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ASSESSING ASSET MANAGEMENT IN AEC/FM: UNVEILING LIMITATIONS AND ADVANCING SOLUTIONS WITH DIGITAL TWIN

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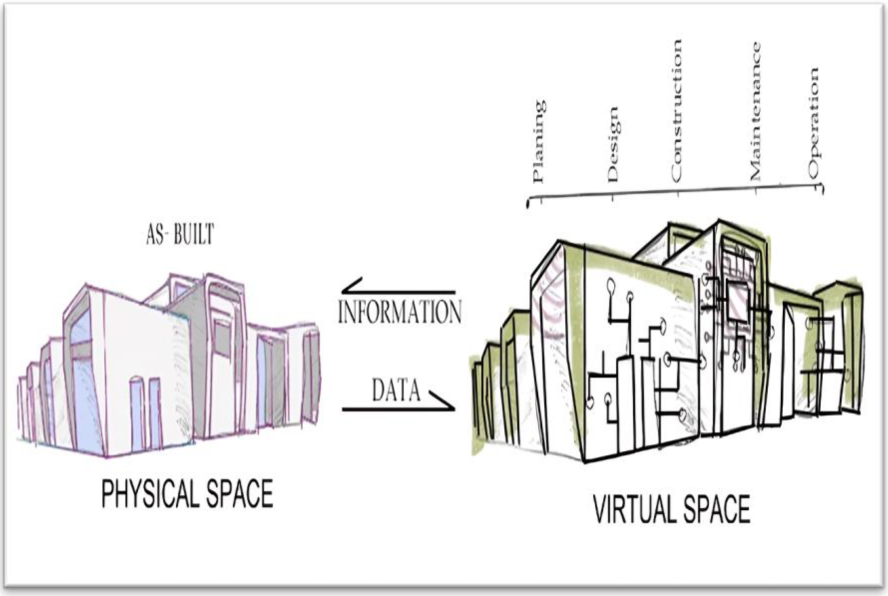

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Cover: Digital twin for asset management

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Declaration of Original Work

I, Abdelmoneim Mohamed Abdelmoneim Abdelmoti, the undersigned, a graduate student at the United Arab Emirates University (UAEU), and the author of this thesis entitled "*Assessing Asset Management in AEC/FM: Unveiling Limitations and Advancing Solutions with Digital Twin*", hereby, solemnly declare that this is the original research work done by me under the supervision of Dr./Prof. Muhammad Tariq Shafiq, in the College of Engineering at UAEU. This work has not previously formed the basis for the award of any academic degree, diploma or a similar title at this or any other university. Any materials borrowed from other sources (whether published or unpublished) and relied upon or included in my thesis have been properly cited and acknowledged in accordance with appropriate academic conventions. I further declare that there is no potential conflict of interest with respect to the research, data collection, authorship, presentation and/or publication of this thesis.

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Abstract

In recent years, the concept of Digital Twins (DTs) has emerged as a transformative technological innovation with the potential to revolutionize asset management practices. A Digital Twin is a digital representation closely linked to a physical entity, enabling bidirectional information exchange and data-driven decision-making. Within the realm of Architecture, Engineering, and Construction/Facilities Management (AEC/FM), DTs offer a diverse array of applications for enhancing asset management.

This thesis aims to demystify the concept of DTs and explore their existing applications in asset management, particularly within the AEC/FM industry. To achieve this, the research employs a two-fold approach: a systematic review of existing literature followed by structured interviews with FM professionals.

The systematic literature review revealed that the construction processes of DTs are still in their nascent stages. However, it unveiled a multitude of potential applications for DTs across the entire lifecycle of assets. These applications encompass sustainable retrofitting, predictive maintenance, and the preservation of heritage assets.

The interviews conducted with FM experts provided valuable insights into the current state of facility management, the challenges faced by FM personnel, and a glimpse into the future of the industry. Moreover, these discussions led to recommendations for further research in this evolving domain.

In summary, this thesis advances our understanding of DT and sheds light on its multifaceted applications in asset management, with a particular focus on the dynamic landscape of the AEC/FM industry. It underscores the transformative potential of DT as a tool for optimizing asset performance and decision-making throughout the asset lifecycle.

Keywords: Architecture, Engineering, and Construction (AEC), Digital Twin (DT), Asset Management, Facility Management (FM), Building Information Modeling (BIM).

Title and Abstract (in Arabic)

تقييم إدارة الأصول في AEC/FM: الكشف عن القيود وتطوير الحلول باستخدام التوأم الرقمي

الملخص

في السنوات الأخيرة، برز مفهوم التوأم الرقمي كابتكار تكنولوجي تحويلي مع القدرة على إحداث ثورة في ممارسات إدارة الأصول. التوأم الرقمي هو تمثيل رقمي مرتبط ارتباطًا وثيقًا بكيان مادي، مما يتيح تبادل المعلومات ثنائي الاتجاه واتخاذ القرارات المستندة إلى البيانات. في مجال الهندسة المعمارية والهندسة والبناء/إدارة المرافق، يقدم التؤم الرقمي مجموعة متنوعة من التطبيقات لتعزيز إدارة الأصول.

تهدف هذه الأطروحة إلى إزالة الغموض عن عملية بناء التوائم الرقمية واستكشاف تطبيقاتها الحالية في إدارة الأصول، لا سيما في صناعة إدارة المرافق. ولتحقيق ذلك، يستخدم البحث نهجا ذا شقين: مراجعة منهجية للأدبيات الموجودة تليها مقابلات منظمة مع المتخصصين في إدارة المرافق.

كشفت المراجعة المنهجية للأدبيات أن عمليات بناء التوائم الرقمية لا تزال في مراحلها الأولى. ومع ذلك، فقد كشفت عن العديد من التطبيقات المحتملة للتوائم الرقمية عبر دورة حياة الأصول بأكملها. وتشمل هذه التطبيقات التعديل التحديثي المستدام، والصيانة التنبؤية، والحفاظ على الأصول التراثية.

قدمت المقابلات التي أجريت مع خبراء إدارة المرافق رؤى قيمة حول الوضع الحالي لإدارة المرافق، والتحديات التي يواجها موظفو إدارة المرافق، ولمحة عن مستقبل الصناعة. علاوة على ذلك، أدت هذه المناقشات إلى توصيات لإجراء مزيد من البحث في هذا المجال المتطور.

باختصار، تعمل هذه الأطروحة على تطوير فهمنا لعملية بناء التوأم الرقمي وتلقي الضوء على تطبيقاتها متعددة الأوجه في إدارة الأصول، مع التركيز بشكل خاص على المشهد الديناميكي لصناعة إدارة المرافق. وهو يؤكد على الإمكانات التحويلية للتوائم الرقمية كأداة لتحسين أداء الأصول واتخاذ القرار طوال دورة حياة الأصول.

مفاهيم البحث الرئيسية: الهندسة المعمارية والهندسة والبناء، التوأم الرقمي، إدارة الأصول، إدارة المرافق، نمذجة معلومات البناء.

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Furthermore, I acknowledge the United Arab Emirates University for providing the resources and environment that facilitated this research.

Thank you all for being a part of this important chapter in my academic life.

Dedication

To my beloved parents and friends,

Your unwavering support made this possible.

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List of Abbreviations

AEC	Architecture/Engineering/Construction
AI	Artificial Intelligence
AIM	Asset Information Model
BIM	Building Information Models
BIFM	British Institute of Facilities Management
CAD	Computer-Aided Design
DT	Digital Twins
FM	Facilities Management
HBIM	Historic Building Information Modeling
IoT	Internet of Things
LiDAR	Light Detecting and Ranging
NASA	National Aeronautical Space Administration
NGO	Non-Governmental Organization
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
TTM	Time to Market
UAE	United Arab Emirates
UAEU	United Arab Emirates University
UML	Unified Modeling Language
WoS	Web of Science

Chapter 1: Introduction

This chapter initiates the comprehensive research study within this thesis. It begins by exploring the historical context of the research field, highlighting key developments and milestones in digitalization and digital twins. Next, it identifies the research problem through a critical analysis of existing literature, setting the stage for the research aim and objectives. The chapter concludes by outlining the thesis structure and previewing the upcoming chapters.

The development of technology has taken many forms and is evolving at a rapid pace to provide comfort and efficiency in every aspect of human life. Technological advances and digitalization over the past decade have transformed the way services are offered in various domains such as healthcare, transportation, education, governance, and construction (Afzal & Shafiq, 2021; F. Jiang et al., 2017). In simpler terms, digitalization refers to the adoption of advanced information technology to automate, streamline, and improve the operations of businesses (Gobble, 2018). The emergence of technologies, such as AI, machine learning, IoT, cloud computing, blockchains, and big data analytics, has made the transition to digitalization easier. One of the domains leveraging the use of digitalization is the construction and architectural industries (Alaloul et al., 2018), whereby architects incorporate technology into their designs, showcasing distinctive architectural forms while reducing energy, water, and raw material consumption (L. Zhang et al., 2019). This informative and digital architecture provides a higher level of comfort for end users (W. Zhang et al., 2019). In particular, digitalization can serve as an aid for making the asset management process in the Architecture, Engineering, and Construction (AEC) industry more efficient.

1.1 Background

1.1.1 Traditional Facility Management Approaches

Facility Management (FM) involves the comprehensive management of an organization's physical assets, encompassing property, infrastructure, and human resources (van der Voordt, 2017). This discipline includes managing security, safety, environmental factors, and the procurement of supplies and services necessary to ensure the smooth operation of facilities. The primary goal of FM is to ensure the proper maintenance and efficient utilization of an organization’s physical assets, thereby supporting the overall mission and objectives of the organization (van der Voordt, 2017). This concept encompasses the comprehensive management of property, physical infrastructure, and human resources, all aimed at elevating service quality, minimizing operating costs, and amplifying overall business value. Although the term “FM” might be relatively recent, the practice of FM has roots tracing back through the annals of organizational history.

The emergence of FM as a recognized and professionalized field commenced in the early 1980s, marking a pivotal moment in its evolution (van der Voordt, 2017). During this era, organizations such as the National Facility Management Association (NFMA) and the International Facilities Management Association (IFMA) came into existence, solidifying FM’s presence in the corporate landscape. Simultaneously, academic institutions began to establish FM research and education programs, further advancing the development of the discipline.

Fast-forwarding to contemporary Abu Dhabi, the facility management industry plays an integral role in maintaining and enhancing the rapidly growing built environment. The Emirate has witnessed substantial investments in various sectors, necessitating efficient management and maintenance of the sprawling developments. With foresight, the Emirate recognized the crucial role of FM in supporting its ambitious development plans as early as the 1990s (MarkNtel advisors, n.d.).

The FM market in UAE is primarily driven by the construction industry, which is experiencing significant growth, providing FM service providers with lucrative opportunities. This expansion includes commercial and residential buildings as well as industrial projects (Abdelmonein et al., 2022). Moreover, an increasing number of tourists has led to extensive construction activity in hotels, malls, and other facilities.

The UAE Facility Management Market is poised for robust growth, with a projected Compound Annual Growth Rate (CAGR) of approximately 9.0% during the forecast period from 2023 to 2028 (MarkNtel advisors, n.d.). As the financial hub of the Middle East, the UAE has emerged as one of the most promising markets for FM services. The growth of this market is driven by various initiatives and efforts by the UAE government aimed at diversifying the nation's economy from traditional oil exports to non-oil sectors.

Despite the global attention paid to developing the facility management sector, some outdated practices persist due to various reasons, including tradition, budget constraints, or lack of awareness. While Computerized Maintenance Management Systems (CMMS) are widely available, some organizations still rely on paper-based maintenance logs and spreadsheets for tracking equipment maintenance and repair tasks (Korka et al., 1997). This outdated method can be inefficient, prone to errors, and lacks the real-time capabilities of modern CMMS software (Korka et al., 1997).

Many organizations persist in utilizing a reactive maintenance approach, where they address problems as they arise, rather than adopting proactive strategies to forestall equipment breakdowns. This can culminate in increased operational expenses, heightened downtime, and disruptive disruptions (Limble, 2023). Additionally, certain facilities continue to depend on manual tracking and oversight of energy consumption, neglecting the adoption of contemporary energy management systems and building automation technologies. Instead of integrating proactive safety measures and conducting pre-emptive risk assessments, some organizations opt to take action only after safety incidents transpire (Sanguinetti et al., 2018). This outmoded method is fraught with the risk of accidents and violations of regulatory standards. In conveying essential facility information to employees and visitors, some entities still employ traditional means like printed notices and bulletin boards. However, this approach may prove less efficient when compared to contemporary digital communication methods, which encompass mobile applications and email updates.

1.1.2 Digital Twin

During the 1990s, the construction and architectural industries attempted to digitize with the advent of computers and e-mails (Abdelmoti et al., 2021). The methods and tools for information exchange provided by digitization altered the industry's workflow. As shown in Figure 1, since the late 1980s, engineers have transformed manual drawings into technical drawings using CAD software to improve accuracy and enhance creativity (Singh et al., 2021). Therefore, virtual environments have become an integral part of computing and automation. Later, in the next decade, 2D CAD representations were replaced by 3D illustrations. This was followed by the emergence of BIM (Azhar, 2011; Azhar et al., 2012), IoT (Atzori et al., 2010), digital warehouses and databases, and DT (Wu et al., 2021).

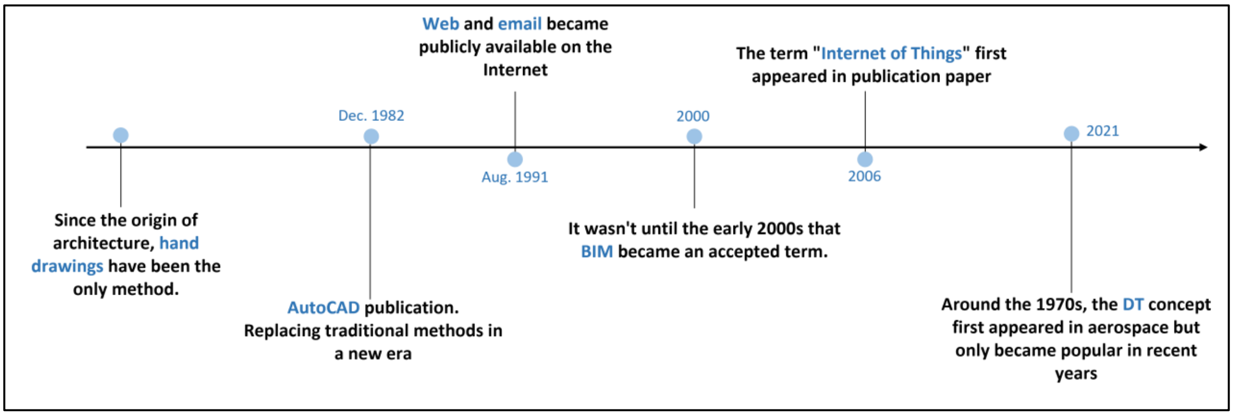

Figure 1: Evolution of Digital Twins.

Tuegel et al. introduced the term "DT" in 2011 by replicating an aircraft's behavior in a digital model, to anticipate an aircraft's lifecycle (Tuegel et al., 2011). NASA later defined DT as "an integrated Multiphysics, multiscale, probabilistic simulation of an as-built vehicle or system that uses the best physical models, sensor updates, fleet history, etc., to mirror the life of its corresponding flying twin (Glaessgen & Stargel, 2012, p. 7)". Based on the literature, DT can be summarized as a digital representation of a physical production system file that uses integrated simulation data and integration services and includes data from many sources collected throughout the product lifecycle (Chen, 2017; Vrabič et al., 2018; Zheng et al., 2019). In 2019, Madni et al. defined DT as a virtual instance of a physical (dual) system that continuously updates performance, maintenance, and health data throughout the physical system's life cycle (Madni et al., 2019). This simply entails building a highly complicated virtual model that serves as the counterpart (or twin) of a physical object (Wu et al., 2021). Physical objects can include automobiles, structures, bridges, and jet engines. Data collected by sensors attached to physical assets can be linked to virtual models (Madni et al., 2019).

Consequently, DT enables its users to encapsulate crucial and complex details on the functions of physical objects in the real world.

DT, as a system, is made up of three key subsystems: 1) connecting data and information between virtual and physical objects, 2) connecting physical and virtual objects in real space, and 3) connecting virtual and physical objects in virtual space (Abdelmoti et al., 2021). This highlights the value of DT as a tool for engineers and operators to understand both, the current and potential performance of the object whose DT has been created. The prediction of potential performance is based on the analysis of data generated from sensors and external sources (Pan & Zhang, 2021). With this knowledge, businesses can develop more quickly, and they can also overcome previous barriers related to complex life cycles and asset management (Pan & Zhang, 2021). DT provides an unprecedented view of building performance from multiple angles. Furthermore, it helps identify potential mistakes during the build and manage phases and troubleshoot problems remotely (Alizadehsalehi & Yitmen, 2021). For instance, data can be used to replace faulty products or parts, saving time and money (Wu et al., 2021). With the advent of IoT, DT implementation has become cost-effective and widely adopted across all industries (Madni et al., 2019). The global market size of DT is estimated to reach USD 96.49 billion by 2029 from USD 8.88 billion in 2022, with a Compound Annual Growth Rate of 40.6% (Fortune Business Insights, 2022). This technology is used in many end-use industries as it enables improved production scheduling, lower operating costs, increased productivity of existing systems, and faster TTM (Wu et al., 2021).

1.1.2.1 Digital Twin Applications

DT is a virtual/digital replica of an entity, such as a device, person, process, or system, which helps companies make model-based decisions. It is changing the way work is done in different industries with different business applications. DT finds its application in several fields are described below.

- Logistics and supply chain: DT aids in testing of packaging materials for errors before being packaged (DHL, 2019). Furthermore, it can be used to determine material feasibility since they can analyze how different packaging conditions may affect product delivery, which enhances shipment protection. Moreover, DT can be used to test warehouse layouts for efficient design. It can aid in the design of distribution routes and inventory storage sites (DHL, 2019), as it carries information about the traffic situation, road planning, and construction of road networks.

- Healthcare: DT can help healthcare providers virtualize the healthcare experience to improve patient care, cost, and performance. The operational efficiency of healthcare operations can be improved by creating a DT of the hospital, operational strategies, capabilities, staff, and models of care to examine operational performance. As well as improving personalized care through the modeling of genome codes (Dilmegani, 2022b), physiological characteristics, and lifestyles of patients, it may also allow healthcare companies to provide medicines tailored to each individual's needs.
- Manufacturing: High-tech equipment produces large quantities of data that can be used to create DT. Using the digital model before the launch of a product can help engineers test its viability. In response to the test results, engineers begin developing or focusing on a feasible product (Dilmegani, 2022c), and companies can design a variety of variations of the product to offer their customers customized products and services, and to help engineers determine which products are defective or underperforming by monitoring and analyzing the final products. Furthermore, it helps to forecast possible machine failure times (Dilmegani, 2022c), enabling businesses cut back on non-value-added maintenance tasks and increase overall machine efficiency because technicians can respond to problems before they arise. However, because digital models are device-specific virtual replicas that demand a scientific talent for pricey data to develop and maintain (Dilmegani, 2022d), their application for predictive maintenance duties is not scalable.
- Space: Physical twins were utilized in aerospace engineering before DT. The Apollo 13 program in the 1970s is one instance when NASA experts on earth were able to recreate the ship's state and discover solutions when pressing problems arose. The DT idea was first presented by NASA's John Vickers later in

2002. According to a poll report from Business Wire (Miskinis, 2019), 75% of air force executives have expressed their support for the technology, demonstrating its importance in the aerospace industry today. To protect the safety of all on board, engineers employ DT to use predictive analytics to foresee any potential issues with the airframes, engines, or other components.

- Automobile: In the car industry (Damjanovic-Behrendt, 2018) DT are utilized to build a virtual representation of a linked vehicle. Even before production begins, automobile businesses use technology to build the ultimate car product. They model and examine both the manufacturing process and potential issues when the vehicle is put into service. DTs are useful for companies that manufacture autonomous vehicles, even though they can be used in the traditional automotive production sector (Dilmegani, 2022a). Self-driving cars are equipped with a variety of sensors that gather information about the automobile and its surroundings (Sudzus, 2015). Companies are ensuring that unforeseen damage and injuries will be kept to a minimum by building DTs of their cars and thoroughly testing them due to the liability concerns around autonomous vehicles. Road testing and vehicle maintenance are a couple of the automotive industry’s uses for digital twins.
- Retail: To enhance the quality of the consumer experience, retailers might develop DTs for their customer personas. For instance, retailers might use their digital models to deliver the right fashion clothes products to shoppers (Vijayakumar, 2020).
- Construction: DT can enable better understanding of how a building is working in real-time (Opoku et al., 2021). Future building planning and design can make use of the data gathered from the DT. It is expected that the digital twin will be applied in many other fields in the future, as most studies predict a brilliant future for this technology.

1.2 Research Problem

In the United Arab Emirates (UAE), a nation renowned for its rapid economic growth and ambitious infrastructure development projects, effective FM has become increasingly vital. The definition and scope of FM are determined by the local culture, the organization's interests, and the personal interests of people (Sarasoja, 2004). By 2006, the BIFM, a recognized NGO, defined FM as "The integration of processes within an organization to maintain and develop the agreed services which support and improve the effectiveness of its primary activities (Waheed & Fernie, 2009, p. 259)".

FM is a well-established discipline in the construction industry which is getting global attention for its critical role in managing and maintaining building projects. The roots of FM can be found in the custodial role of building superintendents and caretakers, who are primarily concerned with building maintenance, cleaning, and tenant security (Price, 2002). It is also important to recognize that as buildings are becoming more complex alongside increasing operational costs, the need for tactical as well as strategic management functions have grown. This has increased the profile of the FM discipline along with other support functions like human resources and information technology management.

Nevertheless, contemporary FM practices, specifically asset management, within the UAE exhibit notable weaknesses, potentially impeding the nation's capacity to optimize asset performance, maintain infrastructure sustainability, and ensure efficient resource allocation. Despite the digitalization efforts, current asset management practices are heavily document oriented. These deficiencies include reactive maintenance practices (Becerik-Gerber et al., 2012), limited access to real-time asset data (Mawed et al., 2020), inadequate predictive maintenance capabilities (Hosamo et al., 2022a), challenges in achieving sustainability goals (Silva et al., 2018), locked information in documents and difficulties in retrieving relevant information when needed (Abdelmoti et al., 2021). The confluence of these challenges highlights the necessity for innovative approaches to asset management in the UAE.

Emerging as a transformative technological solution, DTs hold a promise to address these weaknesses comprehensively. However, the extent to which DTs can be successfully integrated into the UAE's asset management practices remains an unexplored dimension of research. Hence, the principal research problem addressed in this thesis is as follows: "To what extent can DTs be leveraged to mitigate the weaknesses in current asset management practices in the United Arab Emirates, with a focus on enhancing efficiency, sustainability, and infrastructure resilience?"

This research problem encapsulates the central challenge that this thesis endeavours to tackle: the inadequacies in traditional asset management practices within the UAE and the potential role of Digital Twins in ameliorating these limitations. By concentrating on the UAE as a specific context, this research aims to provide insights that are both academically pertinent and pragmatically significant for the nation's continued advancement.

The following research questions will be addressed in this study.

1. What are the key weaknesses and challenges in current asset management practices within the UAE, Abu Dhabi, particularly in the AEC/FM sector?
2. To what extent can DTs be effectively integrated into the asset management practices within the UAE?

1.3 Research Objectives

The primary aim of this thesis is to investigate the potential of DTs in addressing weaknesses in current asset management practices within the UAE, particularly the Emirate of Abu Dhabi, with a focus on enhancing efficiency, digitalization, and FM industry needs. To achieve this aim, we address the following research objectives:

1 To understand the theoretical underpinning and concepts related to DT in relation to its potential applications in asset management.

2 To investigate the integration of DTs with asset management digitalization practices for efficiency, including factors such as maintenance optimization and real-time data utilization.

3 To identify and analyze the potential challenges and barriers associated with the adoption and implementation of DT in UAE's asset management context.

4 To formulate recommendations and guidelines for organizations in the UAE seeking to integrate DT technology.

1.4 Research Scope

The scope of this research includes understanding applications of DTs in FM practices from a review of existing literature to gain insights into the various applications. This study also explores DT applications within the UAE context as interviews have been done with industry experts in the UAE to analysis the weaknesses and challenges in current asset management practices, to gather insights and perspectives on the practical applicability of DTs in the local facility management landscape, particularly in the context of facility management. Furthermore, identification and analysis of potential challenges and barriers associated with DT implementation in facility management are highlighted, followed by practical recommendations for addressing these challenges.

1.5 Thesis Organization

Figure 2 presents the overview of the thesis organization. As illustrated, this thesis is organized into five stages that are explained through six chapters. Stage 1 encompasses Chapter 1 that explains the evolution and applications of DT. In addition, it highlights the research problem under study and the associated research questions. In addition, the research objectives are highlighted. As a follow-up to the Introduction Chapter, the thesis is structured as follows:

Stage 2 involves Chapter 2, which reviews the related work on DT in the AEC/FM industry. In particular, a literature review is provided by categorizing the related articles into 5 categories: 1) DT technology, 2) DT creation, 3) DT for heritage restoration, 4) DT for sustainability, and 5) DT for asset management.

Chapter 3 within stage 3 describes the methodology for interview-based analysis. It presents the criteria for candidate selection criteria and formulation of interview questions.

Chapter 4 integrated within stage 4, presents the analysis of interview responses. In particular, it extracts the issues prevailing in the current FM approaches and discusses how DT can aid in addressing these issues.

Stage 5 includes Chapters 5 and 6. The open challenges and possible solutions for DT implementation are explained in Chapter 5. The thesis is concluded with limitations and future research directions in Chapter 6.

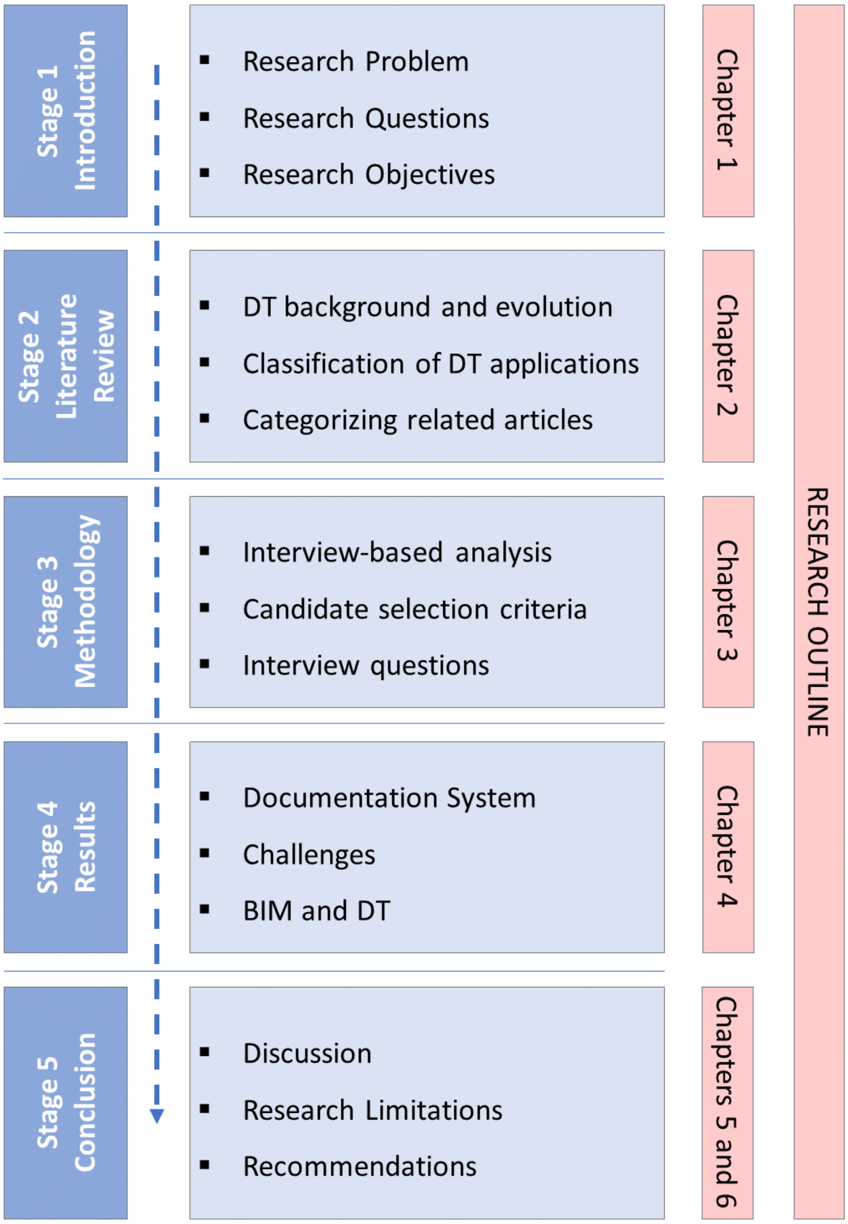

Figure 2: Thesis organization.

Chapter 2: Digital Twin in Facility Management – A Literature Review

In this chapter, we delve into an extensive exploration of how DTs are applied within the asset management domain of the AEC/FM industry. The chapter unfolds in several sections, starting with a detailed explanation of the research methodology employed to conduct this literature review. Following that, we present the results of bibliometric analysis conducted on the relevant studies we considered for this review. This analysis offers valuable insights into the overall landscape of research in this field, highlighting key trends, seminal works, and areas of interest within the application of DT in asset management. Lastly, this chapter concludes with a comprehensive categorization of DT applications within asset management in the AEC/FM industry. This categorization aims to provide readers with a structured understanding of how DT techniques are employed in various aspects of asset management, shedding light on the diverse range of applications and their potential benefits in this industry.

2.1 Literature Methodology

Figure 3 illustrates the methodology adopted for literature review in this thesis. The first step is to conduct a detailed literature review, using PRISMA, to understand the overall concept of digital twins and its relationship with assessment management in construction projects. The next step involves analyzing web, image, and news searches, as well as Google trends. Based on the results of the search of the documents, it appears that the keywords and terms of the current study are of global interest and focus (Ullah et al., 2021). Our research methods include keyword analysis, observations of annual publication trends, mapping of scientific keywords, co-author analysis, analysis of affiliated organizations, analysis of the country of export origin, and analysis of citation data. The final step is to categorize relevant articles based on their focus area and discuss each category. The literature review is then concluded with future research directions.

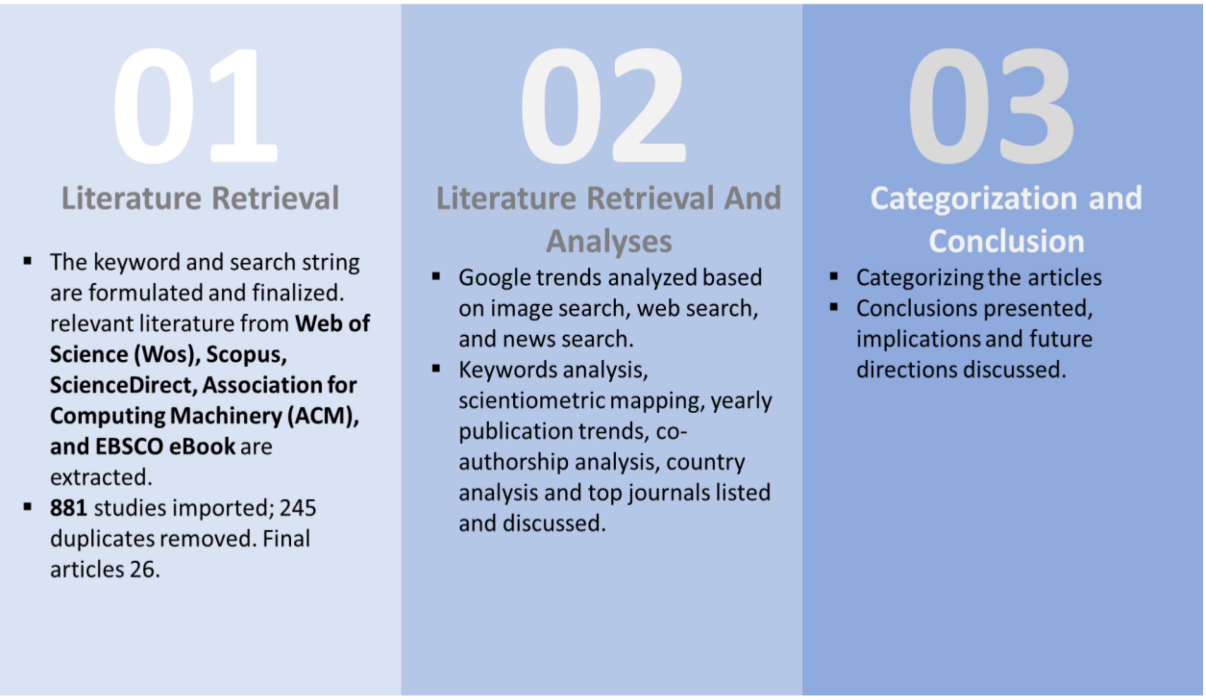

Figure 3: Adopted systematic review methodology.

In step 1 of the methodology, the relevant articles are retrieved from ACM, EBSCO, ScienceDirect, Scopus, and WoS databases using the following keywords: “digital twin”, “building”, and “asset management”. Table 1 presents the search strings used to retrieve articles from the considered databases. These strings are developed using keywords. In total, 1072 articles that were in English language were retrieved without any time bound.

The article types include original research articles, reviews, conference papers, short papers, and book chapters. This practice is in line with the claim made by Akram et al. There is a high level of quality and reliability in these article types (Akram et al., 2019). An initial investigation based on article titles revealed 345 duplicate studies indexed in the considered databases. As a result, 736 articles were considered for screening.

Table 1: Search string and numbers of retrieved articles for the considered databases.

Database	Search string	Results
Scopus	TITLE-ABS-KEY ("Digital twin" AND building) TITLE-ABS-KEY ("Digital twin" AND "asset management")	484
WoS	((TI=("digital twin" AND (building OR "asset management"))) OR AB=("digital twin" AND (building OR "asset management"))) OR AK=("digital twin" AND (building OR "asset management"))	326
EBSCO	KW ("digital twin" AND building) OR KW ("digital twin" AND "asset") OR TI ("digital twin" AND building) OR TI ("digital twin" AND "asset") OR AB ("digital twin" AND building) OR AB ("digital twin" AND "asset")	76
ScienceDirect	Title, abstract, keywords: "digital twin" AND (building OR "asset management")	77
ACM	[[Publication Title: "digital twin"] AND [[Publication Title: building] OR [Publication Title: "asset management"]]] OR [[Abstract: "digital twin"] AND [[Abstract: building] OR [Abstract: "asset management"]]] OR [[Keywords: "digital twin"] AND [[Keywords: building] OR [Keywords: "asset management"]]]	109

The PRISMA systematic flow diagram is illustrated in Figure 4. As part of the systematic review process, the following seven points from the PRISMA guidelines are taken into account:

1. The titles, summaries, or keywords of articles must contain the selected keywords.
2. ACM, EBSCO, ScienceDirect, Scopus, and WoS databases are the information sources.
3. Table 1 shows the search strings that were used to retrieve articles from the databases.
4. In the selection process, keywords are searched and screened, duplications are eliminated, and abstracts and keywords are read for qualitative analysis.
5. Articles retrieved from databases were analyzed and read in detail, and keywords were combined using the VOSviewer tool (Van Eck & Waltman, 2010).

6. Keywords, classifications, publication trends, article types, primary sources, scientometric mapping, co-authors, organizational affiliations, and source countries are included in the data.

7. DTs and their application in different categories are included in the summary measures.

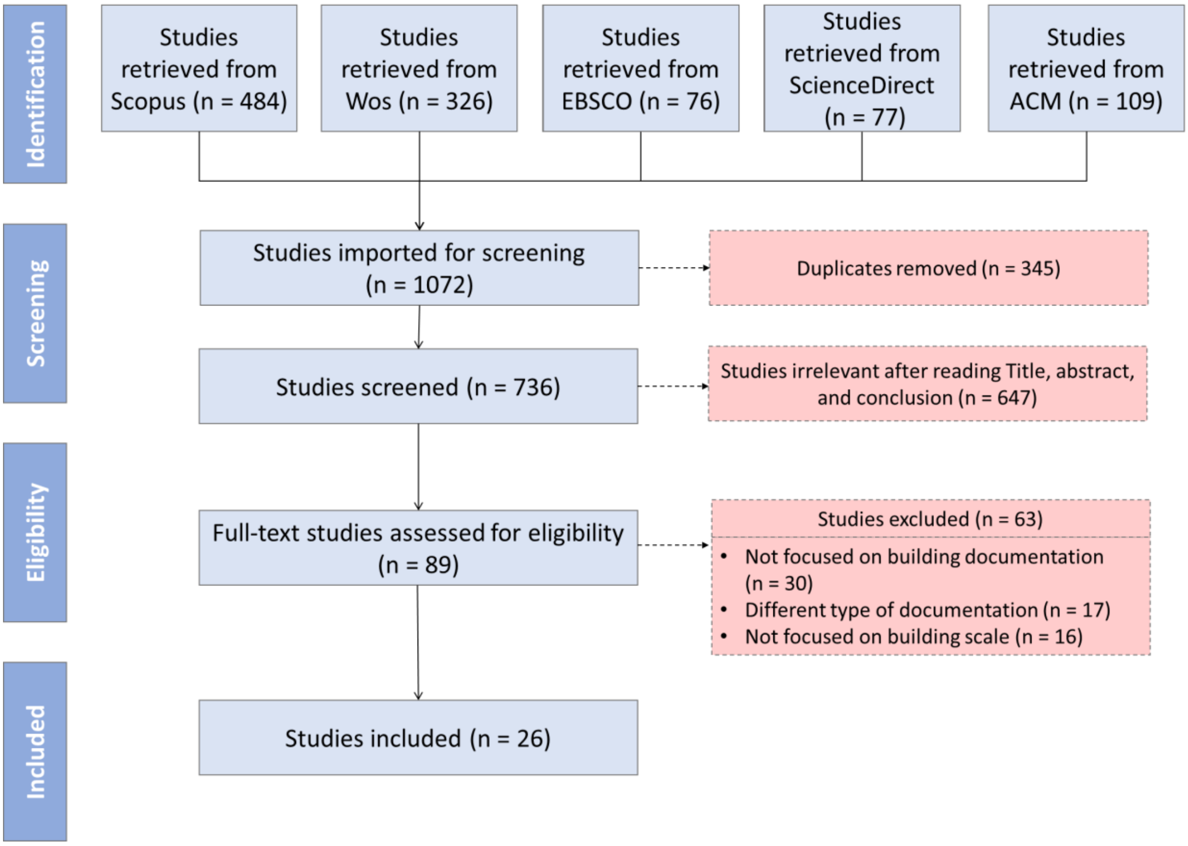

Figure 4: PRISMA systematic review flow diagram.

2.2 Literature Results

2.2.1 Google Trend Analysis

DTs for documentation and asset management are investigated using a Google trend analysis to highlight the global interest in the keywords and themes used in this study (Figures 5–7). Our study compares three keywords: “digital twin”, “sustainable buildings”, and “digital documentation”, as well as their search trends over five years (5 June 2016 to 4 June 2021). A total of three types of searches are analyzed: general web searches, image searches, and news searches.

As illustrated in Figure 5, the term “digital twin” is the most searched for on the web. There is almost a similar trend between the terms “sustainable buildings” and “digital documentation”. Furthermore, searches for “digital twin” have increased over time. Figure 6 illustrates the image-based search trends for the mentioned keywords. As is the case with web searches, the most common search is “digital twin”. Yet, there are fewer image searches for “digital documentation”. Figure 7 illustrates the news searches for the three keywords. There are more searches for “digital twin” than for “sustainable buildings” and “digital documentation”. All the keywords have fewer news-based trends than the overall web and image searches.

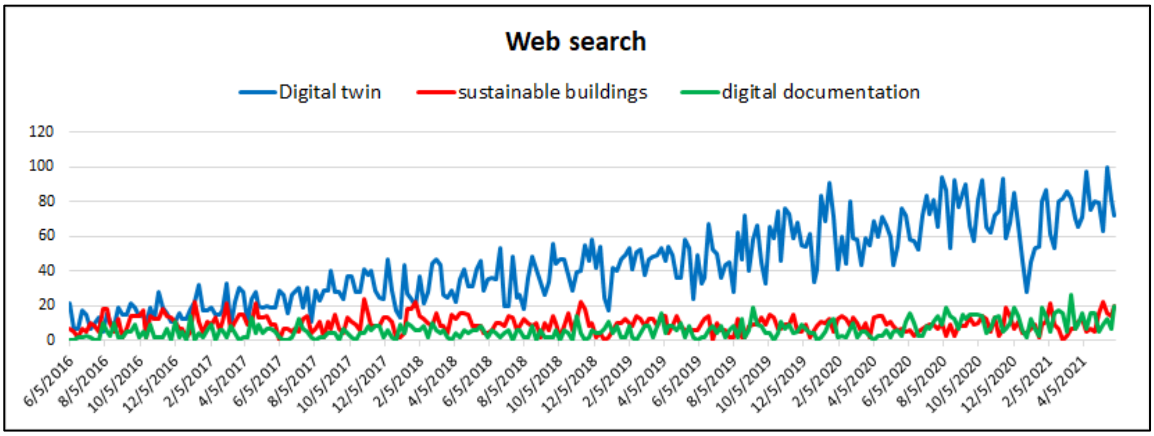

Figure 5: Google web search trend for the current study’s keywords.

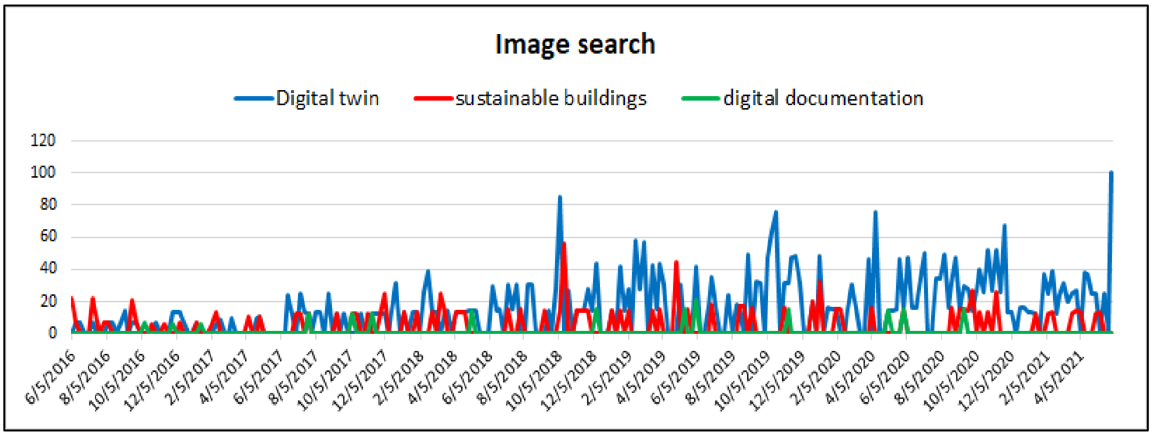

Figure 6: Google image search trend for the current study’s keywords.

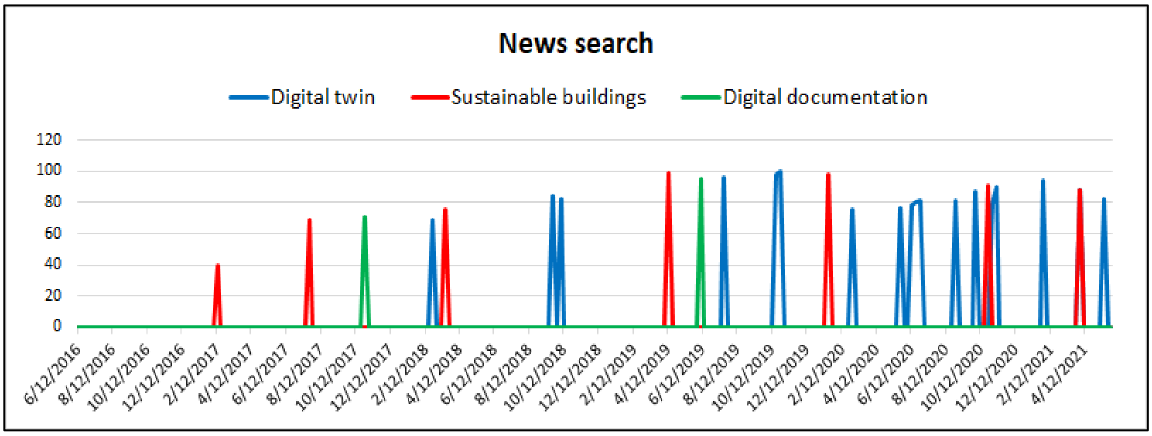

Figure 7: Google news search trend for the current study's keywords.

2.2.2 Yearly Publication Trends for the Retrieved Articles

Based on Scopus, WoS, EBSCO, ScienceDirect, and ACM databases, Figure 8 presents the yearly publication trends for articles. Publications on the topic under study began appearing after 2016, increasing afterward. Almost 90% of the articles in this study were published within the last 4 years, and 71% were published after 2019, showing the ever-increasing use of DTs for asset management. Further, there were no articles found before 2016, indicating that the field is a relatively new one.

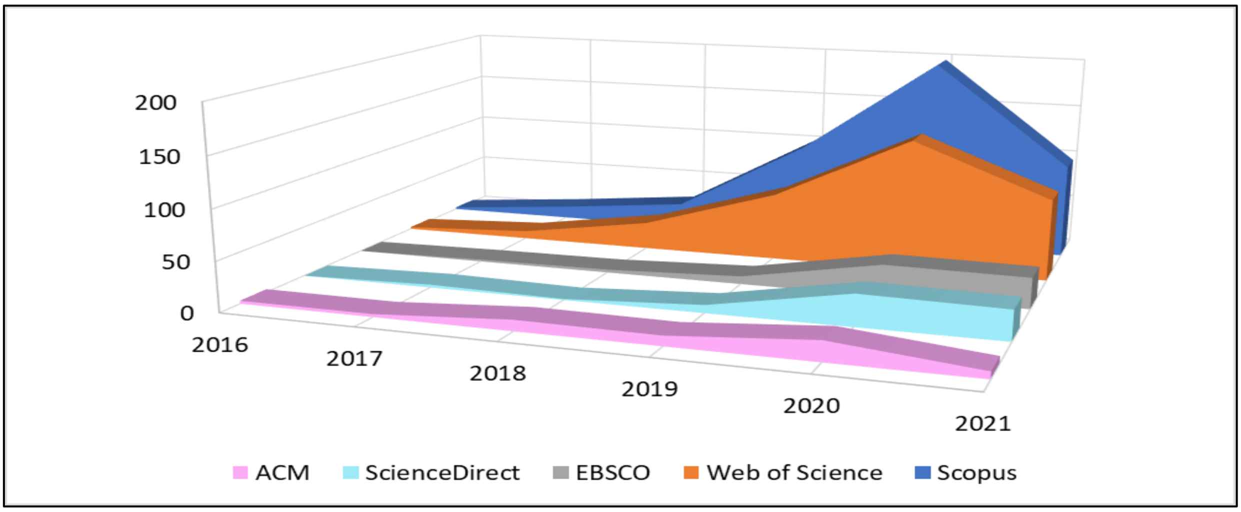

Figure 8: Yearly distribution of retrieved articles from the considered databases.

2.2.3 Classification of Retrieved Articles based on Focus Area

In Figure 9, based on the information extracted from the databases, it can be seen that DT is among the top 10 areas of research, with over 35% (46.8% ScienceDirect, 34% Scopus, 34.6% WoS, and 27.3% EBSCO) of the retrieved articles belonging to the Engineering category. As a result, DTs are widely accepted and understood by investors and engineers, as well as saving money. Because DTs facilitate better financial decisions, improve team collaboration, predict maintenance, and accelerate risk assessment, these tools help make better financial decisions.

It is followed by the "Computer Science" category, which contains more than 18% of the retrieved articles, another technology-focused area. The number of fields that may benefit from DTs is impressive, as it covers many fields, including energy, business management, decision science, telecommunications, etc.

Figure 9: Articles' categorization.

2.2.4 Types of Retrieved Documents

Following the analysis of yearly trends and research areas, the types of retrieved documents are investigated. The documents are limited to 11 types: journal articles, proceedings papers, review articles, early access, book chapters, editorial materials, news items, notes, books, trade publications, and magazine articles. Since original journal articles (original research and reviews), conference articles, and book chapters generally report on research findings and new developments, we prioritized them during the extraction process. 47.6% of the database's retrieved articles are classified as original research, followed by proceedings papers (42%) and book chapters (3.7%). As revealed in table 2, Scopus indexes more conference papers than any other database, as indicated by its high percentage of papers.

Table 2: Types of retrieved documents.

Document type	**Databases**				
	WoS	**Scopus**	**EBSCO**	**ACM**	**ScienceDirect**
Journal articles	192	208	55	1	68
Proceedings papers	111	249	0	102	0
Review articles	18	19	0	0	0
Early access	9	0	0	0	0
Book chapters	3	21	10	0	7
Editorial materials	2	3	0	0	1
News items	2	0	0	2	0
Notes	1	2	0	0	0
Books	0	2	0	0	0
Trade publications	0	0	5	0	0
Magazine articles	0	0	3	4	0

2.2.5 Keyword Mapping

The main component of research detection is keywords. The study of keywords in articles helps readers comprehend the major ideas, trends, and developments in the field of research. VOSviewer constructs a keyword network using natural language processing algorithms and text mining techniques and then employs grouping techniques to investigate their relationships and arrange knowledge. Some databases employ “index keywords” as topic names in addition to author-generated keywords to incorporate pertinent keywords that the author may have overlooked. This study does a scientific quantitative analysis using both the authors’ and the index’s keywords. The full counting method was used to perform a keyword co-occurrence analysis in VOSviewer while employing a minimum inclusion criterion to reduce the number of terms. For the Scopus database, WoS database, and ScienceDirect database, the minimum keyword co-occurrence threshold is set at 10, 5, and 3 respectively.

The findings of the keyword co-occurrence analysis for the Scopus and WoS databases are displayed in Table 3. 56 of the 3534 keywords that were retrieved from Scopus after establishing the minimum inclusion criteria were chosen for analysis. 1439 keywords were retrieved for WoS, and 59 were chosen for the final analysis. 14 out of the 327 keywords that were taken from ScienceDirect were chosen.

Table 4 lists the top 10 of the 56 Scopus-selected keywords along with their frequency, total number of links, and total link strength. The total link strength is a positive value that indicates the number of articles in which two keywords co-occurred, and the number of links demonstrates the relationship between the co-occurrence of the two keywords.

The findings reveal that “digital twin” is the most commonly used keyword, appearing 314 times overall and accounting for 40% of the top keywords. “BIM” is the second most used keyword, with 113 occurrences and a 14.4% market share. Less than 10% is the share for each of the other top keywords.

Given the links (Table 4), it can be seen that the inquiry is concentrated on DT-enabled lifecycle analysis and asset management in the AEC sector. The most links were found for “digital twin”, which was followed by “BIM”, “architectural designs”, and “IoT”. “BIM” has the most total links, followed by “IoT” and “digital twin”, in terms of link strength.

Table 3: Keyword co-occurrence analysis.

Assessment	Consideration	Scopus results	WoS results	ScienceDirect
Type of analysis	Co-authorship	-	-	-
Counting method	Full counting	3534	1439	327
Unit of analysis	All keywords	56	59	14
Minimum occurrence	-	10	5	3

Table 4: Top 10 keywords, their number of links, and total link strength for Scopus.

Keyword	Frequency	Number of links	Total link strength
Digital Twin	314	933	94
BIM	113	613	170
IoT	75	357	109
Architectural designs	64	368	47
Lifecycle	56	266	51
Information management	38	224	48
Industry 4.0	33	126	42
Manufacture	31	106	37
AI	30	130	44
Embedded systems	30	130	38

The network visualization of the 56 chosen keywords from the Scopus database that co-occurred at least ten times is shown in Figure 10. The circle sizes in the network visualization represent the weights of the keywords, and the co-occurrences of the keywords are shown as co-occurrences. The keywords are arranged into five clusters, which are represented by the colors red, green, blue, orange, and yellow in the picture.

The five clusters show that DT research is concentrated on five connected areas for asset management and lifecycle analysis: Industry 4.0 and smart manufacturing are represented by the red cluster, BIM and the AEC sector by the green cluster, IoT by the blue cluster, life cycle management by the orange cluster, and smart and sustainable cities by the orange cluster (yellow cluster). The one cluster (yellow) appears more detached because this inquiry is not particularly focused on DT-enabled sustainable architecture, but the four clusters (red, green, blue, and orange) indicate a very close linkage.

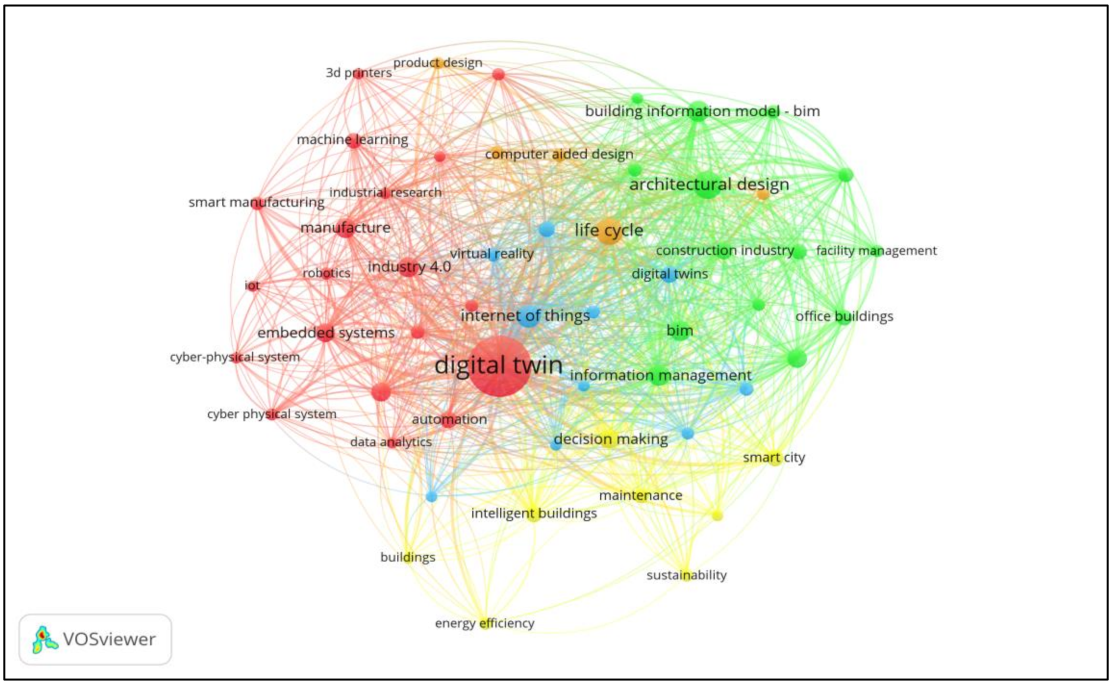

Figure 10: Scopus keyword mapping.

Table 5: Top 10 keywords, their number of links, and total link strength for WoS.

Keyword	Frequency	Number of links	Total link strength
Digital twin	175	415	85
BIM	51	202	99
System	38	134	73
Design	32	113	44
IoT	32	152	88
Model	27	87	53
Industry 4.0	26	98	54
Simulation	26	71	35
Management	17	79	34
Framework	16	89	43

Table 5 lists the top 10 of the 59 chosen WoS keywords along with their frequency, total number of links, and total link strength. With 175 occurrences, “digital twin” is the most used keyword and accounts for around 40% of the top keywords.

"BIM" comes in at number two with 51 instances and a share of about 11.59%. Less than 10% is the share for each of the other top keywords. The most linkages were found for "digital twin" in Table 5, followed by "BIM", "IoT", and "System". "BIM" is the keyword with the most total links, followed by "IoT" and "digital twin".

The network visualization of the 59 chosen terms from the WoS database that co-occurred at least five times is displayed in Figure 11. The keywords in the picture are divided into five clusters, each represented by a different color—red, green, yellow, blue, or orange. The five clusters show that DT research is concentrated on five connected areas for asset management and lifecycle analysis: Industry 4.0 (yellow cluster), Industry 4.0 framework and difficulties (blue cluster), modeling of smart manufacturing systems (red cluster), BIM-enabled asset management (green cluster), and DT system (green cluster) (orange cluster). All five clusters are connected quite closely in the image.

Table 6 lists the top 10 ScienceDirect keywords along with their frequency, total number of links, and total link strength. "Digital twin" is the most utilized keyword, appearing 47 times, and accounting for about 54.65% of the top keywords. "BIM" comes in at number two with 10 instances and a share of about 11.62%. Each of the other top keywords has a share that is under 10%. The term with the highest total link strength is "digital twin", with "BIM" coming in second with the biggest number of links (Table 6).

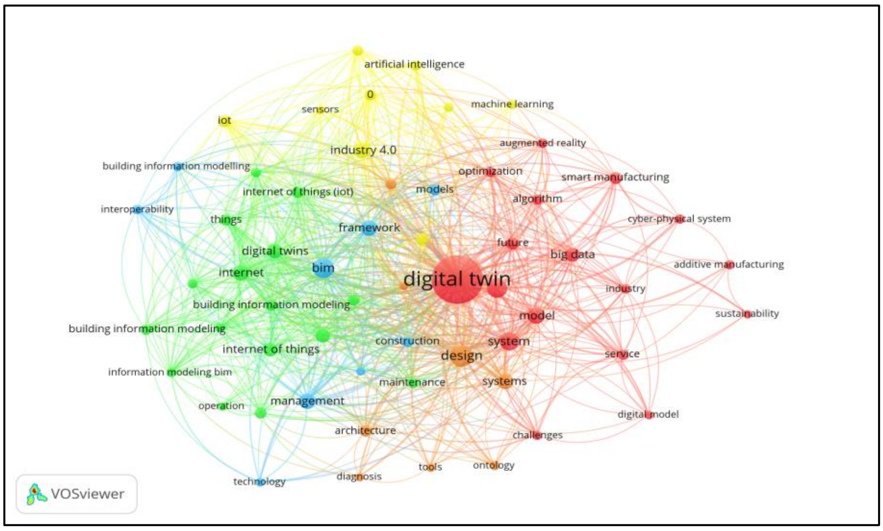

Figure 11: WoS keyword mapping.

Table 6: Top 10 keywords, their number of links, and total link strength for ScienceDirect.

Keyword	**Frequency**	**Number of links**	**Total link strength**
Digital twin	47	31	14
BIM	10	12	6
Industry 4.0	5	5	3
Machine learning	5	3	2
Smart cities	4	6	4
Additive manufacturing	3	1	1
Artificial intelligence	3	3	3
Asset management	3	4	2
Cyber-physical systems	3	4	3
Industry foundation classes	3	4	3

The network visualization of the 14 chosen terms from the ScienceDirect database that co-occurred at least three times is shown in Figure 12. The keywords are divided into five clusters, each represented by a different hue (green, red, blue, yellow, or orange). The five clusters show that DT research for asset management and lifecycle analysis is concentrated on five overlapping topics: 1) DT in manufacturing (green cluster); 2) AI and Industry 4.0 (red cluster); 3) BIM and IoT (blue cluster); 4) asset management (yellow cluster); and 5) smart cities (orange cluster). The image demonstrates that the clusters are disjointed, possibly as a result of the few studies that were successfully retrieved from the database. These studies have DTs as their central emphasis in various places.

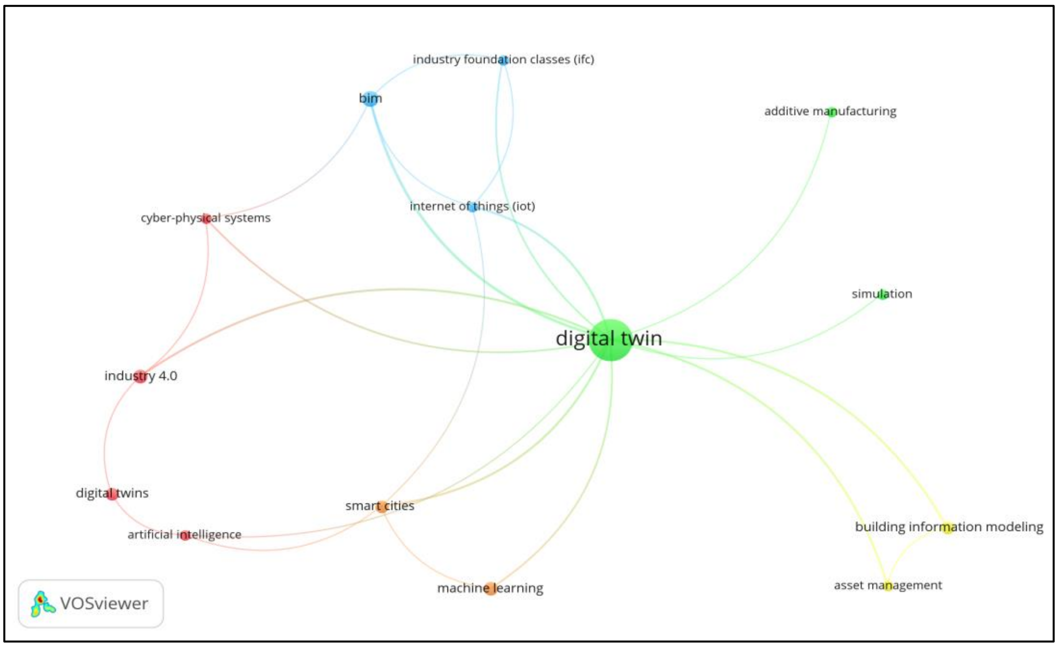

Figure 12: ScienceDirect keyword mapping

2.2.6 Co-authorship Analysis

The co-authorship filter in VOSviewer was used to count the number of citations to significant documents and to keep track of the names of all authors. For Scopus and WoS, an author must contribute a minimum of three research articles. There were 1179 authors listed for WoS articles. For Scopus, 169 writers were listed, and 19 for ACM. Table 7 displays the top contributors to WoS and Scopus after the minimal inclusion criteria were met by 11 writers and six authors, respectively.

Table 7: Co-authorship analysis.

Assessment	Consideration	Scopus results	WoS results
Type of analysis	Co-authorship	-	-
Counting method	Full counting	169	1179
Units of analysis	Authors	6	11
Minimum Occurrence	-	3	3

The top writers who have contributed to the two different types of research repositories are shown in Figure 13 along with the publications they have been cited in. The most significant contributions to papers recovered from WoS were from A.K. Parlikad, Q.C. Lu, and X. Xie. However, S. Kaewunruen's four publications take the top spot in terms of citations with 57. Additionally, Figure 12 displays the outcomes for all shortlisted authors that Scopus was able to locate for papers with three or more contributions. With eight contributions and 54 citations, A.K. Parlikad is in first place. X. Xie is close behind with seven contributions and 43 citations. Based on data gathered from Scopus, WoS, and ACM, Figure 13 shows the number of citations concerning the number of documents for the top 10 contributing authors.

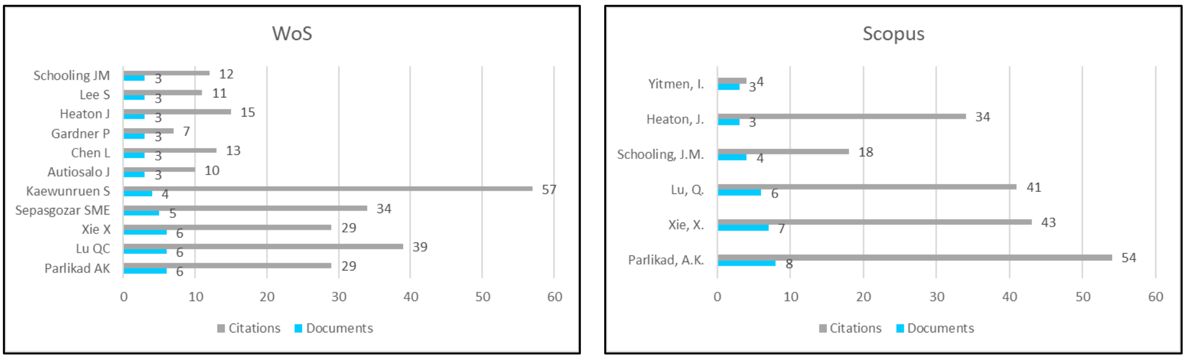

Figure 13: Author citation analysis. WoS database (**left**) and Scopus database (**right**).

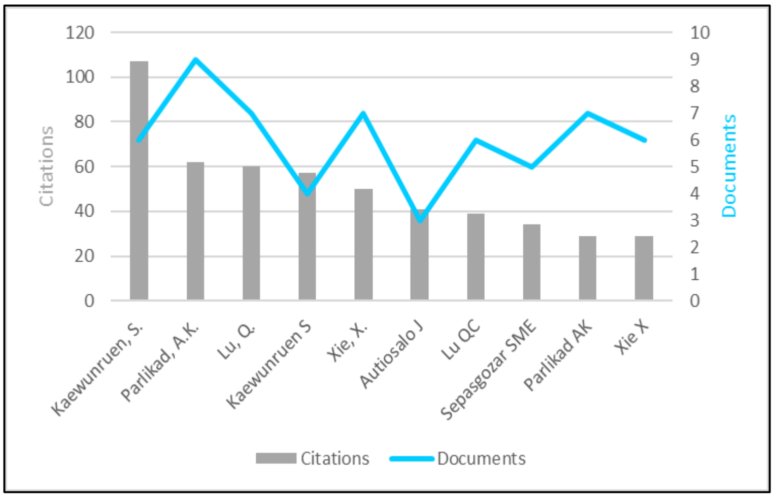

Figure 14: Top contributing authors based on citations.

2.2.6.1 Co-authorship analysis based on organizational affiliations

To examine authors' organizational affiliations, minimum inclusion standards for two papers per organization were developed. The publications that WoS and Scopus were able to retrieve are linked to a total of 469 organizations. As a result, as indicated in Table 8, 107 organizations were shortlisted for Scopus with no minimum contribution, and 27 organizations for WoS with a minimum contribution of three.

Table 8: Co-authorship analysis based on organizational affiliations.

Assessment	**Consideration**	**Scopus results**	**WoS results**
Type of analysis	Co-authorship	-	-
Counting methods	Full counting	107	469
Units	Organizations	107	27
Minimum occurrence	-	1	3

Table 9 lists the major organizations that contribute to the Scopus and WoS databases based on the number of articles retrieved. With 22 documents and 99 citations, the University of Cambridge is in the lead. Polytechnic di Milano is second with 13 documents and 102 citations, while the University of Sheffield is third with 7 documents and 17 citations. The Beijing Institute of Technology is one special operations organization, and four of its documents received 114 citations.

Table 9: Top contributing organizations.

Organization	**Indexing**	**Documents**	**Citations**
University of Cambridge	WoS, Scopus	22	99
Polytechnic di Milano	WoS, Scopus	13	102
University Of Sheffield	WoS, Scopus	7	17
Aalto University	WoS, Scopus	6	39
University of California, Irvine	WoS, Scopus	6	37
University of Birmingham	WoS, Scopus	5	62
Norwegian University of Science and Technology	WoS, Scopus	5	5
Delft University of Technology	WoS, Scopus	4	59
Chalmers University of Technology	WoS, Scopus	4	19
Beijing Institute of Technology	WoS, Scopus	4	114

2.2.6.2 Co-authorship analysis based on country of origin

It was also established which nations contributed the most documents to the two repositories. For Scopus and WoS, a minimum inclusion criterion of three documents per nation was used for the study. The WoS repository and Scopus both feature contributions from 48 nations. Following the application of limitations, nine nations via Scopus and 31 via WoS-retrieved items were pre-selected, as shown in Table 10.

Table 10: Co-authorship analysis based on country of origin.

Assessment	Consideration	Scopus results	WoS results
Type of analysis	Co-authorship	-	-
Counting methods	Full counting	26	48
Units	Countries	9	31
Minimum occurrence	-	3	3

Figure 15 shows a map of the top nations by the number of documents and citations that they contribute to the WoS and Scopus archives. The United States provided the most documents (57), accounting for over 13% of the articles retrieved, followed by the United Kingdom (51) and China (50), each accounting for over 11.2%. The United States leads in terms of citations with 477, followed by China (452) and the United Kingdom (221). Germany, India, and the Netherlands are some additional nations that receive a lot of citations.

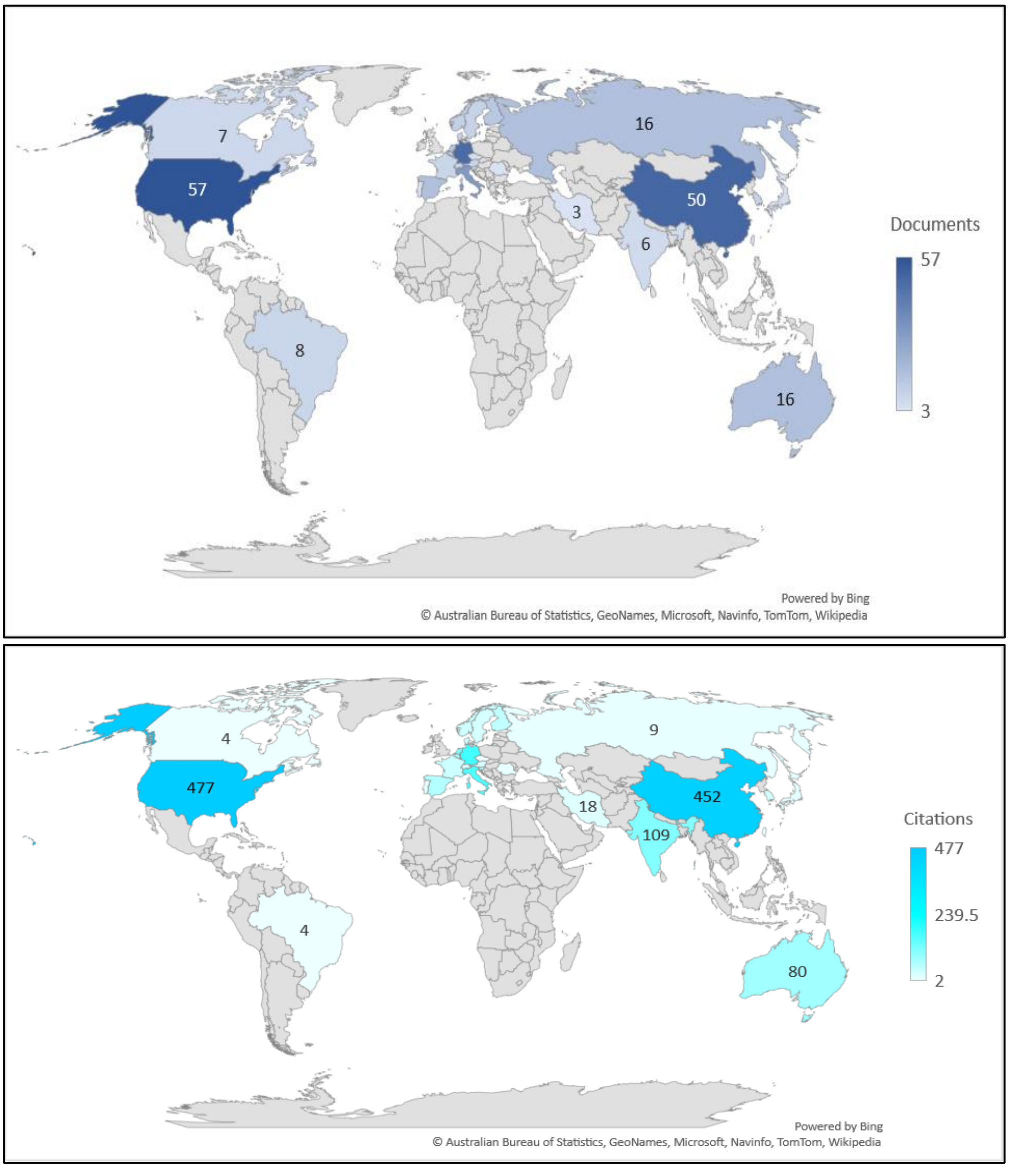

Figure 15: Country of origin analysis.

2.3 Categorization of the Included Articles

Based on their focus areas, the articles included in this study are categorized in this section. As illustrated in Figure 16, we divide the 26 included articles into five groups. The contributions of the articles and the categories are described below.

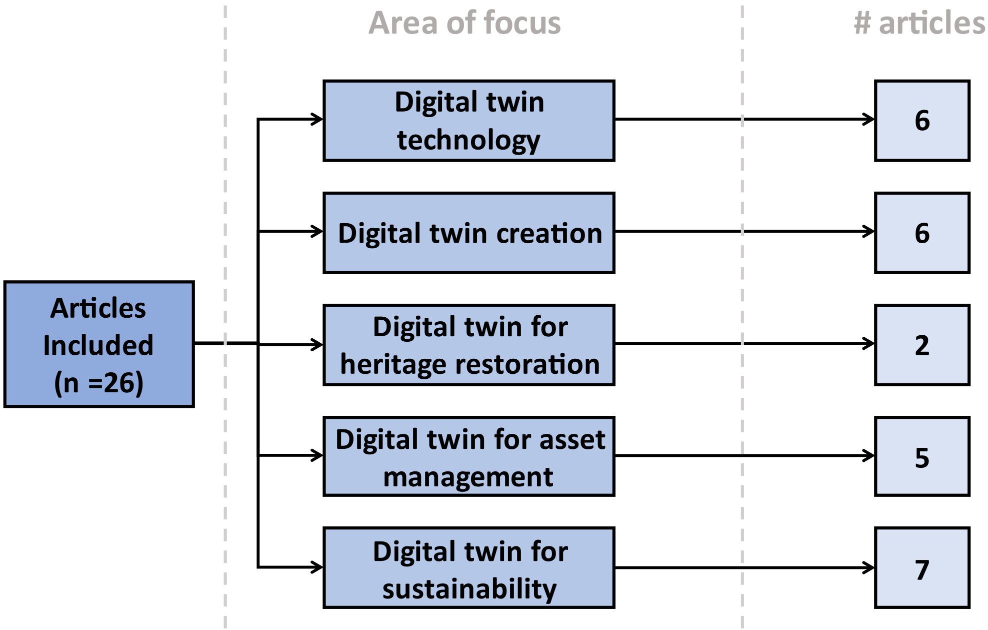

Figure 16: Categorization of the included articles in the systematic review.

2.3.1 Digital Twin Technology

The definitions, uses, and implementation difficulties of DTs in many industries are examined in this section. The concepts, traits, applications, and difficulties of DT technology are the main topics of the articles in this category.

To examine the pre-existing DT definitions, (Barricelli et al., 2019) looked at over 75 articles. Additionally, the authors discussed the primary DT features and the many application fields where the technology has been applied. The authors divided the application into three groups based on their analysis: manufacturing, aviation, and healthcare. Two DT lifecycles were described by the authors. One lifecycle involves a physical entity that needs to have a twin manufactured, while the other involves a physical thing that currently exists but does not have a twin. When designing the former, the physical thing and its twin are both considered at the same time, whereas when designing the latter, the goal is to link the physical object to its twin. The writers also emphasized problems with digital implementation, including ethical concerns, data security and privacy, deployment costs, governmental rules and regulations, and technical constraints. The use of DTs in the manufacturing, aviation, and healthcare sectors has been extensively researched. However, additional study is necessary before the method may be applied to other industries.

A qualitative study by (Camposano et al., 2021) examined how Finnish AEC/FM practitioners understood DTs. In their study, 28 project managers, C-level executives, and experts in related fields participated in semi-structured interviews with the authors in 2018 and 2019. The authors discovered from participant replies that individuals were more likely to comprehend the technological vision and execution for businesses than they were to understand specific DT elements. The qualities of DTs that the respondents used to distinguish them from the digital model included dynamic time, virtual representation, greater dimensional abstraction, bidirectional data flow between the actual object and its twin, technology components, and high actor interdependency. Conclusion: The AEC/FM practitioners mainly use straightforward metaphors notwithstanding their disagreement on a common definition of DTs. As a result, the practitioners need to be made aware of a common understanding of the technology and its advantages for gaining inter-organizational adoption.

To assess the structural and functional descriptions of DTs for the built environment, (Davila Delgado & Oyedele, 2021) surveyed 54 articles. Three different structural and functional model types were extracted by the authors. While the functional model also contains process and communication models, the structural model also includes conceptual models, system architectures, and data models. Based on the retrieved descriptions, six process models and four categories of conceptual models were defined. Prototypical, model-based, interface-oriented, and service-based are the categories for conceptual models that have been established. The process model categories include optimal operations, optimized designs, forecasts and simulations, asset monitoring, DT creation, and DT synchronization. Prognosis and simulation models, according to the authors, are primarily applicable to AEC industry implementations.

In a bibliometric review, (Ozturk, 2021) examined the applicability and difficulties of DT in the AEC/FM sector. The author discovered that DT adoption in the AEC/FM business is concentrated on five areas based on an examination of 151 articles:

Building lifecycle management is the first step, followed by virtual-based information use, virtual-physical building integration, information-based predictive management, and information integrated manufacturing.

To examine current DT applications supporting safety management, Agnusdei et al. conducted another bibliometric and systematic study (Agnusdei et al., 2021). According to the authors, research on integrated DT and safety management is concentrated in six areas: Decision-making and offshore applications, IoT and lifecycle methods, Industry 4.0, machine learning for DT and safety assistance, safety engineering, hazards and risk management, and industry 4.0 are just a few of the topics covered.

In conclusion, DT technology seems to have promise for the AEC/FM sector, but there are still several issues, including technological constraints and data ownership issues, that need to be resolved before it can be widely adopted in practical settings.

2.3.2 Digital Twin Creation

A digital twin is a virtual version of a physical system, process, or item that allows for two-way data exchange with the original physical thing (Tao et al., 2018). Identifying the many components of the physical system and their interrelationships is the first and most important stage in constructing a twin using the discrete-event simulation technique (H. Jiang et al., 2021). The identified constituents, manufacturing processes, and interrelationships must all be represented to represent the physical system in a digital space (Ruiz et al., 2014), which is the second phase. The connection and interaction between the physical system and its digital representation models are part of the third step in developing a DT. This step should involve the implementation of a data interaction technology (Liu et al., 2020) that combines middleware, a memory database, and a relational database to implement the physical-digital interaction (H. Jiang et al., 2021).

To quickly develop a shop floor’s DT, (H. Jiang et al., 2021) applied the discrete event simulation modeling technique. However, the authors ignored predictive simulations in favor of a narrow focus on proactive simulations. At the Aalto University in Finland, (Adamenko et al., 2020; Khajavi et al., 2019) used a simulation approach to generate a DT of an office building. By compiling and examining 25,000 sensor readings, this was done. The building's facade was equipped with a wireless sensor network that was used to gather data. Due to frequent battery discharge, disruption of data transmission channels, and the quantity and placement of the sensors, the trials showed that the majority of technical DT generation concerns were related to data collecting through sensors (Khajavi et al., 2019).

A DT can also be produced utilizing a data-based or system-based DT (Adamenko et al., 2020). The data-based approach allows users to quickly acquire an overview of the system's performance because the data from the physical system is organized according to criteria like functionality. If the consumers are just exposed to the data and not the technical details of the physical system, the data-based approach may be effective. A system-based method, in contrast, builds and combines multiple virtual models of the physical system to provide a representation that is remarkably accurate to reality.

A system-based creation rather than a data-based creation can offer a more thorough understanding of the operation of the physical system. However, developing a system-based DT necessitates thorough familiarity with the system's and its constituent parts' technical specifications. A hybrid data- and system-based model was suggested (Adamenko et al., 2020) to improve the prediction performance of data-based models and increase the effectiveness of the current performance analysis.

With an emphasis on the operation and maintenance stage of the building development lifecycle, (Q. Lu, Parlikad, et al., 2020; V. Q. Lu et al., 2019) offered an architecture for DT creation at both the building and city levels. By creating a DT of the West Cambridge campus of the University of Cambridge in the UK, the authors illustrated the viability of the suggested architecture. The use case that was put into practice combined diverse data sources with effective and efficient data analysis, decision-making, and querying. The authors also emphasized the difficulties that arise when DTs are created, including heterogeneous data sources, automated data integration from multiple sources, data synchronization, and data quality.

The ability to use the developed DT to add value must be understood. Through the benefits management process, the advantages of DT and the associated costs and risks should be identified (Love & Matthews, 2019). This process entails defining and structuring benefits, planning benefits realization, carrying out the benefits realization plan, assessing and evaluating the results, and identifying the possibility of future benefits. Love and Matthews (Love & Matthews, 2019) suggested a business dependence network based on an empirical assessment of nine projects to analyze the post-creation advantages of a DT.

In conclusion, a simulation-based strategy is appropriate for developing a DT (H. Jiang et al., 2021). To improve the reactive, proactive, and predictive performance of the simulated virtual model, an integrated data- and system-based model should be taken into consideration (Adamenko et al., 2020). However, as the majority of errors are introduced at this point (Khajavi et al., 2019), care must be taken when gathering sensor data for the construction of virtual models. The focus of DTs in the AEC/FM sector right now is primarily on how to establish a DT (Love & Matthews, 2019). There is a need for more research on how to utilize a DT's advantages after it has been established.

2.3.3 Digital Twins for Heritage Restoration

Historic monuments and structures are priceless resources that leave a historical legacy for future generations. These structures deteriorate over time, and restoration is necessary to maintain their aesthetic value and serve their original functions (Gopinath & Ramadoss, 2021). The most important step in heritage building restoration is documentation since poor documentation can result in ineffective project management, excessive maintenance costs, and lost time (Gursel et al., 2009), A diverse range of qualitative and quantitative data is frequently obtained and individually assessed by many stakeholders as part of heritage building documentation. Duplicate efforts and insufficient documentation may result from a lack of cooperation and communication among stakeholders (Khalil et al., 2021). The documentation and repair processes for heritage structures can now take advantage of recent technological advancements to overcome data fragmentation problems and lack of governability.

Data can be divided into four categories based on the examination of several documentation areas involved in the restoration of historic buildings: 1) Archeological/historical data, related to the historical context of the building; 2) Geometrical data, related to the shape and features of the building; 3) Pathology data, related to building decay or damage; and 4) Performance data, related to the building's performance in terms of energy, thermal, comfort, safety, and security (Khalil et al., 2021). In this situation, historic building information modeling (HBIM) can assist in the integration and administration of textual and graphical data from many sources without the need for manual intervention and can also improve stakeholder collaboration and communication.

Additionally, DTs make it possible to model the correlations between data from sensors and the location of an old building, which helps to reduce risks associated with its original layout, use, and occupancy (Jouan & Hallot, 2019). The development of a heritage building preventive restoration mechanism is made possible by an integrated HBIM-DT methodology. The interaction between the actual on-site building and the digital model is improved by HBIM models with real-time IoT data and DT technologies, enabling non-specialist stakeholders to participate in the decision-making process (Jouan & Hallot, 2019).

In conclusion, DT technology has demonstrated remarkable potential for damage prediction and restoration of historic buildings. The process of structuring this information in digital data models is difficult, and the digitalization of heritage restorations using DTs necessitates a thorough understanding of the cultural site (Jouan & Hallot, 2020).

2.3.4 Digital Twin for Asset Management

The majority of the publications in this category concentrate on using DTs to manage assets during their entire lifecycle. Making decisions that affect assets is an essential step in asset management (Vieira et al., 2021). Data/information management is necessary for making well-informed decisions (Vieira et al., 2021).

Asset management benefits from digitization. In contrast to advanced digital controls, which guarantee a reduction in unexpected downtime of assets with cost-effective management, sensors, for instance, can assist in data collection. In a conceptual essay, Macchi et al. (Macchi et al., 2018) examined the use of DTs in asset management, particularly in the asset-related decision-making process, to highlight the need for decision support in asset lifecycle management and reflect the potential of a DT for decision support. Four concepts and two components make up the asset-related decision-making process:

Principles:

- Lifecycle-based thinking (decision-making should incorporate long-term objectives).
- Systematization (relevance of the decision on the system and not only on the individual components).
- Risk orientation: after making a decision, use a risk management strategy.
- Asset-centric orientation: emphasizes the data and information related to an asset.

The decision-making process involves many factors, all of which should be taken into account when choosing an item.

- Asset lifecycle: how the choice will ultimately effect the asset.
- Asset hierarchical control level: at what level (strategic, tactical, or operational) was the decision made? ensures that the choice is supported by all levels.

Proper data/information management is necessary for the decision-making process (Ouertani et al., 2008). DTs can close the gap that now exists between data/information management and asset lifecycle management. The significance of DTs in asset-related decision-making has been demonstrated by (Macchi et al., 2018) by evaluating use cases drawn from projects based on the authors' prior experiences. The phases of the asset life cycle and asset management levels (i.e., strategic, tactical, and operational) are used to categorize these use cases (i.e., beginning of life, middle of life, and end of life). For asset configuration, reconfiguration, planning, commissioning, condition monitoring, and health evaluation, DT data can be employed.

James and Ajith (Heaton & Parlikad, 2020) established an Asset Information Model (AIM) that permits the production of DTs and described the design and development of DTs utilizing a BIM-based approach. The AIM is the data and information about assets at a level necessary for an asset management system to operate properly. The West Cambridge campus case study served as the writers' example for the notion. The following procedures were taken to construct the AIM to facilitate the development of DTs:

- Classification of assets within a BIM model (depending on output, such as heating, ventilation, power, and lighting). Use diagrams created using UML to describe the classification system.
- Creation of an AIM relational database using the defined classification system's UML diagrams.
- Creation of a single unified model by linking BIM models to the database (aka federated model).

The case study that was taken into consideration in (Heaton & Parlikad, 2020) consists of four BIM models that each depict a different building on the West Cambridge campus. Three of the structures were finished, and one was still being built. Using a LiDAR scanner mounted on an automobile, a point cloud dataset was generated, and the utilities such as water, sewage, power, and communications were modeled as 3D geometry. The first stage of creating the AIM was classifying the 6881 assets from two BIM models, or two buildings. The second step involved the creation of 149 relational database tables and 41 UML diagrams. The final phase federates the point cloud LiDAR data, BIM models, and 3D geometry. The AIM relational database and federated 3D model were linked once the categorized assets from the BIM models were exported to it. The BIM models exported 6881 assets and related data in total.

The difficulties and facets of developing DTs for production system management were covered by Vitalii et al. (Dolgov et al., 2021). An information model and an evaluation system are made up of the DT. The information model, which was built using the data gathered for management, was divided into three sections: starting data, which is conditionally constant; a production schedule, which varies frequently; and status and statistics, which are continually changing. Following information model data collection, the enterprise (producing system) was simulated using the data gathered. The simulation allowed for the evaluation and management of production capacity in various situations, the certification of essential equipment or composition, the verification of a plan or schedule, and the creation of recommendations for enhancing enterprise effectiveness.

The literature and industry-defined standards affecting BIM and asset management throughout the operation and maintenance phase were examined by Lu et al. (Q. Lu, Xie, et al., 2020). The authors proposed a three-layer DT-enabled framework for managing smart assets, with the first layer representing the digital equivalent of the physical system, the second layer focusing on the fusion of asset data and big data analytics, and the third layer representing the interaction between human operators and the DT. The development of dynamic digital models that automatically learn and update the status of their physical counterpart assets is aided by DT-based asset management. The interaction between smart assets and various stakeholders involved in the asset management process, however, was not the study’s primary emphasis. Bolshakov et al. (Bolshakov et al., 2020) outlined many methods for setting up DTs to manage the lifecycle of technical systems, assets, and infrastructures. They also emphasized the significance of formal definitions and standardization to put DTs into reality.

In conclusion, DTs can facilitate data and asset management connections to facilitate effective asset-related decision-making (Macchi et al., 2018). Additionally, the intelligence and integration of the total asset management system are enhanced by AI-supported decision-making (Q. Lu, Xie, et al., 2020). An intimate connection between the stakeholders and the asset management process is made possible through effective and efficient DT-based communication and cooperation (Q. Lu, Xie, et al., 2020). The absence of definition and formalization of the data necessary to develop and update the asset management model, however, continues to impede the implementation of DTs for asset management (Bolshakov et al., 2020).

2.3.5 Digital Twin for Sustainability

The articles in this category concentrate on using DTs to evaluate a structure's sustainability. To instruct construction participants in environmentally friendly planning, design, and operation of a construction project, (Kaewunruen & Xu, 2018) used BIM and a DT to assess the design, construction, and maintenance processes of a railway station in London. The authors converted the structure's 3D model into a 6D BIM model that included cost and time estimates as well as calculations for carbon emissions. They demonstrated how BIM may be used to foresee a structure's viability in an urgent or dangerous circumstance. To determine the most cost- and carbon-effective renovation option, they also used a DT to simulate three options for a structure in the event of a fire. However, because there aren't enough design details available for the building under consideration and its surroundings, the study's implemented models can't ensure the highest level of accuracy.

A DT-enabled lifecycle assessment for the sustainability and vulnerability assessment of a subway station in China was introduced by Kaewunruen et al. (Kaewunruen et al., 2020). A DT was used by the authors to compare the predicted costs and carbon emissions at each step of the project lifespan. The modeling findings showed that the costliest phase is construction, whereas the costliest phase for carbon emissions is operation and maintenance. To determine the cost and carbon emissions effectiveness of various renovation choices, the authors analyzed various materials and ran simulations. The proposed model, however, was static and not self-updatable, which makes it difficult to manage risk dynamics throughout a project.

A framework for converting the manual static sustainability assessment to a DT and IoT-enabled approach was put forth by Tagliabue et al. (Tagliabue et al., 2021). The suggested framework was assessed in a real-world scenario for a building housing academic facilities at the University of Brescia. The authors demonstrated the value of the DT in decision-making about sustainability. Orozco-Messana et al. (Orozco-Messana et al., 2021) concentrated on creating a process for a resource-efficient DT model of a neighborhood to assess its sustainability assessment and lifespan analysis.

To create daily building energy benchmarks, Francisco et al. (Francisco et al., 2020) used data from smart meters. These benchmarks were broken down into different periods, including the peak summer period, an occupied period during the school year, an unoccupied period during the school year, and an occupied period during the summer. The simulation results showed that periodically segmented energy scores were significantly different from the score for the entire time across all of the buildings under examination. The authors proposed DT-enabled energy management platforms to incorporate separated daily efficiency data.

Wangen et al. (Wang et al., 2020). proposed a DT-based framework for a green building maintenance system. The proposed framework enables the stakeholders involved in the operation phase to solve the problem of insufficient informatization and automatic management ability of green building maintenance. The feasibility of the proposed framework is verified by developing a prototype based on Bentley Systems software. The simulation results reveal that the framework can reflect the accurate and real-time status of green buildings and can improve the efficiency of green building maintenance by automatic management. However, the proposed framework involves complex cross-application communication without considering heterogeneity among different data islands.

Jakobi et al. (Jakobi et al., 2019) showcased how BIM can be used to reduce the performance gap brought on by discrepancies between various planning phases throughout a project's lifecycle. The proposed model was nevertheless evaluated theoretically by the authors rather than empirically.

In conclusion, the lack of standardized processes can result in inconsistent and erroneous models when DTs are used for sustainability. Furthermore, it can be difficult to protect the privacy of sensitive and important data under current copyright legislation (Kaewunruen & Xu, 2018). To increase building resilience and sustainability, DTs can also optimize construction efficiency, cost, carbon emission, and buildability (Kaewunruen et al., 2020). Integrating temporally divided daily energy indicators into a digital twin is advised to further increase a building's energy efficiency (Francisco et al., 2020).

2.4 Literature Discussion

DTs provide for the integration and communication of virtual instances and their physical counterparts. Many studies have proposed DT applications in the AEC/FM industry for better planning, design, construction, and assent management practices. The use of DTs in the AEC/FM sector can primarily be divided into three categories: heritage restoration (Jouan & Hallot, 2019; Khalil et al., 2021), asset management (Bolshakov et al., 2020; Dolgov et al., 2021; Heaton & Parlikad, 2020; Q. Lu, Xie, et al., 2020; Macchi et al., 2018), and sustainability (Francisco et al., 2020; Jakobi et al., 2019; Kaewunruen et al., 2020; Kaewunruen & Xu, 2018; Orozco-Messana et al., 2021; Tagliabue et al., 2021; Wang et al., 2020). The applications of DT within these categories are summarized as follows.

- Restoration of historic buildings
- Damage prediction
- Asset management
- Asset-related decision-making
- Production system management
- Sustainable design and planning
- Vulnerability and sustainability assessment for project lifecycle
- Environment-friendly decision-making
- Energy management
- Green building maintenance

Although digital twin applications have enhanced performance in the AEC/FM sector (Hosamo et al., 2022b), many issues need to be resolved for extensive, effective technology adoption. The following are these difficulties:

- Data collection: A DT requires a significant amount of data from several sources. It can be difficult to gather these data, particularly if they belong to private organizations (Uhlemann et al., 2017). Additionally, moving the data to a central location involves significant network overhead, energy use, and financial expense (Ismail & Materwala, 2020). Using distributed technologies like federated learning to build DTs that can do away with the transport of huge data to a centralized place is one possible approach (Ramu et al., 2022).

- Data heterogeneity: DTs use data from various sources and in a variety of formats. A hurdle in realizing DT is the integration and interoperability of these disparate spatial-temporal data (Mercier-Laurent & Monsone, 2019). The heterogeneous and growing volume of data with various meanings and syntaxes required for DTs cannot be stored or managed by conventional databases (Qi et al., 2021).

- Data privacy and security: Due to the presence of sensitive and crucial information, enormous amounts of DT data are constantly threatened in terms of privacy and security (Wu et al., 2021). Therefore, DT implementation must adhere to the most recent standards for privacy and security (Fuller et al., 2020). Recent developments have demonstrated the usage of blockchain (Ismail & Materwala, 2019) to increase DT process transparency and confidence (Putz et al., 2021).

- Absence of standards: Interoperability and consistent standards are essential for the effective implementation of DTs (Lim et al., 2020). Lack of agreement on the many standards, protocols, and procedures is impeding current adoption (Re Cecconi et al., 2017).

- High implementation costs: The use of DTs necessitates the use of several sensors to sense and gather data. Costs associated with data transport, connectivity, and hardware deployment rise as a result (Botín-Sanabria et al., 2022). Additionally, a well-connected IT infrastructure that supports IoT and data analytics is needed for the effective and efficient deployment and operation of DTs (Fuller et al., 2020).

To summarize, the prior works on DT for the AEC/FM industry focus on the definition, creation, and application of DT technology. The works on DT applications are categorized into: asset management, restoration of historic buildings, and sustainability. However, to our knowledge, no prior work discusses the limitations of current asset management practices. This thesis addresses this gap by extracting the challenges in the current FM approaches from responses obtained through interviews. In addition, the thesis highlights the advantages of DT for efficient asset management and discusses open challenges and possible solutions for DT implementation.

Chapter 3: Methodology

In this chapter, we delve into the realm of asset management practices within the United Arab Emirates (UAE) by conducting interviews with industry experts. We commence by providing an overview of the research tools at our disposal, followed by outlining the guidelines for conducting these interviews. These guidelines not only elucidate the criteria for selecting interview candidates but also outline the specific questions that will be asked during the interviews.

FM must be integrated into improving business performance and developing it in the future. Organizations should see FM as a function supporting operations, rather than as a strategic component. Rather than being an operational issue, FM should play a bigger role in business development. According to (Nutt, 2000), FM aims to improve the infrastructure and logistics of all types of businesses and public institutions in all sectors. In contrast, this focus is on strategic aspects of FM that do not exist in practice. Human resources must be developed along with financial resources to effectively manage the facility, human resources must be developed along with financial resources, as technological developments usually do not coincide with improvements in human resources in the market, so it may take many years to adopt an advanced strategy (Novack, 2019). One of the most promising modern technologies, BIM has proven to help move the market forward in a quantum leap. With several studies conducted in recent years, it has become a widely used tool in the AEC/FM industry for providing digital information on projects. During different phases of the lifecycle, BIM evolves to meet the needs of project management, risk management, and facility management (F. Zhang et al., 2022). In addition, BIM has been widely adopted in sustainable development (Santos et al., 2019), and opportunities for its integration with other interdisciplinary technologies have also been found. The most important question here is, are the FM staff in UAE familiar with new technologies such as BIM and DT? Are FM firms interested in applying such modern methods? What should be automated first? To this end, in this chapter, we explain the research methodology adopted to analyze the current practices in FM and identify the challenges within.

3.1 Research Tools

This thesis seeks to uncover the challenges faced by organizations, particularly in the AEC/FM sector, and to evaluate the potential integration of DTs as a solution to address these challenges. Therefore, selecting the appropriate research tools is a crucial step in ensuring the validity and reliability of the study's findings. Several research tools and methods were considered to achieve the research objectives, including:

- Surveys: Initially contemplated as a means of gathering data from a broad sample of participants. However, due to the complex and nuanced nature of asset management practices, and the need for detailed insights, surveys were deemed less suitable as the primary data collection method.
- Structured Interviews: Emerged as the primary research tool. This choice was influenced by several factors: 1) In-Depth Exploration: Structured interviews allow for a deep exploration of participants' experiences, perspectives, and insights related to asset management practices. This aligns with the research's exploratory nature, facilitating a thorough examination of weaknesses and challenges (Wright et al., 1989). 2) Expert Insights: Interviews provide direct access to industry experts, practitioners, and stakeholders with specialized knowledge and practical experience in asset management within the UAE. These experts offered valuable insights that could not be captured through other research methods (Wright et al., 1989). 3) Qualitative Data Collection: Asset management practices often involve qualitative aspects that require a nuanced understanding. Structured interviews facilitated the collection of qualitative data, ensuring the research captured both quantitative and qualitative dimensions of the topic (Wright et al., 1989).
- Data Analysis Software: To manage and analyse the data collected through structured interviews, IBM SPSS Statistics was selected as the software tool. The choice was guided by its robust capabilities for quantitative data analysis, including descriptive statistics, inferential statistics, and data visualization (Pallant, 2020).

Structured interviews are employed in this thesis as it is a qualitative research method characterized by a systematic and predefined set of questions posed to participants in a consistent and standardized manner (Bernard et al., 2010). Unlike unstructured or semi-structured interviews, where questions may vary across interviews and can evolve during the conversation, structured interviews adhere to a fixed script of questions, ensuring uniformity in data collection. The choice of it was guided by several compelling reasons since it provides a standardized approach to data collection, ensuring that each participant responds to the same set of questions. This standardization enhances the reliability of the data collected. Add to that, the structured nature of interviews facilitates easy comparison of responses across participants, enabling systematic data analysis. This comparability is particularly valuable for identifying patterns and common themes related to weaknesses in asset management practices. Structured interviews, in conjunction with IBM SPSS Statistics for data analysis, allowed for a rigorous examination of asset management practices in the UAE, focusing on Abu Dhabi, and the potential integration of Digital Twins to address identified weaknesses. Figure 17 illustrates the overall research methodology employed in this thesis.

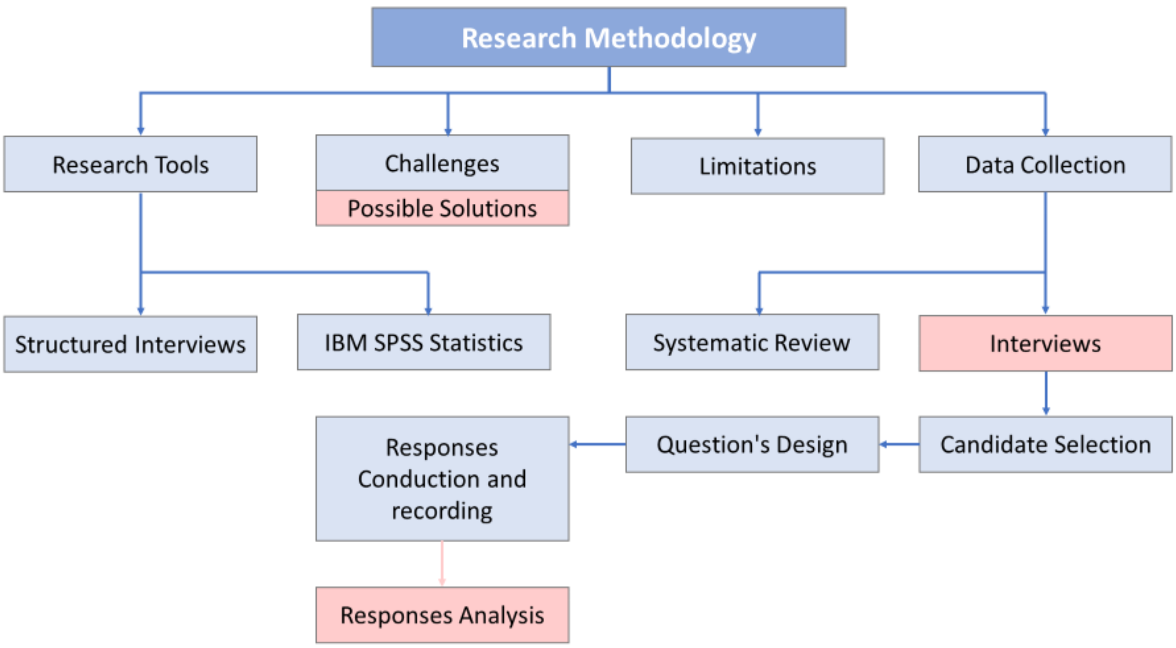

Figure 17: Research methodology.

3.2 Interviews Guidelines

The selection of interviews as the primary research methodology for this study is closely aligned with the overarching research objectives, as outlined below:

- To Understand Theoretical Underpinning and Concepts (Objective 1): Interviews were chosen as a methodology to provide a bridge between theory and practice. By engaging with professionals and experts in the field of asset management, we aimed to gain real-world insights into how theoretical concepts related to Digital Twins can be applied in practice. Interviews allowed us to explore the practical nuances of Digital Twins and their potential applications in asset management within the UAE context.
- To Investigate Integration with Digitalization Practices (Objective 2): Interviews facilitated an in-depth exploration of the integration of Digital Twins with digitalization practices in asset management. Through conversations with industry stakeholders, we sought to understand how Digital Twins contribute to efficiency improvements, maintenance optimization, and the utilization of real-time data. By delving into real-life experiences and implementations, we aimed to uncover best practices and challenges associated with this integration.
- To Identify Challenges and Barriers (Objective 3): Interviews served as a crucial method for uncovering the potential challenges and barriers specific to the UAE's asset management context. By engaging with practitioners and decision-makers, we gained firsthand insights into the challenges faced by FM employees. These insights were essential for addressing Objective 3, which focused on understanding the hurdles to successful integration.
- To Formulate Recommendations and Guidelines (Objective 4): Interviews were instrumental in generating data that forms the basis for formulating practical recommendations and guidelines. By gathering insights from professionals who navigate the complexities of asset management, we were able to distill their knowledge into actionable recommendations. These recommendations are aimed at assisting organizations in the UAE seeking to integrate Digital Twins into their asset management practices effectively.

The present interview study was conducted among 14 facility management employees to obtain a deeper understanding of their problems and the obstacles they face while performing their duties, which will help us find innovative ways in which the digital twin can help the industry. The interviewees were selected based on convenience. The inclusion criteria for participants were: (i) more than one year of experience in the FM industry in the emirate of Abu Dhabi, (ii) English speaker, and (iii) a variety of positions.

Before conducting interviews, we had to understand the following characteristics of a good qualitative interview, (a) that it flows naturally, and (b) that it is rich in detail. The key is remembering that you are not just there to talk but to listen. The goal of our interviews is to be neutral, but at the same time look for the specifics. Our goal was to create a relaxed environment in which the interviewees would be more comfortable and able to speak freely. Therefore, we asked them whether they preferred to have a face-to-face or Zoom meeting. Furthermore, the key concepts of an interview can be identified as follows (Somekh & Lewin, 2004):

- Value: refers to both the interview itself and the words of the interviewees.
- Trust: The research is considered ethical if it demonstrates objectivity, accuracy, and honesty.
- Meaning: The meaning the interviewer aims to convey.
- Wording: This is the wording of the questions asked in the interview. Correctly observed that “the shorter the interviewer’s question and the longer the subject’s response, the better the interview.”

To keep the interviewee motivated by avoiding boredom, we have reduced these questions to a minimum without compromising on important information. The interview began with an explanation of the aim and purpose of the study. We also ensured that no sensitive questions were asked in the structured interviews. 8 interviews were conducted face-to-face, and 6 others were conducted via Zoom meeting depending on the participants’ comfort.

3.2.1 Importance of Interviews

This study adopted structured interviews to seek expert opinions about the most common challenges in the field of FM in the UAE. Structured interviews are data collection methods in which questions are asked in a prescribed order and the responses between participants are easily comparable (Campion et al., 1997). It can be a useful tool for identifying patterns and highlighting areas for further research (Campion et al., 1997). While structured interviews are primarily qualitative in nature, the questions can include both closed ended (quantitative) and open-ended (qualitative) components. This allowed for the collection of both numerical data and detailed qualitative insights. This approach of structured interview is best suited for this research for the following reasons:

- Reduced risk of bias by asking the same questions in the same order to all participants.
- Interviewing different job titles, from technicians to managers (site to office), helps to understand challenges at their roots.
- To identify the main challenges faced by FM professionals through first-hand interactions.
- Providing experts with an opportunity to speak more extensively about issues raised by the researcher and introducing new issues related to the topic.
- Give the participant space to propose some solutions from his point of view.

3.2.2 Candidate Selection

Participants were selected to cover different aspects of the facility management industry based on their backgrounds and years of experience. To conduct the research, the authors made a list of FM companies involved in malls, university campuses, offices, and even housing project management. Several emails were sent to these offices requesting their participation, and in some cases, phone calls were made. It was possible to find and recruit participants using this method, even hard-to-reach managers. To ensure a variety of backgrounds and perspectives, both genders of different ages and academic degrees were invited to participate in the study for the authors to gain an understanding of the perspectives of young people new to the market as well as those of the older generation with experience.

14 Shortlisted participants were contacted, and interview dates were scheduled. Interviews were conducted either face to face or using the online meeting platforms Zoom and Microsoft Teams depending on the participants' preferences. At the beginning of the session, a transcript was read asking for consent to anonymously use the participants' feedback. An average of 20 minutes was spent and recorded in each interview. Using the recorded sessions, written transcripts of the discussions were generated. The results of the study are analyzed using statistical analysis software, SPSS (IBM SPSS Statistics | IBM, n.d.).

3.2.3 Interviews Questions

Different aspects of FM duties were considered during these interviews to evaluate the impact of digitalization on key aspects and situation-specific factors. The interview questions comprised five main sections, Table 11 presents the category and contents of the questions for each section.

Table 11: Interview questionnaire categories and their contents.

Section	**Category**	**Contents**
1	Demographic and qualification	Experience, educational background, role, and enrolled courses.
2	Documentation system	Used tools, user preferences, satisfaction, and suggestions.
3	Challenges	Addressing some common challenges that they might be facing.
4	Data security	Type of data used, who's responsible for data security, and the action taken in case of losing it.
5	BIM and DT	Examples where automation can help facility management and familiarity with DT.

The interview structure included 22 questions, as presented in Table 12. The first 5 questions were questions to provide demographic data (job title, education, and experience). Question Q6 aims to identify the current most common tools and software in the FM industry in the UAE. Q7-Q9 investigated opinions on document type, actability, and employee satisfaction, to ascertain whether the change is required. Q10 considers employee suggestions regarding speeding up finding the targeted documents.

Q11-Q16 discusses the problems and obstacles that may face workers in the facilities management field and identifies the different problem-solving methods that companies follow, which may help identify new innovative methods. Q17 determines the type of information exchanged in the process, while Q18-Q20 determines the measures taken to ensure the information's safety. Q21 directly determines whether the participant is aware of BIM or DT. The last question is probably the most crucial, the author asked the participants to take a few minutes to think about an answer. Q22 Was thinking of an example where automation can help facility management tasks.

Table 12: Structured interview questions.

ID	Category	Question
Q1	Demographic and qualifications	For how long have you been working in this field?
Q2		What is your educational background?
Q3		What is your role in the management process?
Q4		Have you taken any courses related to facility management? What is it?
Q5		Does the company you work for pay to enroll in courses?
Q6	Documentation system	Are there any software and tools that you are using for management tasks?
Q7		What is more comfortable to deal with? Paper or Digital documentation?
Q8		If there is a need for a document how do you find it? How often do you need to deal with documents?
Q9		Are you happy with the way that FM documents are stored?
Q10		In your opinion, what can be done to speed up how we find FM documents?
Q11	Challenges	Any problems or challenges you would like to address in either finding, updating, or managing FM information?
Q12		How do you update information and data in your system?
Q13		Have you come across any innovative solution or digital system for FM which not yet been adopted in your company?
Q14		How often do engineering drawings not match reality?
Q15		Do you need permission to get or update the data? From whom? Does it interrupt the process?
Q16		If you have any property or a part of it without available drawings, how do you manage FM tasks on that building?
Q17	Data security	What kind of information is used for FM management?

Table 12: Structured interview questions (Continued).

ID	Category	Question
Q18		How do you ensure the security of collected data?
Q19		What do you do to reduce the risk of losing data?
Q20		Have you ever lost the data? What was the action taken in that case?
Q21	BIM and DT	Are you aware of digital technology for management like BIM and DT?
Q22		Can you address or think of some examples where automation can help facility management tasks?

Chapter 4: Analysis of Responses

The preceding chapters have provided the context for the application of DT in asset management and have outlined the rigorous methodology adopted in this thesis. The thesis focus now shifts to a comprehensive examination of the insights collected from the responses of interview participants representing diverse organizations and viewpoints. These valuable insights will form the basis for actionable recommendations.

To this end, this chapter aims to uncover the common themes that run through the participants' narratives, identify recurring patterns, understand the challenges, and shed light on the opportunities in the realm of digital twin integration.

In parallel with the analysis, this chapter concludes with a set of carefully crafted recommendations, that are derived from a synthesis of expertise and research findings. These recommendations are designed to bridge the gap between existing weaknesses and the transformative potential of DT in asset management.

4.1 Interviews Results

This thesis organizes the interview responses into five distinct categories. First, it delves into demographic information encompassing factors such as participants' years of experience, educational backgrounds, occupations, enrolled courses related to facility management, and sources of funding. Second, it explores the tools, software, and methods of documentation preferred by participants, assessing their level of satisfaction with the current storage of facility management documents and potential improvements for expediting the document retrieval process. Third, it examines the challenges faced in finding, updating, or managing facility management information, along with participants' awareness of innovative solutions or digital systems that can address these challenges. Fourth, it investigates the responsibilities related to data security, the measures taken to mitigate risks, and the protocols to follow in the event of data loss. Fifth, it evaluates participants' awareness of BIM and DT, offering examples where automation can enhance facility management tasks.

4.1.1 Demographic and Qualifications

The varying years of experience in the field of facilities management among the participants can provide valuable insights into generational differences and how accumulated experiences affect an employee's capacity to adapt to changes. To capture this diversity, we deliberately chose participants with a spectrum of experience, ranging from a minimum of one year to a maximum of seventeen years. The average experience among the participants is 6.7 years, as illustrated in Figure 18.

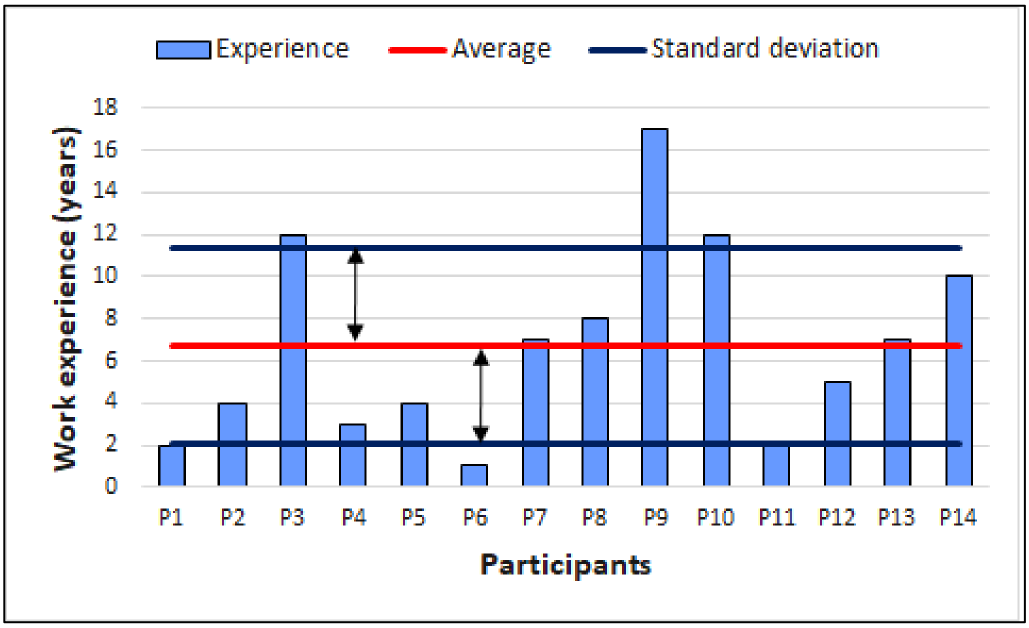

Figure 18: Answers to Q1 – participants' experience.

As depicted in Figure 19, it can be observed that among the participants, only three hold a master's degree, with two of them serving as heads of departments. Most of the participants come from a mechanical background, with four individuals possessing a diploma in mechanical engineering, one holding a master's degree in the same field, and one being a mechanical technician. This group accounts for nearly 43% of the total participants. Following closely is the field of civil engineering, represented by two individuals with a diploma and one with a master's degree, constituting approximately 21.4% of the participants. The remaining participants have diverse educational backgrounds, including business administration, economics, and electrical engineering. Their roles encompass a wide range of responsibilities, spanning equipment operations, supplier interactions, asset verification, asset tagging, documentation, staff management, and basic maintenance.

Figure 19: Answers to Q2 and Q3 – participants' educational qualifications and their roles.

Considering the growing demand for continuous learning in the workplace, we sought to explore the extent to which participants had embraced professional development opportunities, specifically in the field of FM. LinkedIn's 2019 Workplace Learning Report revealed that a substantial 74% of employees expressed a desire to enhance their skills during their spare time (Linkedin, n.d.). Consequently, we embarked on an investigation to understand whether participants had taken courses related to FM, the nature of these courses, and how they were financed, whether through individual efforts or company support. Our findings indicate that 57% of companies were willing to cover course expenses for their employees. Notably, within companies that did not provide financial support, a significant 85.7% of workers did not engage in any courses, compared to just 28.6% of employees in companies offering financial assistance. Most participants did enroll in various courses, spanning subjects such as Microsoft Office, asset performance management, safety, and, most notably, the “Certified Facility Manager” course, which attracted 62.5% of course enrollees, as illustrated in Figure 20.

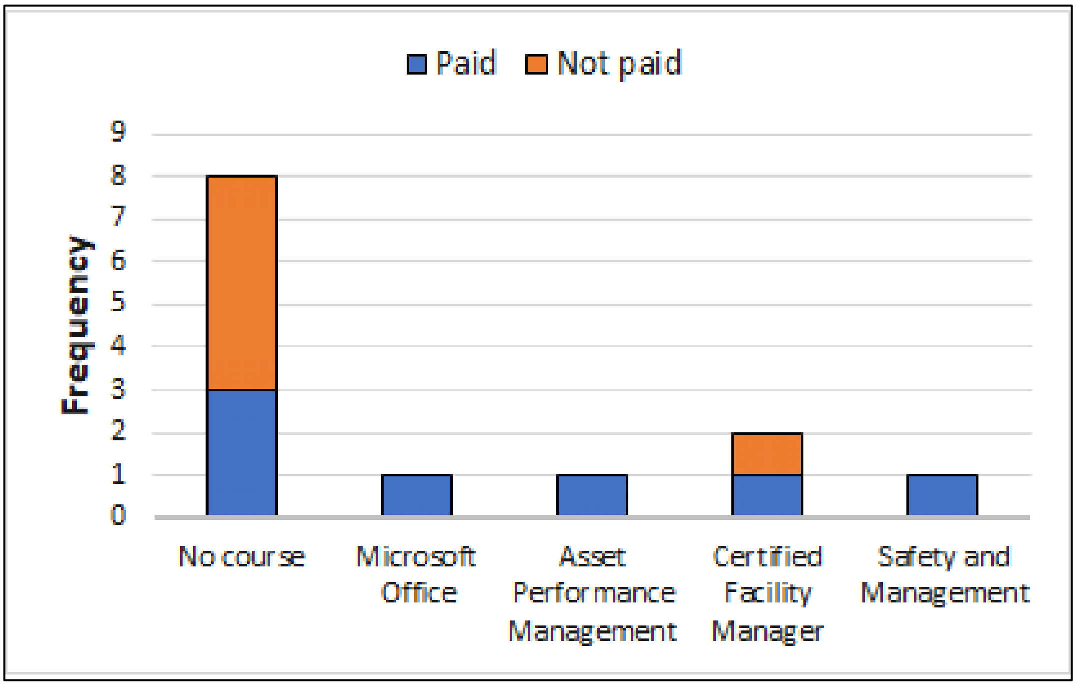

Figure 20: Answers to Q4 and Q5 - paid or non-paid courses related to facility management.

4.1.2 Documentation System

To maintain effective management control, it is essential to prioritize documentation. Each phase of a process must be carefully recorded to pinpoint any potential issues, minimize wastage, and uphold established practices. Furthermore, maintaining comprehensive documentation aids in the identification of areas that require enhancement, ultimately facilitating quality improvement and process optimization.

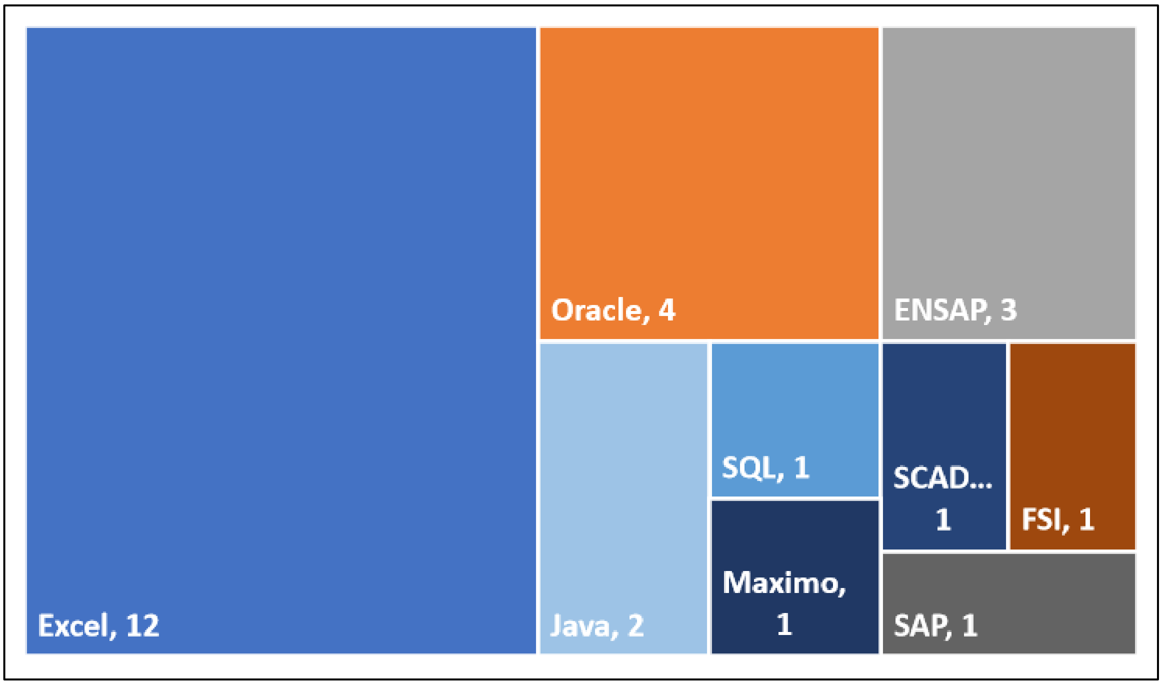

Figure 21: Answers to Q6 - software used for task management.

Question 6 enquires about the tools and programs used in facility management duties on an ongoing basis. Based on the participants' responses as shown in Figure 21, Excel is the most common software in the FM process for documentation, as it constituted 46% of the mentioned software, followed by Oracle at 15.4%, ENSAP at 11.5%, then Java at 7.7%. Many other tools were mentioned once such as SQL, Maximo, SAP, FSI, and SCADA.

When Q7 was asked about whether the participants preferred digital or paper documentation, the majority chose digital, at a rate of 85.7%, and only two people chose paperwork. Interestingly, these two were the only technicians included in the study, and when asked about the reasons, they justified this by their permanent presence outside the office, as they constantly move between facilities, so paper documents are more suitable for the nature of their work instead of returning to the office for updating everything digitally every time.

All participants agreed that they deal with documents daily. The majority stated that they either depend on the email (35.3%) or the team leader (23.5%) to provide the needed documents, as illustrated in Figure 22. The least common method is getting from the controller where it represented only 5.9%. Equally, 42.8% of them are happy with the way that FM documents are stored and 42.8% are not, while only 14.4% are partially satisfied.

Regarding their proposals to speed up the document access process, the most common suggestion 28.6% was that a specific party should be assigned to provide the necessary data for the site or facility, as this would save them the trouble of searching. The second proposal 21.4%, which was suggested by the technicians and a civil engineer, is to provide a smart tablet with internet to access the system anywhere or secure online storage. Interesting proposals were also presented as having a direct connection with the employees, providing a Maximo system, or just having proper organization, as displayed in Figure 23.

When the participants were asked in Q9 if they were happy with the way that FM documents are stored, 57.1% expressed their dissatisfaction, while 14.3% said they were partially happy, and 28.6% were happy with the current storage methods.

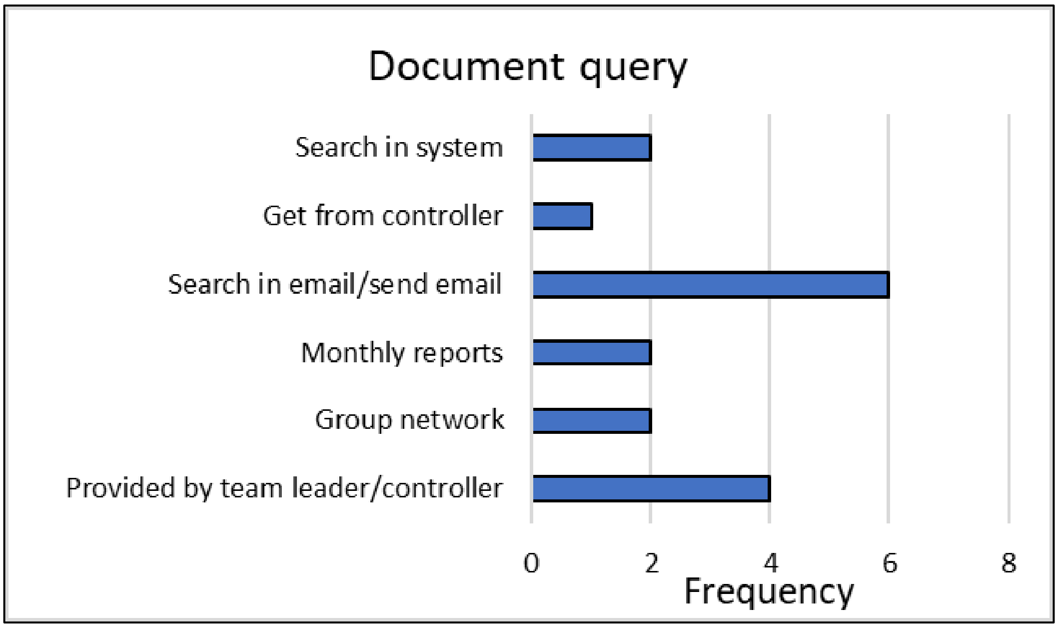

Figure 22: Answers to Q8 – methods used for document query.

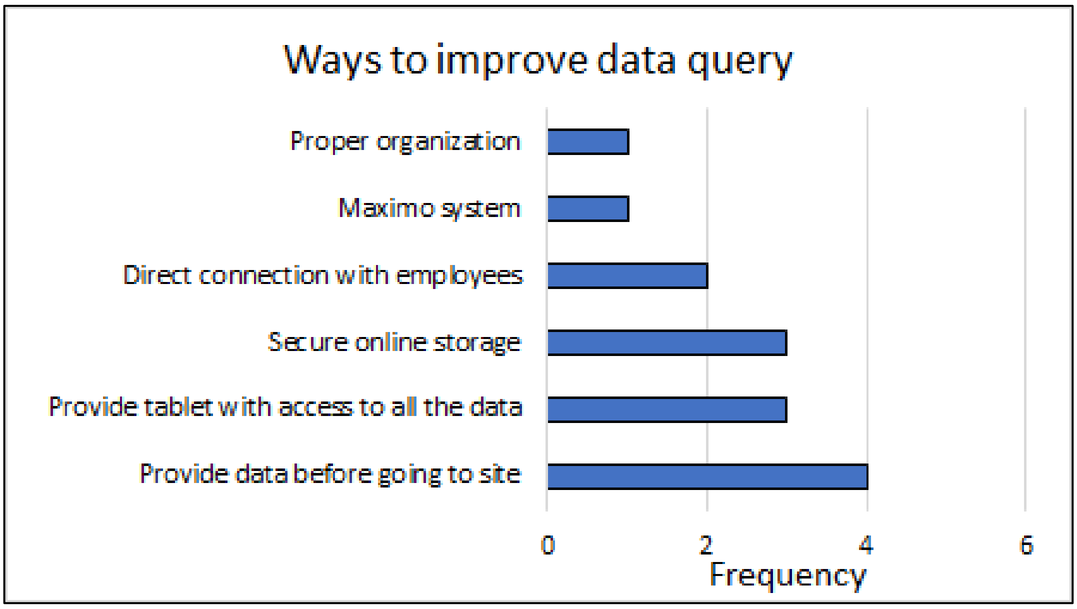

Figure 23: Answers to Q10 – ways to speed up document query.

4.1.3 Challenges

Through direct inquiries regarding the issues encountered in the facility management process, we gained insights into the common obstacles hindering its efficiency. As depicted in Figure 24, numerous challenges were identified, including difficulties in obtaining access permissions, dealing with paper documents, sifting through multiple emails, and encountering incorrect drawings. However, it is noteworthy that a significant 41.2% of the issues stemmed from communication and coordination shortcomings, followed by a slow manual data update at 23.5%, and delays in obtaining or incomplete information at 11.8%.

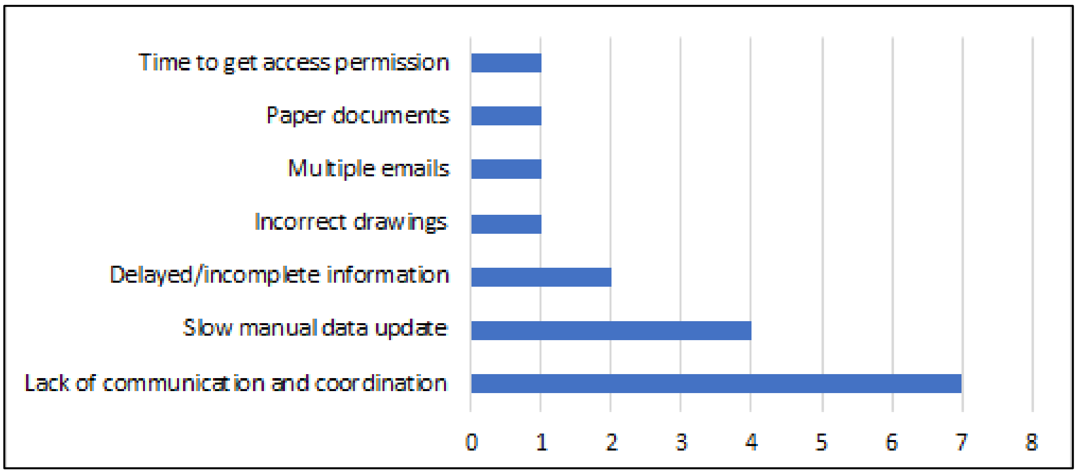

Figure 24: Answers to Q11 – challenges faced in managing facility management information.

Q12 showed that 85.8% of the participants updated information and data manually, only 7.1% used the scanner, and the same percentage did not enter the information themselves, but by software engineers. Figure 25 displays the participants' answers regarding Q13 on their awareness of innovative solution for FM that is not adopted by their organizations, where 57.1% answered yes, 37.5% of them mentioned BIM, 25% mentioned asset tracking software, while 42.9% admitted that they are not aware of any methods used out of the organization.

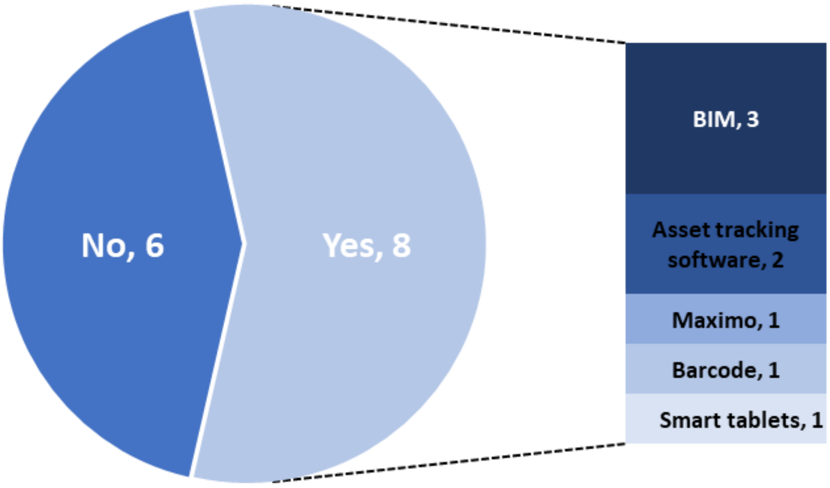

Figure 25: Answers to Q13 – awareness regarding innovative facility management solutions that are not being used in the participant's organization.

In Q15 regarding whether they need permission to get or update the data, 78.6% of the participants stated that they need a permit as illustrated in Figure 26, but 27.3% of them indicated that they need a permit only in some special cases, such as high-risk area, and only 21.4% of the participants do not need any permission. 54.5% of the permits are requested from department managers. In other cases, permits are required from civil defense, IT department, document controller, consultancy, or the engineer in case of technicians.

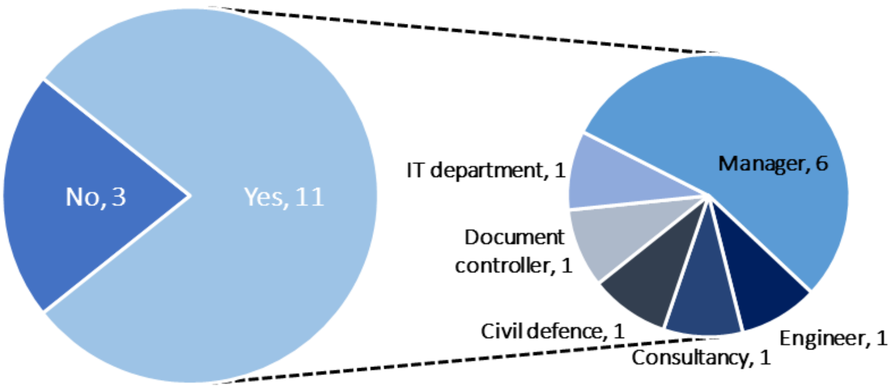

Figure 26: Answers to Q15 – permission for data update.

Based on the experiences of the participants, it seems that 71.4% have faced the problem of the drawings not matching reality, 50% of them believe that this happens very often, while 28.5% have not been exposed to such a situation and believe that it doesn’t happen often. When they were asked about the measures taken in that case as Figure 27 shows, their answers were either contacting the supplier, preparing an AutoCAD drawing, or physical inspection. While 64.3% of the participants said that preparing AutoCAD drawings is a must, 21.4% of them think that physical inspection is enough in most cases.

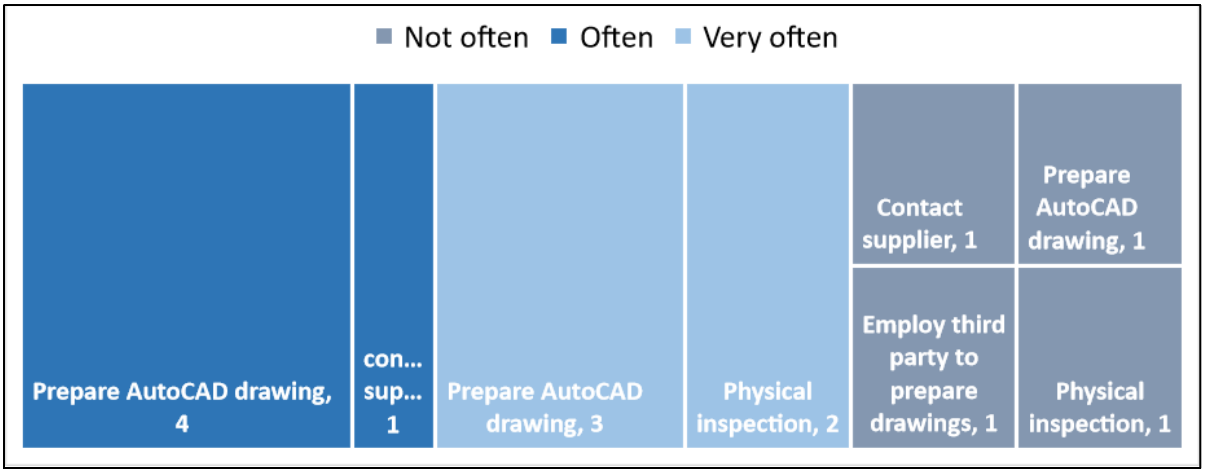

Figure 27: Answers to Q14 and Q16 – frequency of incorrect drawings and how to manage and deal with missing data.

4.1.4 Data Security

Creating, acquiring, saving, and exchanging data is an essential part of any company's operations. By protecting it from internal and external corruption and illegal access, a company can avoid financial loss, reputational damage, and degradation of consumer trust. Given the importance of data security related to facility management, the author tried to understand more about the type of data used, who is responsible for its security, and the methods followed to protect it (Denning & Denning, 1979).

Participants were asked about the type of information used for FM management, The most frequent answer among the participants was Emails, as 71.4% of the participants mentioned it and it represented 20% of the mentioned answers, followed by diagrams and bills mentioned by 64.3% with a percentage of 18% for each. Checklists, schedules, permits, FAR registers, sheets, and WhatsApp group chats are also used for exchanging information as they were also mentioned several times, while handover documents, materials requests, official letters, and plans were mentioned only once, as shown in Figure 28.

When asked about how to ensure the security of collected data, most of the participants were not sure or confident in their answers. The same people who mentioned email and WhatsApp as a method of sharing data representing the largest percentage (71.4%), placed the responsibility for data protection either on the IT department or the project manager as illustrated in Figure 29. 14.3% of the participants suggested that working offline in an isolated system may help protect data. On the other hand, the technicians suggested solutions such as having folders packed with name cards, verbal information, or signed documents.

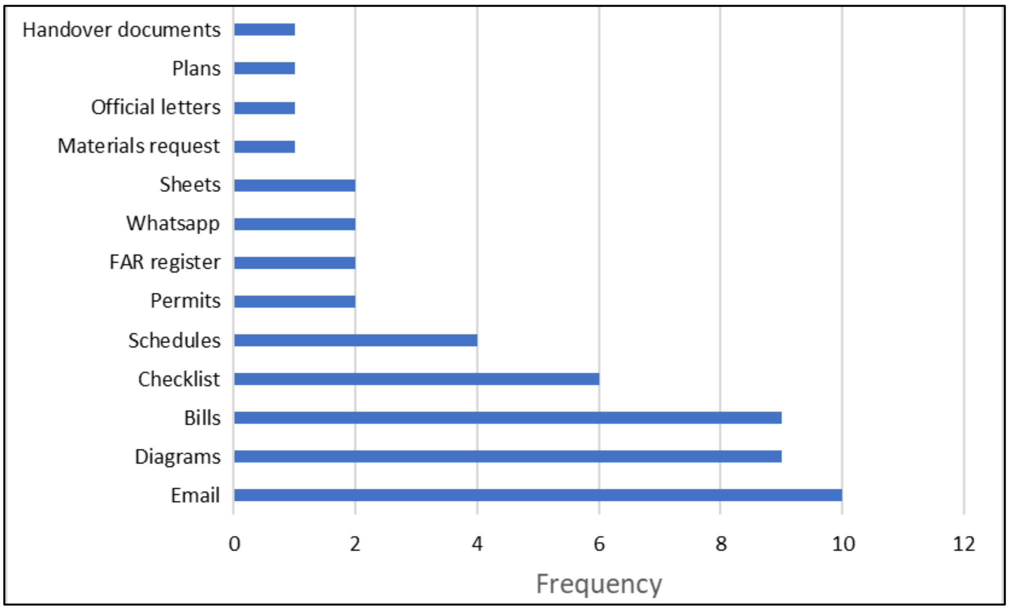

Figure 28: Answers to Q17 – types of information used for facility management.

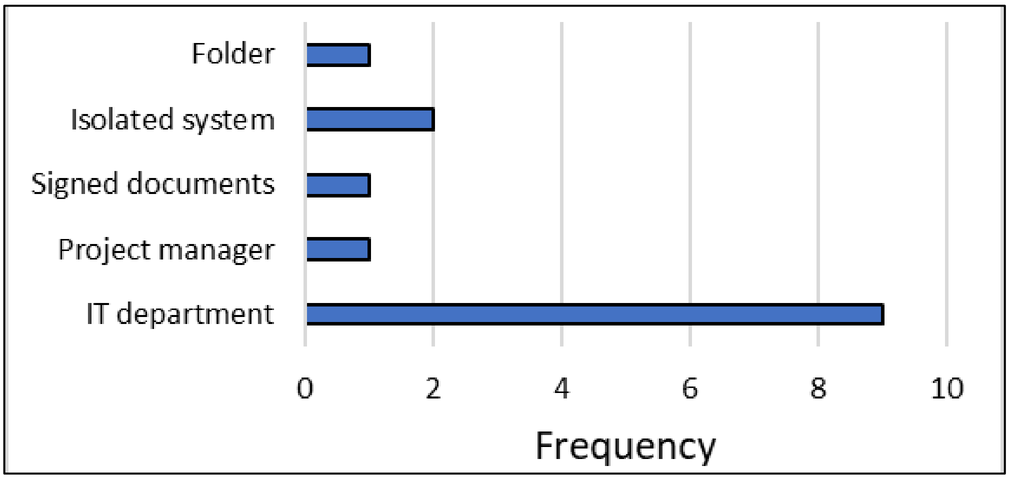

Figure 29: Answers to Q18 – methods to ensure data security.

35.7% of the participants answered Q19 that having a backup might help reduce the risk of losing data, and 21.4% responded that Cloud storage is the solution. 14.3% answered that using email to share information would reduce the risk since it will be stored there in case of a drive failure, and the same percentage answered that simply organizing files helps a lot in protecting data. Some mentioned creating multiple copies of the file or submitting the collected data directly to the office in case of site work.

Question 20 was direct, “Have you ever lost the data? What was the action taken in that case?” 57.1% said No, and 42.9% had gone through this situation, 83.3% of whom recovered the data with help from the IT department, and 16.7% were unable to do so.

Our analysis of both questions showed that those who use cloud storage are less likely to lose data, while those who create backups reduce the chances of losing data, and it is easy to recover. An email was the only case where the participant could not recover the data as displayed in Figure 30.

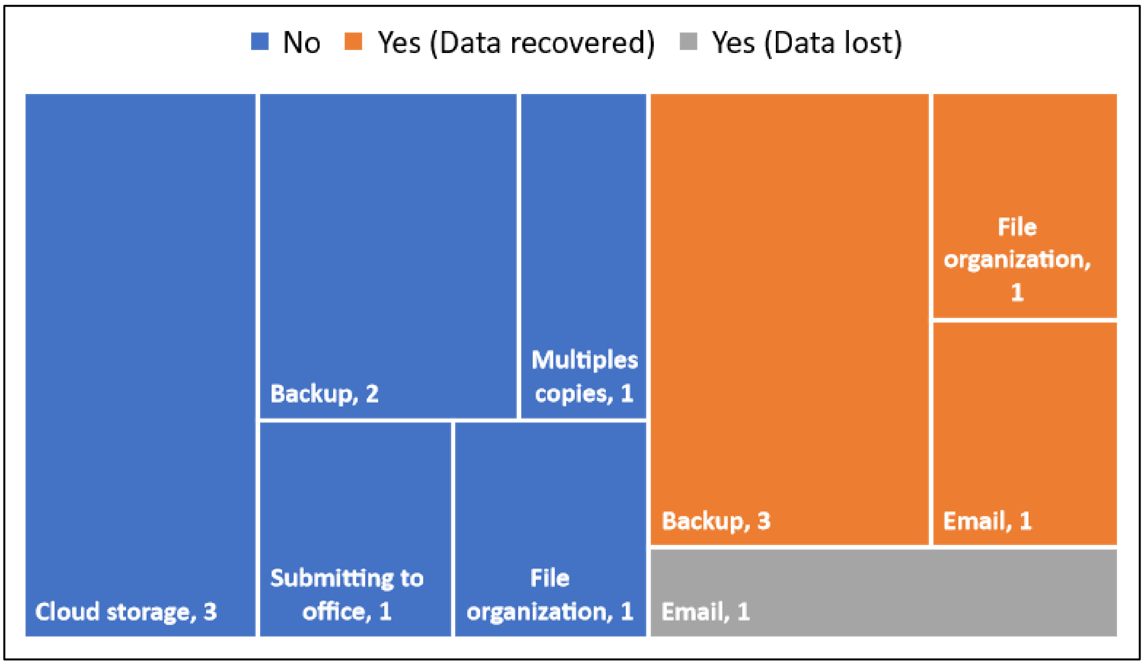

Figure 30: Answers to Q19 and Q20 – an incident of data loss and ways to mitigate the risk of data loss.

4.1.5 Building Model Information and Digital Twin

Moving on to the most important category to measure the participants' awareness of BIM and DT, and what are the areas that facilities management workers may wish to develop to study the possibilities of digital twinning in this regard.

Returning to question 9, the author found that those who are happy or partially happy with the current methods are not aware of either BIM or DT, while all those who were aware of them are the ones who initially indicated their dissatisfaction with the current practices in their organizations. Figure 31 illustrates that 64.3% of the participants do not know what BIM or DT is, 66.7% of them are those who were happy or partially happy with the current methods, and 33.3% represented the unhappy group. Only 7.1% of participants were familiar with BIM and DT. 28.6% of participants were aware that BIM existed.

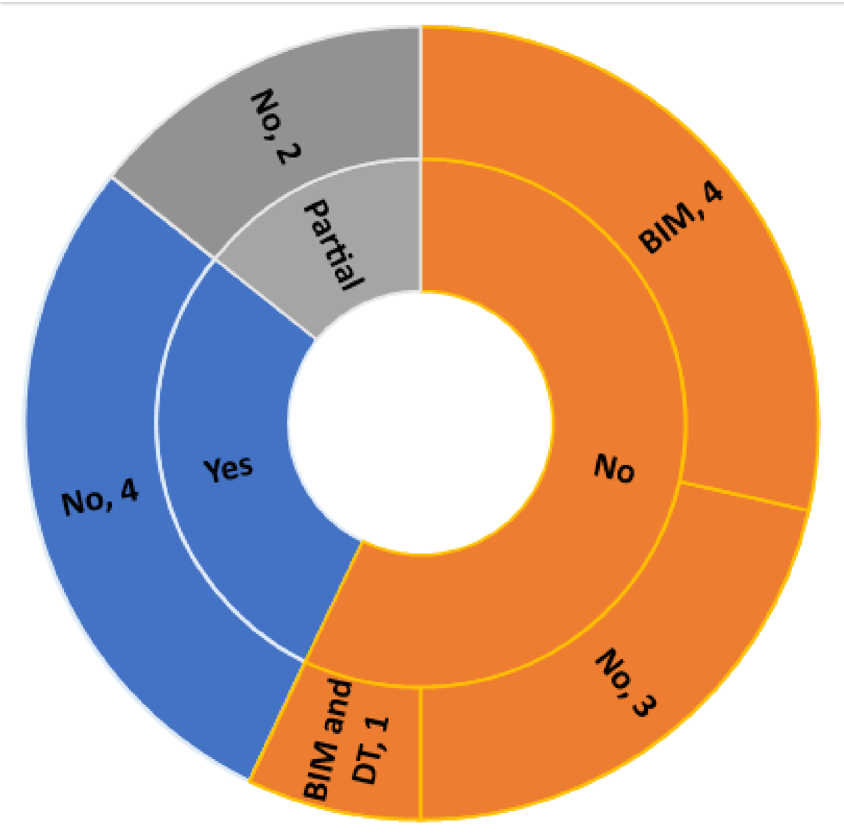

Figure 31: Answers to Q9 and Q21 – satisfaction with the current documentation approach and awareness regarding digital technologies.

"Think of some examples where automation can help facility management tasks?" was the last and most important question. We also asked the participants to take their time and think. A variety of interesting answers were provided, as 50% of the participants indicated that they wished that the process of collecting data from the sites was occurring automatically instead of spending time and energy in navigating, requesting approvals, and entering Places that are physically difficult to reach, while 14.3% said that collecting bills, keeping them for long periods, and comparing prices is a cumbersome process, and it is usually not devoid of human errors, so they wished it would work automatically, and the same percentage of respondents assistive maintenance. Others stated that the automation of data updates and communication may allow employees to focus their energy on other responsibilities and conserve their time and energy as shown in Figure 32.

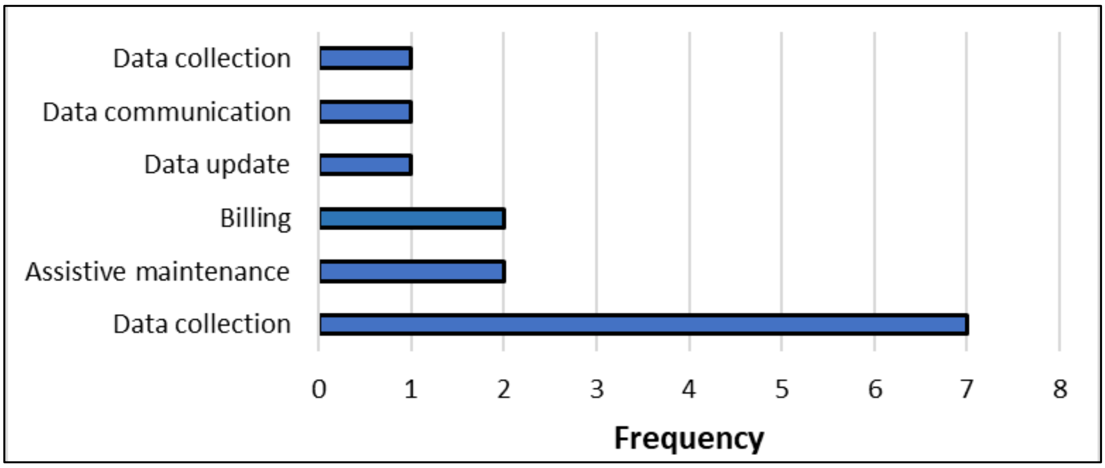

Figure 32: Answers to Q22 – application of automation in facility management.

4.2 Importance of Digital Twin for Facility Management

Table 13 shows the issues, along with their descriptions, that prevail in the current facilities management approach. These issues are extracted from the participant's responses to the interview questions. The table also discusses how digital twins can address these issues, enabling an efficient facility management system.

Table 13: Issues with traditional facility management approach and how digital twins address them.

Issue	Description	Use of digital twin
Delayed data update	Paper-based data update is generally integrated by the end of the day, hindering the immediate availability to different stakeholders	Data is updated in real time using a network of connected sensors (H. Jiang et al., 2021; Jouan & Hallot, 2019, 2020; Khajavi et al., 2019; Tagliabue et al., 2021)
Data privacy	Paper-based documents can be easily accessed by anyone, breaching the privacy of the data owner	Data in a digital twin can only be accessed based on access control rights. Any unauthorized access will be recorded by the system (Adamenko et al., 2020; Tagliabue et al., 2021)
Data integrity	Isolated and manual data updates can be easily modified by an attacker	Data is updated automatically and any manual change in data is recorded by the system. Consequently, data manipulation by a malicious user is discouraged, enhancing data integrity (Adamenko et al., 2020; Kaewunruen & Xu, 2018; Q. Lu, Parlikad, et al., 2020)
Manual errors	Manual data entry by an engineer is often prone to errors	Data in a digital twin is updated automatically using sensors without any human intervention (Adamenko et al., 2020)
Missing information	Paper-based documents are difficult to manage and can be easily misplaced	Data is available in the centralized storage and is replicated for high availability (Gursel et al., 2009; Ouertani et al., 2008)
Delayed information retrieval	Data retrieval typically involves permissions from various stakeholders that introduce delays	Data can be retrieved and accessed in real time based on access control rights (Francisco et al., 2020; Kaewunruen & Xu, 2018; Ouertani et al., 2008; Tagliabue et al., 2021)
Inefficiency	The FM data and documentation are scattered across different sites and providers.	Digital twin stores all data in one place which enables improvement in operational efficiency. Centralized and visual information is easy to utilize and always available to all stakeholders. Furthermore, digital twin improves efficiency by predictive maintenance, i.e., simulating scenarios and predicting future challenges (Jouan & Hallot, 2019; Khajavi et al., 2019; Khalil et al., 2021; V. Q. Lu et al., 2019)

4.3 Findings

In this section, we discuss the findings extracted from the participants' responses and map them to the research questions and research objectives of this thesis, to demonstrate how the study has effectively addressed its goals.

4.3.1 Responses to the Research Questions

Research Question 1: What are the key weaknesses and challenges in current asset management practices within the UAE, particularly in the AEC/FM sector?

Finding: Current asset management practices within the UAE, particularly in the AEC/FM sector, are confronted with several key weaknesses and challenges. One critical aspect that demands attention is the prevalent use of outdated and rudimentary tools and software for documentation. It is imperative to replace these archaic tools with more advanced solutions that can save time and energy. The challenges in this realm extend to documentation management, data access, and information retrieval issues. Furthermore, there are significant hurdles related to communication and coordination, manual data updates, and delays in obtaining vital information. Discrepancies between project drawings and the actual physical reality are also a notable concern, which can lead to operational inefficiencies. In addition to these issues, it is essential to evaluate data security measures and practices for safeguarding sensitive information. Protecting data from breaches and unauthorized access is a paramount concern that requires diligent attention in asset management practices within the UAE. Addressing these weaknesses and challenges is crucial for enhancing the overall effectiveness and efficiency of asset management in the AEC/FM sector in the UAE.

Research Question 2: To what extent can Digital Twins (DTs) be effectively integrated into asset management practices within the UAE?

Findings: The study assesses participants' awareness of BIM and DT, revealing a prevailing lack of awareness, particularly among those who express satisfaction with their current practices. Furthermore, participants' input regarding areas in facility management where automation can be beneficial is explored. The discussion unveiled that automation is most sought after for tasks such as data capture, billing, and predictive maintenance.

4.3.2 Research Objectives Fulfilment

The interview responses revealed that while most participants were not fully aware of digital technologies such as BIM and DT, a notable percentage expressed a desire for automation to enhance facility management tasks, such as data collection and maintenance (addresses objective 1). Furthermore, our findings revealed that participants faced challenges in accessing and updating facility management data efficiently due to manual processes, with delays caused by permissions and communication issues, inefficient data storage, and security concerns. DT can effectively address the identified challenges in asset management practices by providing real-time data updates, ensuring privacy and data security, and providing real-time decision-making (addresses objectives 2 and 3). Based on the identified challenges and the potential benefits of digital twins, recommendations and guidelines can be formulated for organizations in the UAE. For instance, recommendations could include the adoption of real-time data monitoring through digital twins, enhancing data security through access controls, and centralizing data management for increased efficiency (addresses objective 4).

Chapter 5: Discussions and Recommendations

The previous chapters have explored the theoretical foundations, the methodology involving structured interviews, and the exposure of deficiencies within contemporary asset management practices. This chapter thoroughly examines the challenges uncovered in our literature review and through the input of participants. It delves into the intricacies of these challenges and strives to unravel their implications within the realm of asset management. These insights are drawn from both academic inquiry and the perspectives of industry experts.

5.1 Open Challenges

As discussed throughout this thesis, DT is a digital model of the physical environment, system, or entity that enables testing, integration, and simulations without impacting the real-world counterpart. It has various advantages including improved quality, efficiency, and reliability. However, it's clear that the technology currently faces several challenges as discussed below.

- <u>Standardization:</u> As illustrated in the literature review, (Q. Lu, Xie, et al., 2020) and (Bolshakov et al., 2020) assured that current DT implementation lacks uniform modeling technique (Pantovic et al., 2022) and industry standards in terms of data type used for the creation of digital twin (i.e., structured, unstructured, or semi-structured), data format (i.e., text, images, or videos), and communication protocols for data transfer (i.e., Bluetooth, Wifi, or optics). Through the interviews, it became evident that there is a significant absence of standardization in asset management practices. This conclusion is drawn from the responses to specific questions, such as Q6, Q8, Q12, and Q15, which revealed that companies employ diverse methodologies, regulations, techniques, and tools, leading to a lack of uniformity and consistency across the industry. Standardization can enable domain and user understanding, development, implementation, and interoperability of dual object migration and effective reuse of DT.

- Cost and Resource Constraints: The interviews brought to light a significant challenge in asset management practices – cost and resource constraints. As (Longo et al., 2019) discussed that creating and maintaining digital twins may be costly, especially for small businesses with limited resources. This challenge is evident in the responses to several questions, underscoring the financial and resource limitations faced by many organizations in the industry. For instance, when asked about their access to professional development courses (Q4 and Q5), it was revealed that a substantial percentage of companies were unwilling to financially support their employees in enrolling for such courses, which, in turn, hindered the acquisition of new skills and knowledge. Training employees, as highlighted in the literature, is only one aspect of the overall cost of implementing digital twins (Barricelli et al., 2019). Moreover, the interviews revealed that deployment costs are a common concern in the digital twin implementation process, amplifying the significance of financial considerations (Q6). To alleviate the financial burden associated with digital twin implementation, companies might explore cost-sharing structures, outsourcing opportunities, or the utilization of open-source digital twin platforms.
- Interoperability: To improve interoperability, it is critical to push for industry standards (e.g., ISO 55000) and promote the use of open APIs (Platenius-Mohr et al., 2020). Many organizations manage assets using disparate software and hardware solutions that may or may not be compatible with the digital twin ecosystem. 12 out of 14 participants in the study explained that their companies rely primarily on programs such as Excel. Also, in the literature review (Mercier-Laurent & Monsone, 2019; Qi et al., 2021) explained that this can impede efficient data exchange and collaboration and must be dealt with in order to achieve successful digital twinning in the future.
- Data Integration and Quality: Integrating data from various sources and ensuring its quality is one of the primary challenges of digital twin implementation (Abdelmoti et al., 2021). Ten of the participants explained that they rely heavily on email to share data in a written manner, which demonstrates the lack of a unified platform for sharing data between the different parts involved in the

management process. Ozturk (Ozturk, 2021) Illustrated that even in the case of using sensors, different sensors and systems generate heterogeneous data, which can result in inconsistencies and errors. Consequently, implementing data standardization and cleansing processes to ensure data quality or employing technologies like blockchain for data verification and traceability can help in such cases (Huang et al., 2020).

- Security and Privacy: Barricelli et al. (Barricelli et al., 2019) emphasized that it is crucial to safeguard sensitive asset data and the security of the digital twin infrastructure. Asset management systems are significantly at risk from cybersecurity attacks. Unfortunately, during the interviews, we noticed that the majority of participants are not sufficiently aware of the importance of data security, as most of them explained that they just avoid losing information by sharing it via email. Encryption, access limits, and regular security audits are some examples of effective cybersecurity measures that should be put in place.
- Scalability: It is essential to develop scalable architectures and cloud-based solutions for an increasing number of assets while optimizing computational resources for a successful future digital twin (Khan et al., 2022). Since most of the participants admitted that the failure of engineering drawings to match reality is a recurring scenario as asset portfolios grow, scalability becomes a major challenge. It can be complex and resource-intensive to create and maintain digital twins for large numbers of assets.

5.2 Possible Solutions

In the following, we discuss some possible solutions for an efficient implementation of DT based on recommendations from the studies covered in the review chapter and interviews response's analysis.

- Human-Centric Design: While designing digital twin interfaces, take the FM employee's and operator's needs into account. Macchi et al. (Macchi et al., 2018), Heaton and Parlikad (Heaton & Parlikad, 2020), and Dolgov et al. (Dolgov et al., 2021) all hinted that FM employees can adopt dashboards with user-friendly interfaces and make better decisions when using augmented reality (Zhu et al., 2019).

- Real-time Monitoring and Analytics: The technicians' answers to Q10 centered around the lack of sufficient information for maintenance, which forces them to return several times wasting time and energy. Therefore, monitoring and analytics of real-time data are critical to providing actionable insights. This can aid in early defect identification and preventive maintenance, resulting in less downtime and lower expenses.
- Collaborative Ecosystems: Encourage stakeholder engagement, including asset owners, facility managers, and technology suppliers. (Kaur et al., 2020) Recommended that building a collaborative environment can result in the co-creation of digital twin solutions and the sharing of advantages.
- Machine Learning and AI Integration: To improve the predicting skills of digital twins, machine learning algorithms and AI methodologies must be used. These technologies can aid in the detection of asset irregularities as well as the optimization of maintenance schedules (Kaur et al., 2020).
- Digital Twin Lifecycle Management: (Ozturk, 2021) and (Macchi et al., 2018) proved that a thorough plan for managing the complete digital twin lifecycle, from development and validation through decommissioning, can ensure a relevant and successful DT in the long term (Lim et al., 2020).

Chapter 6: Conclusion

In this thesis, we embarked on a journey to explore the transformative potential of digital twins in the realm of asset management. Through a comprehensive examination of current asset management practices and in-depth interviews with industry experts, we have unveiled critical weaknesses that persist in traditional approaches. These findings serve as a poignant reminder of the urgent need for innovative solutions to address the challenges faced by asset-intensive organizations. To address these weaknesses, we have outlined several recommendations for future research, such as advanced data integration techniques and human-machine interaction improvements. These areas of research offer promising avenues for innovation and advancement in the field of digital twin asset management.

This thesis contributes to the growing body of knowledge in this field and serves as a call for action. The journey towards effective digital twin asset management is ongoing, and as we continue to push the boundaries of innovation, we can look forward to a future where asset management is not merely a reactive process but a proactive, data-driven, and sustainable endeavor.

In closing, it is evident that the integration of digital twin technology into asset management practices holds immense promise. By embracing the digital twin paradigm, organizations can overcome the limitations of traditional methods and unlock new possibilities for optimizing asset performance, reducing costs, and fostering sustainability. As we move forward, researchers, practitioners, and policymakers must collaborate in a concerted effort to realize the full potential of digital twins in asset management.

In the words of Peter Drucker, “The best way to predict the future is to create it”. We hope that this thesis spurs additional research, cooperation, and the development of a brighter future for asset management via digital twins.

6.1 Research Limitations

In this study, we explored where digital twinning might benefit the facilities management industry, but there are also common research limitations. Recognizing boundaries is the first step toward overcoming them.

First, we cannot be certain that the answers covered in the study represent the opinion of the facilities management sector in Abu Dhabi, as the sample size does not exceed fourteen participants from six different companies. The reason for a small sample size is that it was not possible to convince more companies to participate, as they lacked motivation, and the thesis was limited by time, budget, and access to resources.

Furthermore, the results and conclusions in this thesis may differ based on the organizations and individuals interviewed. It may not apply to every asset management practice. Since the first interview was conducted in November 2022, and some participants mentioned that their companies aim to implement BIM by next year, the research may not capture the latest information on asset management technology and industry practices. Add to that the possibility of respondent bias or interpretation bias in interviews and surveys. Interviewees may likely have differing opinions or interpretations of what constitutes a "weakness" in asset management practices.

The biggest obstacle is to find good quality and reliable data on digital twin applications and asset management practices, limiting the study's depth and accuracy. The research also included sensitive and proprietary information from organizations, which restricted us to ethical restrictions on the ability to share details and depth of analysis.

6.2 Recommendations for Future Research

Future research can overcome most of the limitations, as more reliable information and studies on digital twins will be published. In addition, a larger sample size in similar research will produce more accurate and realistic data, but to be able to do this, organizations and individuals must be motivated to participate in such research. Recommendations for future research in the field of digital twins in asset management address the identified weaknesses and open challenges revealed by the author through our interviews and research. Here are some recommendations for future related work:

- <u>DT Predictive Maintenance Models:</u> The design and usability of human-machine interfaces for digital twins in asset management will be investigated, focusing on how augmented reality, virtual reality, and file format processing may improve user experience, and decision-making for FM workers should be prioritized.

- Legal and Ethical Considerations: Investigate the legal and ethical implications of digital twins in asset management, especially regarding data privacy, liability, and ownership then develop guidelines and frameworks to address these concerns.

Each of these two areas of future research has a potential impact on improving asset management practices, reducing costs, enhancing sustainability, and addressing the challenges identified through the interviews conducted. In addition, the multidisciplinary nature of digital twin technology must be kept in mind as interdisciplinary research collaborations are required to effectively address complex asset management problems.

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Digital Twins (DTs) have emerged as a transformative innovation for asset management, especially in AEC/FM. This thesis explores DTs' applications in asset management, using a systematic literature review and interviews with FM professionals. The review found DTs offer potential for sustainable retrofitting, predictive maintenance, and heritage asset preservation. Interviews provided insights into FM challenges and future trends.

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