challenges related to diversity in source systems and interoperability, pose further barriers to widespread adoption [24]. Given that construction projects involve multiple stakeholders, some companies or individuals may be slow to embrace digital twin technology because of security concerns and protection of ownership rights.

Therefore, it is clear that the use of digital twin technology, which is still relatively new and has only recently been adopted in the construction industry has certain disadvantages and risks that can negatively affect its development. Adopting new technology presents significant challenges due to various factors, notably the risks which accompany adaptation, unpredictability, questions regarding the efficiency, reliability and viability of the technology in the future. However, there is a general agreement that with advancement in digital twin technology over the coming years, it will mature into a more established and reliable solution [37]. For this reason, the impediments to implementation are expected to reduce, allowing the technology to reach its full potential and induce positive changes in the construction industry. Hence, the study summarizes through Table 6 on the ranking for barriers towards digital twin adoption.

Table 6
Ranking for barriers towards digital twin adoption

Item	Factors	Mean	Rank
B4	Financial Uncertainties	4.70	1
B1	Complexity of Digital Twin Technology	4.56	2
B2	Lack of Standardization	4.48	3
B3	Cyber Security and Intellectual Property Right	4.35	4
B6	Diversity in Source System and Interoperability Issue	4.35	4
B5	Novelty of Technology	4.26	5

5.2 Major Drivers of Digital Twin Adoption in Malaysian Construction Practice

The literature analysis has identified 20 factors that foster the use of digital twin technology in the construction industry. This paper aims to enhance understanding of the factors affecting the implementation of digital twin technology (Table 1). Four main themes of drivers were identified, corresponding to the building life cycle phases described in section 2. 2. Some of these themes were principle-based drivers that were emphasised during the actualisation phase while others were construction-based drivers propelled during the construction phase, operational performance drivers during the operating phase and preservation-driven factors during the maintenance phase.

The operational performance driver got the highest mean score, implying that it has the most significant impact on utilising the digital twin approach during the operational phase of the building life cycle. This finding supports the assertion made by Delgado *et al.,* [14] states that the overarching goal of digital twin technology is to increase the productivity and functionality of 'buildings'. Construction professionals recognise that digital twin technology is significant for improving building performance, energy efficiency, continuous monitoring and optimisation, and occupant satisfaction during the building's use phase. This emphasises the relevance of digital twins as an efficient approach to modern construction, focusing on sustainability in the context of making a contribution toward finding the ways to create a more sustainable world. Table 7 below shows the ranking and mean scores of the above mentioned drivers.

Table 7
Ranking for main drivers towards digital twin adoption

Item	Factors	Mean	Rank
OP	Operational Performance Drivers	4.38	1
PO	Production-Oriented Drivers	4.33	2
PB	Principle-Based Drivers	4.29	3
PD	Preservation-Driven Factors	4.13	4

The second group comprises production-oriented drivers, with principle-based drivers following closely behind. The following drivers are more associated with the design and construction phases. Since the results discussed above show positive effects from introducing a digital twin early in a project, it is possible to conclude that digital twin serves as a foundation for a better built environment. This is not bad because, at this stage, digital twins enable key players to enhance construction activities, improve engagement, and reduce the likelihood of costly errors [11]. Thus, the outcomes of this approach outweigh the initial costs.

They received the lowest mean scores as they are the factors that relate to the conservation and maintenance of building condition. Respondents do not think that this aspect significant in their decision-making regarding the use of digital twins for constructing buildings and other structures. However, literature analysis implies that some of the applications of digital twins (DT) in the manufacturing industry include real-time monitoring, production control, production planning, predictive maintenance, defect detection, and monitoring the status of different systems [43, 49].

Therefore, this perception may depend on respondents' geographical sampling and the research experience of the participants. Given that the uptake of DT among developing nations is low, this driver of preservation is underutilised. Overall, the scores for all four drivers are slightly above 4, which is the passing grade in most courses. It was on a five-point Likert scale, with a score of 0 given for "strongly disagree" while 5 was given to "strongly agree". This implies that the participants regard these drivers as very crucial in applying digital twin technology in construction projects. Through the survey, the authors present the ratings of perceived drivers, which can significantly aid in setting priorities and developing corresponding strategies for applying digital twins in construction.

5.3 Theoretical Contribution

This paper investigates the theoretical contributions of examining the extent of digital twin applications within several construction processes. Based on this, the literature review sheds light on new perspectives, thereby extending the understanding of the field, regarding the concept of digital twin technology and discussing opportunities for innovation in the context of the construction industry. This study classifies various Digital Twin adoption in Malaysian construction practices drivers into four main themes: principle-based drivers, production drivers, operational performance, and preservation factors. These categories illustrate the principles that govern activity at all phases of the building life cycle, namely conception, construction, utilisation and rejuvenation. Therefore, the study enhances our understanding of the aspects that lead to the acceptance of the DT technology. This comprehensive list of determinants reveals the critical drivers for integrating digital twins into the construction industry.

5.4 Practical Contribution

This study provides the information about current state and recent advancements associated with digital twin applications in the Malaysian construction industry. This valuable information helps organisations understand the drivers of digital twin implementation at different phase of the construction life cycle. If these factors are well understood and given due importance by those within the construction industry, digital twin technology can offer several advantages at various stages of a construction project, including design, build, management and maintenance. Such integrations can lead to optimised building performance, reduced costs (as radical novelties may not always add value), increased sustainability, and an enriched experience for users of the built environment.

The principal factors identified that enhance the efficiency and effectiveness of the construction practices in Malaysia are operational performance drivers. These drivers imply that companies should abandon traditional methods and incorporate digital twin technology. Such a shift is likely to bring about necessary positive changes in pursuit of sustainable development within the construction industry. Before elaborating on the lessons drawn from this study, it is crucial to identify the barriers that must be overcome by governments and construction companies in order to successfully implement new technologies, particularly those related to financial sphere. Additionally, this research can contribute to the government underscoring the importance of adopting digital twin to transform construction companies' operations and achieve sustainable growth. The recommendations provided herein can serve as a stable foundation for knowledge creation and guidance in line with the goals set out in the National Construction Policy 2030 (NCP 2030) to transition the construction industry under the digitisation era. Based on the findings of this research, the following suggestions are made to the stakeholders in order to promote the use of digital twin technology and enhance the development of a digitally driven construction industry in the country.

5.5 Limitations and Future Work

Some challenges encountered during this research stemmed from the limited information available on the implementation of digital twin technology, especially in the setting of Malaysia. Due to this limitation, the research had to focus on international literature relating to the application of DT in similar construction contexts. While these sources provided some useful knowledge and elasticity regarding the framework they presented, they do not encompass all the unique characteristics of the Malaysian construction industry.

Additionally, the study's conclusion are based on perspectives from employees working in Grade 7 construction companies in Kuala Lumpur. For this reason, companies of different size or those located in other states may have diverse opinions and face different limitations regarding the implementation of digital twin concept. Future studies should aim to include a broader selection of companies from various states to gain a more comprehensive understanding of the adoption of digital twin technology in Malaysia.

It is therefore the recommended that future studies prioritise several important areas. Firstly, there is an urgent need to conduct detailed case studies and interviews with the organisations that have successfully implemented digital twins. Such studies will provide tangible and more realistic cooperation views that are not restricted to just theoretical debates. As shown in case studies, the tangible effectiveness and challenges faced during the application and implementation of digital twin innovations ensure a credible proposition of their actuality, possibility, and transmutation of digital twins in our world.

6. Conclusions

The study's conclusions show that the factors driving and hindering the adoption of digital twin technology have been thoroughly tested and corroborated by other studies. The findings suggest that operational performance is the main factor influencing the adoption of digital twin technology. By utilising information relayed in real time and displayed graphically, this technology can enhance the building operation phase and added value in terms of operation and efficiency.

However, the most prominent challenge related to the implementation of technology is financial uncertainty. As far as the priorities are concerned, financial issues are always a concern due to capital-intensive investments that can be quite expensive, volatile ROI, and overall budget constraints. It was also observed that implementing new technology often requires collaboration among communities, government bodies and relevant authorities. Since the utilisation of digital twin solutions in the construction industry depends on each participant's actions, all stakeholders are vital.

The application of digital twin technology is already recognised in the construction sector as an enabler of its digitalisation. Given that the sector still remains in early stages of its approach to digital twins, there is potential to enhance its previously poor history in digitalisation. Both the industrial and aerospace industries have previously utilised digital twin technology, and the construction industry can therefore benefit from a wealth of past practices and initiatives [8]. This paper reveals the potential for the industry to improve project outcomes based on the adaptability of digital twin concepts to the specific requirements and characteristics of the construction sector.

Therefore, according to the conclusions of the study, it is essential to address the financial risks and enhance stakeholder collaboration to harness the best outcomes from applying the concept of digital twins in the construction domain. This strategy will enhance the overall effectiveness and adaptability of the sector while advancing its digitalisation process.

Data Availability Statements
Some or all data, models, or code generated or used during the study are proprietary or confidential in nature and may only be provided with restrictions (e.g., anonymized data).

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References
[1] Abdul-Samad, Zulkiflee, Lim Liang Xin, Wesam Salah Alaloul, and Hafez Salleh. "Towards Industrial Revolution (IR) 4.0 in the Construction Industry: Readiness of Contractors." *Results in Engineering* (2024): 102321. https://doi.org/10.1016/j.rineng.2024.102321

[2] Abusohyon, Islam Asem Salah, Alberto Crupi, Faezeh Bagheri, and Flavio Tonelli. "How to set up the pillars of digital twins technology in our business: Entities, challenges and solutions." *Processes* 9, no. 8 (2021): 1307. https://doi.org/10.3390/pr9081307

[3] Agostinelli, Sofia, Fabrizio Cumo, Giambattista Guidi, and Claudio Tomazzoli. "Cyber-physical systems improving building energy management: Digital twin and artificial intelligence." *Energies* 14, no. 8 (2021): 2338. https://doi.org/10.3390/en14082338

[4] Alaloul, Wesam Salah, Muhammad Altaf, Muhammad Ali Musarat, Muhammad Faisal Javed, and Amir Mosavi. "Systematic review of life cycle assessment and life cycle cost analysis for pavement and a case study." *Sustainability* 13, no. 8 (2021): 4377. https://doi.org/10.3390/su13084377

[5] Ammar, A., and G. B. Dadi. "Towards an Integrated Building Information Modeling (BIM) and Geographic Information System (GIS) Platform for Infrastructure." In *ISARC. Proceedings of the International Symposium on Automation and Robotics in Construction*, vol. 38, pp. 129-136. IAARC Publications, 2021. https://doi.org/10.22260/ISARC2021/0020

[6] Ammar, Ashtarout, Hala Nassereddine, Nadine AbdulBaky, Anwar AbouKansour, Juliano Tannoury, Harald Urban, and Christian Schranz. "Digital twins in the construction industry: a perspective of practitioners and building authority." *Frontiers in Built Environment* 8 (2022): 834671. https://doi.org/10.3389/fbuil.2022.834671

[7] Araújo, Caroline Silva, Dayana Bastos Costa, Fabiano Rogerio Corrêa, and Emerson de Andrade Marques Ferreira. "Digital twins and lean construction: Challenges for future practical applications." In *Proceedings IGLC*, vol. 30. 2022. https://doi.org/10.24928/2022/0126
[8] Ariffin, Erni Yusnida, Nur Emma Mustafa, and Maimunah Sapri. "Awareness on BIM-FM Integration at an Early Stage of The BIM Process Amongst FM Organisations in Malaysia." *Journal of Advanced Research in Technology and Innovation Management* 1, no. 1 (2021): 9-22.
[9] Attaran, Mohsen, and Bilge Gokhan Celik. "Digital Twin: Benefits, use cases, challenges, and opportunities." *Decision Analytics Journal* 6 (2023): 100165. https://doi.org/10.1016/j.dajour.2023.100165
[10] Autodesk Construction Cloud. 2022. Harnessing the Data Advantage in Construction.
[11] Bagireanu, Astrid, Julio Bros-Williamson, Mila Duncheva, and John Currie. "Digital Twins: Towards an Overarching Framework for the Built Environment." (2024).
[12] Barbosa, Filipe, Jonathan Woetzel, and Jan Mischke. *Reinventing construction: A route of higher productivity*. McKinsey Global Institute, 2017.
[13] Boje, Calin, Sylvain Kubicki, Annie Guerriero, Yacine Rezgui, and Alain Zarli. "Digital twins for the built environment." In *Buildings and Semantics*, pp. 179-199. CRC Press, 2022. https://doi.org/10.1201/9781003204381-10
[14] Delgado, Juan Manuel Davila, and Lukumon Oyedele. "Digital Twins for the built environment: learning from conceptual and process models in manufacturing." *Advanced Engineering Informatics* 49 (2021): 101332. https://doi.org/10.1016/j.aei.2021.101332
[15] Dehdasht, Gholamreza, M. Salim Ferwati, Nazirah Zainul Abidin, and Michael Olubukola Oyedeji. "Trends of construction industry in Malaysia and its emerging challenges." *Journal of Financial Management of Property and Construction* 27, no. 2 (2022): 161-178. https://doi.org/10.1108/JFMPC-08-2020-0054
[16] Deng, Min, Carol C. Menassa, and Vineet R. Kamat. "From BIM to digital twins: A systematic review of the evolution of intelligent building representations in the AEC-FM industry." *Journal of Information Technology in Construction* 26 (2021). https://doi.org/10.36680/j.itcon.2021.005
[17] Denis Branthonne. "Can the Construction Industry Catch Up on Digitisation?". *Novade* (2017).
[18] Glodon Company. "Digitalisation in Construction Industry and New Roles of Quantity Surveying Profession". *PR Newswire* (2023).
[19] Göçer, Özgür, Ying Hua, and Kenan Göçer. "A BIM-GIS integrated pre-retrofit model for building data mapping." In *Building Simulation*, vol. 9, pp. 513-527. Springer Berlin Heidelberg, 2016. https://doi.org/10.1007/s12273-016-0293-4
[20] Hair, Joe F., Christian M. Ringle, and Marko Sarstedt. "PLS-SEM: Indeed a silver bullet." *Journal of Marketing theory and Practice* 19, no. 2 (2011): 139-152. https://doi.org/10.2753/MTP1069-6679190202
[21] Jaiswal, Shubham V., Dexter VL Hunt, and Richard J. Davies. "Construction 4.0: A Systematic Review of Its Application in Developing Countries." *Applied Sciences* 14, no. 14 (2024): 6197.
[22] Ismail, Noor Akmal Adillah, Maria Chiozzi, and Robin Drogemuller. "An overview of BIM uptake in Asian developing countries." In *AIP conference Proceedings*, vol. 1903, no. 1. AIP Publishing, 2017. https://doi.org/10.1063/1.5011596
[23] Istanbullu, A., S. Wamuziri, and M. Siddique. "BIM Digital twins environment to enhance construction process." In *IOP Conference Series: Earth and Environmental Science*, vol. 1055, no. 1, p. 012006. IOP Publishing, 2022. https://doi.org/10.1088/1755-1315/1055/1/012006
[24] Jahangir, Muhammad Farhan, Carl Peter Leslie Schultz, and Aliakbar Kamari. "A review of drivers and barriers of Digital Twin adoption in building project development processes." *Journal of Information Technology in Construction (ITcon)* 29, no. 8 (2024): 141-178. https://doi.org/10.36680/j.itcon.2024.008
[25] Javaid, Mohd, Abid Haleem, Ravi Pratap Singh, and Rajiv Suman. "Significance of Quality 4.0 towards comprehensive enhancement in manufacturing sector." *Sensors International* 2 (2021): 100109. https://doi.org/10.1016/j.sintl.2021.100109
[26] El Jazzar, Mahmoud, Christian Schranz, Harald Urban, and Hala Nassereddine. "Integrating construction 4.0 technologies: A four-layer implementation plan." *Frontiers in Built Environment* 7 (2021): 671408. https://doi.org/10.3389/fbuil.2021.671408
[27] Joshi, Ankur, Saket Kale, Satish Chandel, and D. Kumar Pal. "Likert scale: Explored and explained." *British journal of applied science & technology* 7, no. 4 (2015): 396-403. https://doi.org/10.9734/BJAST/2015/14975
[28] Jotham Lim. "Cover Story: Digital Twins IoT and AI?". *The Edge Malaysia*. 2021.
[29] Khajavi, Siavash H., Naser Hossein Motlagh, Alireza Jaribion, Liss C. Werner, and Jan Holmström. "Digital twin: vision, benefits, boundaries, and creation for buildings." *IEEE access* 7 (2019): 147406-147419. https://doi.org/10.1109/ACCESS.2019.2946515

[30] Khudzari, F, R A Rahman, and S K Ayer. 2021. "Factors Affecting the Adoption of Emerging Technologies in the Malaysian Construction Industry". *IOP Conference Series: Earth and Environmental Science* 641 (1): 12006. https://doi.org/10.1088/1755-1315/641/1/012006
[31] Liu, Zhansheng, Xintong Meng, Zezhong Xing, and Antong Jiang. "Digital twin-based safety risk coupling of prefabricated building hoisting." *Sensors* 21, no. 11 (2021): 3583. https://doi.org/10.3390/s21113583
[32] Madubuike, Obinna C., Chimay J. Anumba, and Rana Khallaf. "A review of digital twin applications in construction." *Journal of Information Technology in Construction* 27 (2022). https://doi.org/10.36680/j.itcon.2022.008
[33] Mansour, Husam, Eeydzah Aminudin, Balqis Omar, Rozana Zakaria, Santi Edra Nisa Lau, and Ali Al-Sarayreh. "Industry 4.0 and construction performance: From literature review to conceptual framework." *Malays. Constr. Res. J* 13 (2021): 53-67.
[34] Biörck, Jonas, Jose Luis Blanco, Jan Mischke, Maria João Ribeirinho, David Rockhill, Erik Sjödin, and Gernot Strube. "How construction can emerge stronger after coronavirus." *McKinsey & Company* (2020).
[35] Melvin Leong. "Digital Twin and BIM in the Global Water and Building Industries". *The Star*. 2020.
[36] Michael, Judith, Jérôme Pfeiffer, Bernhard Rumpe, and Andreas Wortmann. "Integration challenges for digital twin systems-of-systems." In *Proceedings of the 10th IEEE/ACM International Workshop on Software Engineering for Systems-of-Systems and Software Ecosystems*, pp. 9-12. 2022. https://doi.org/10.1145/3528229.3529384
[37] Moshood, Taofeeq D., James OB Rotimi, Wajiha Shahzad, and J. A. Bamgbade. "Infrastructure digital twin technology: A new paradigm for future construction industry." *Technology in Society* 77 (2024): 102519. https://doi.org/10.1016/j.techsoc.2024.102519
[38] Müller, Roger, and Mark Veser. "The current state of nonfinancial reporting in Switzerland and beyond." *Die Unternehmung* 74, no. 3 (2020): 296-311. https://doi.org/10.5771/0042-059X-2020-3-296
[39] Nour El-Din, Mohamed, Pedro F. Pereira, João Poças Martins, and Nuno MM Ramos. "Digital twins for construction assets using BIM standard specifications." *Buildings* 12, no. 12 (2022): 2155. https://doi.org/10.3390/buildings12122155
[40] Oesterreich, Thuy Duong, and Frank Teuteberg. "Understanding the implications of digitisation and automation in the context of Industry 4.0: A triangulation approach and elements of a research agenda for the construction industry." *Computers in industry* 83 (2016): 121-139. https://doi.org/10.1016/j.compind.2016.09.006
[41] Opoku, De-Graft Joe, Srinath Perera, Robert Osei-Kyei, Maria Rashidi, Tosin Famakinwa, and Keivan Bamdad. "Drivers for digital twin adoption in the construction industry: A systematic literature review." *Buildings* 12, no. 2 (2022): 113. https://doi.org/10.3390/buildings12020113
[42] Opoku, De-Graft Joe, Srinath Perera, Robert Osei-Kyei, and Maria Rashidi. "Digital twin application in the construction industry: A literature review." *Journal of Building Engineering* 40 (2021): 102726. https://doi.org/10.1016/j.jobe.2021.102726
[43] Opoku, De-Graft Joe, Srinath Perera, Robert Osei-Kyei, Maria Rashidi, Keivan Bamdad, and Tosin Famakinwa. "Barriers to the adoption of digital twin in the construction industry: A literature review." In *Informatics*, vol. 10, no. 1, p. 14. MDPI, 2023. https://doi.org/10.3390/informatics10010014
[44] Page, Matthew J., David Moher, Patrick M. Bossuyt, Isabelle Boutron, Tammy C. Hoffmann, Cynthia D. Mulrow, Larissa Shamseer et al. "PRISMA 2020 explanation and elaboration: updated guidance and exemplars for reporting systematic reviews." *bmj* 372 (2021). https://doi.org/10.1136/bmj.n160
[45] Philipp Gerbert et al., "The Transformative Power of Building Information Modeling Digital in Engineering and Construction". *Boston Consulting Group*. 2016.
[46] Rafiq, Waqas, Muhammad Ali Musarat, Muhammad Altaf, Madzlan Napiah, Muslich Hartadi Sutanto, Wesam Salah Alaloul, Muhammad Faisal Javed, and Amir Mosavi. "Life cycle cost analysis comparison of hot mix asphalt and reclaimed asphalt pavement: A case study." *Sustainability* 13, no. 8 (2021): 4411. https://doi.org/10.3390/su13084411
[47] Rameezdeen, Raufdeen. 2008. 'Study of Linkages Between Construction Sector And', no. 1958: 1–15.
[48] Rasheed, Adil, Omer San, and Trond Kvamsdal. "Digital twin: Values, challenges and enablers from a modeling perspective." *IEEE access* 8 (2020): 21980-22012. https://doi.org/10.1109/ACCESS.2020.2970143
[49] Talib, Rozilah, Nik Norzahariah Ashikin N. Mohamed, Nafisah Ya'cob, Ng Jia Jian, and Mazura Mahdzir. "Sustainable Construction Method: Key Issues of BIM Implementation in Malaysia." *Journal of Advanced Research in Technology and Innovation Management* 8, no. 1 (2023): 1-15.
[50] Saad, Syed, Wesam Salah Alaloul, Syed Ammad, Muhammad Altaf, and Abdul Hannan Qureshi. "Identification of critical success factors for the adoption of Industrialized Building System (IBS) in Malaysian construction industry." *Ain Shams Engineering Journal* 13, no. 2 (2022): 101547. https://doi.org/10.1016/j.asej.2021.06.031
[51] Sacks, Rafael, Ioannis Brilakis, Ergo Pikas, Haiyan Sally Xie, and Mark Girolami. "Construction with digital twin information systems." *Data-Centric Engineering* 1 (2020): e14. https://doi.org/10.1017/dce.2020.16

[52] Salem, Tareq, and Mihai Dragomir. "Options for and challenges of employing digital twins in construction management." *Applied Sciences* 12, no. 6 (2022): 2928. https://doi.org/10.3390/app12062928
[53] Sargent, Kimberley, Paul Hyland, and Sukanlaya Sawang. "Factors influencing the adoption of information technology in a construction business." *Australasian Journal of Construction Economics and Building, The* 12, no. 2 (2012): 72-86. https://doi.org/10.5130/AJCEB.v12i2.2448
[54] Sepasgozar, Samad ME, Felix Kin Peng Hui, Sara Shirowzhan, Mona Foroozanfar, Liming Yang, and Lu Aye. "Lean practices using building information modeling (Bim) and digital twinning for sustainable construction." *Sustainability* 13, no. 1 (2020): 161. https://doi.org/10.3390/su13010161
[55] Shahzad, Muhammad, Muhammad Tariq Shafiq, Dean Douglas, and Mohamad Kassem. "Digital twins in built environments: an investigation of the characteristics, applications, and challenges." *Buildings* 12, no. 2 (2022): 120. https://doi.org/10.3390/buildings12020120
[56] Sharma, Angira, Edward Kosasih, Jie Zhang, Alexandra Brintrup, and Anisoara Calinescu. "Digital twins: State of the art theory and practice, challenges, and open research questions." *Journal of Industrial Information Integration* 30 (2022): 100383. https://doi.org/10.1016/j.jii.2022.100383
[57] Showkat, Nayeem, and Huma Parveen. "Non-probability and probability sampling." *Media and Communications Study* 6, no. 1 (2017): 1-9.
[58] da Silva, Leonardo Breno Pessoa, Ramon Soltovski, Joseane Pontes, Fernanda Tavares Treinta, Paulo Leitão, Elaine Mosconi, Luis Mauricio Martins de Resende, and Rui Tadashi Yoshino. "Human resources management 4.0: Literature review and trends." *Computers & Industrial Engineering* 168 (2022): 108111. https://doi.org/10.1016/j.cie.2022.108111
[59] Simchenko, N., S. Tsohla, and P. Chyvatkin. "IoT & digital twins concept integration effects on supply chain strategy: challenges and effect." *International Journal of Supply Chain Management* 8, no. 6 (2019): 803-808.
[60] Maningas, Ruel, and Kenrick Matriano. "Digital Horizons: The Transformative Role of Information Systems in the Smart City Landscape." *SMN Digest* 10, no. 1 (2024): 1-1.
[61] Tuhaise, Valerian Vanessa, Joseph Handibry Mbatu Tah, and Fonbeyin Henry Abanda. "Technologies for digital twin applications in construction." *Automation in Construction* 152 (2023): 104931. https://doi.org/10.1016/j.autcon.2023.104931
[62] Waqar, Ahsan, Idris Othman, Hamad Almujibah, Muhammad Basit Khan, Saleh Alotaibi, and Adil AM Elhassan. "Factors influencing adoption of digital twin advanced technologies for smart city development: Evidence from Malaysia." *Buildings* 13, no. 3 (2023): 775. https://doi.org/10.3390/buildings13030775
[63] Xie, M. C., and Wei Pan. "Opportunities and challenges of digital twin applications in modular integrated construction." In *ISARC. Proceedings of the International Symposium on Automation and Robotics in Construction*, vol. 37, pp. 278-284. IAARC Publications, 2020. https://doi.org/10.22260/ISARC2020/0040
[64] Yitmen, Ibrahim, Sepehr Alizadehsalehi, İlknur Akıner, and Muhammed Ernur Akıner. "An adapted model of cognitive digital twins for building lifecycle management." *Applied Sciences* 11, no. 9 (2021): 4276. https://doi.org/10.3390/app11094276
[65] Lin, Yu-Cheng, and Weng-Fong Cheung. "Developing WSN/BIM-based environmental monitoring management system for parking garages in smart cities." *Journal of Management in Engineering* 36, no. 3 (2020): 04020012. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000760