Development of a Framework for the Implementation of Digital Twin for Building Maintenance Management

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“*All our dreams can come true, if we have the courage to pursue them*”

- Walt Disney.

Abstract

Building maintenance (BM) is becoming increasingly challenging due to the overbearing complexity of maintenance-related issues, which result in continuous downtime of buildings and assets. The reoccurrence of issues such as design and construction flaws, the use of substandard materials, occupant misuse, and poor management practices have prompted BM organisations to explore proactive management strategies. Technologies such as Computerised Maintenance Management Systems, Building Information Modelling, and Computer-Aided Facility Management have been employed to address conventional error-prone manual procedures. However, these technologies have limitations, especially regarding real-time data updates, which are crucial for BM. Real-time data ensures the adequate availability of comprehensive information on buildings and assets. Digital Twin (DT), a recent technology, offers real-time data status and predictive capabilities through scenario analysis, thereby enhancing strategic planning and improving decision-making for BM management. However, implementing DT in BM organisations, both in developing and developed countries, presents challenges due to the non-availability of established literature. Therefore, this study explores how DT can be implemented at the organisational level for BM management, with a focus on Nigeria as a developing country, to provide contextual insights.

A sequential mixed research method was employed to collect primary data through closed-end questionnaires with BM experts in Nigeria, followed by semi-structured interviews with BM experts in Nigeria and DT experts from developed countries. A purposive sampling technique was employed to recruit participants for both research methods. Sixty-one expert BM professionals were approached for the preliminary quantitative survey, and questionnaires were distributed to them. A snowball sampling technique was subsequently employed to aid in recruiting eleven DT experts and nine BM professionals for the study interviews.

Findings revealed that maintenance-related issues in Nigeria stem from organisational dynamics, technical complexities, and user-related challenges. While Nigerian BM organisations are transitioning towards proactive strategies, substantial potential remains untapped in predictive strategies that can be achieved through DT. DT can assist BM organisations with activities such as building operations, user comfort, decision-making, operating costs, and fault prediction through various analyses, including performance, diagnostic, prognostic, and optimisation. Although these findings evidently reveal DT's capabilities for BM management, gaps exist between its technical and organisational implementation in literature, posing challenges.

To bridge this gap, the study employed the People, Process, and Technology (PPT) framework as a research lens to identify organisational requirements for DT implementation. These requirements include building owners/clients, maintenance teams, building professionals, and technical staff for the people dimension; workflow and data management for the process dimension; and organisational digitisation for the technology dimension. To connect these dimensions, the Generic Design and Construction Process Protocol was incorporated, which consequently shaped the study's developed framework.

The developed framework illustrates the interconnection among these dimensions in implementing DT for BM management. An expert focus group evaluated the framework, emphasising its usefulness and applicability for DT implementation in BM organisations. The study concluded that BM organisations should place a greater emphasis on the people and process dimensions, as the technology dimension is effective only when the other two dimensions are adequately structured, thus enabling seamless DT implementation. The research contributed both theoretically and practically, conceptualising DT for maintenance activities and providing a framework for a systematic practical DT implementation for BM organisations.

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Chapter One - Introduction

1.0 Introduction

This chapter introduces the study and is organised into the following major sections: It begins with a background of critical concepts such as building maintenance, digital twin, and the necessity for more strategic maintenance activities. It then presents the rationale and emphasises the overarching research question, aim, and objectives. Lastly, it outlines the study's scope and the thesis's structure.

1.1 Background of the Study

Building maintenance (BM) is recognised as a crucial aspect of the operation and maintenance (O&M) phase of a building. Its importance lies in preserving the building and its assets in their original and functional state, ensuring that they serve their intended purposes efficiently (Emoh and Ndulue, 2021). According to the British Standard Institute (BSI) (2011, p.5), BM is the *"combination of all technical, administrative and managerial actions during the lifecycle of a building (or a part of it), intended to retain it or restore it to, a state in which it can perform the required function"*. Hence, BM organisations are saddled with the responsibility of conducting these maintenance activities (Ismail and Motawa, 2019; Chanter and Swallow, 2007). Meanwhile, the O&M phase is recognised as the longest of a building's lifecycle and the most financially demanding when compared to other phases (Villa *et al.*, 2021). It accounts for about 60% of a building's total lifecycle cost, with maintenance procedures comprising approximately 50% of its management cost (Hodavand *et al.*, 2023; Ebekozien, 2021; Mourtzis *et al.*, 2017). In essence, the effectiveness of BM organisations in conducting maintenance activities can significantly reduce a building's operational and management costs.

Maintenance activities are often associated with signs such as building defects, which indicate faults or flaws in the design, construction, materials, or workmanship during the execution of a building, among other causes (Dahal and Dahal, 2020; Okuntade, 2014b). These defects may arise from errors, omissions, or flaws in the construction process and its subsequent usage (Ibitayo *et al.*, 2019; Aliyu *et al.*, 2016). Building defects can result in asset malfunctions that affect the well-being of occupants, necessitating serious intervention (Hodavand *et al.*, 2023; Hosamo *et al.*, 2022b). Studies have established that the complexities of maintenance-related issues, encompassing building defects that lead to maintenance activities, are a worldwide issue in both developed and developing countries, requiring extreme measures (Tan *et al.*, 2024; Fateh and Nikmat, 2023; Kung *et al.*, 2021; Mydin, 2016). In developing countries such as Nigeria, striving for continuous infrastructural development, poor BM managerial practices, inadequate building usage, non-adherence to policy, lack of technological adoption, and insufficient funding also contribute to maintenance-related issues that numerous studies have attempted to address (Emoh and Ndulue, 2021; Osuagwu *et al.*, 2021b; Aghimien *et al.*, 2019), yet persist, emphasising the need for further research.

In a move towards modernising maintenance activities through advances in technology and systems, studies have continued to explore avenues to assist BM organisations in addressing issues posed by conventional maintenance approaches, which largely rely on manual procedures flawed by errors, time wastage, data loss, and high maintenance costs (Kameli *et al.*, 2020; Peng *et al.*, 2020). Such approaches have been applied in areas including building defect detection (Chen *et al.*, 2019; Razali *et al.*, 2019), maintenance documentation (Kameli *et al.*, 2020; Ismail and Motawa, 2019), and maintenance requests (Lu *et al.*, 2020b; Peng *et al.*, 2020), among others. These issues create a need for a more comprehensive approach to managing maintenance activities (Dzulkifli *et al.*, 2021; Marocco and Garofolo, 2021).

Furthermore, the utilisation of systems and technologies such as Computerised Maintenance Management Systems (CMMS), Computer-Aided Facility Management (CAFM), Integrated Workplace Management Systems (IWMS), and Building Information Modelling (BIM) have been a useful approach for managing these maintenance activities (Hosamo *et al.*, 2022b; Ermenyi *et al.*, 2020; Kameli *et al.*, 2020; Mohanta and Das, 2016). While these systems and technologies have the potential to manage maintenance activities, challenges have been identified in their use, particularly regarding the real-time updating of data, which is crucial for managing BM complexities (Deng *et al.*, 2021; Madubuike and Anumba, 2021). To mitigate these issues, incorporating the Internet of Things (IoT), augmented reality (AR), virtual reality (VR), drones, and scanners, among others, alongside these systems and technologies, have helped improve BM management (Ermenyi *et al.*, 2020; Kameli *et al.*, 2020; Musa *et al.*, 2021; Villa *et al.*, 2021).

In recent years, exploring Digital Twin (DT) has garnered attention as a more effective solution to address this gap by offering real-time data status and scenario analysis for managing maintenance complexities (Hodavand *et al.*, 2023). DT encompasses the use of various technological innovations and devices, such as artificial intelligence (AI), IoT, AR, and VR, serving as an effective digital solution for managing maintenance activities (Sharma *et al.*, 2022). It acts as a data collection and integration platform for building sensors, maintenance records, and design models (Hosamo *et al.*, 2023a; Madubuike *et al.*, 2022). Consequently, buildings and their asset status can be monitored in real-time for effective BM management (Lu *et al.*, 2022). By employing DT, BM organisations can strategically transition from reactive to proactive maintenance by simulating building performance and predicting potential issues (Boje *et al.*, 2020). Thus, DT enhances the asset design process, execution, operation, and maintenance by incorporating data throughout its lifecycle (Jiao *et al.*, 2023; Hosamo *et al.*, 2022a).

In brief, DT is described as a virtual replica of a physical structure, system, or process with a bidirectional exchange of data (Pomè and Signorini, 2023; Bolton *et al.*, 2018). Its evolution can be traced back to the early 1990s when discussions on mimicking reality began (Singh *et al.*, 2022). DT has recently experienced progressive growth in both academia and industry as an effective solution for managing complex maintenance-related issues (Jiao *et al.*, 2023; Omrany *et al.*, 2023; Errandonea *et al.*, 2020). These issues stem from organisational inefficiencies due to insufficient documentation, data limitations from inadequate collection and storage, and a centralised data system, thus hindering effective data usage for making informed decisions about maintenance priorities and actions (Ebiloma *et al.*, 2023; Hosamo *et al.*, 2023b; Lu *et al.*, 2022; Mokhtari *et al.*, 2022). By leveraging DT, these issues can be managed by effectively integrating maintenance data, as it centralises data, ensuring BM professionals can access accurate and up-to-date data (Pomè and Signorini, 2023; Oliveira, 2020; Gerber *et al.*, 2019). Such an integration potential resolves challenges related to incomplete maintenance records and improves decision-making (Ebiloma *et al.*, 2023).

For predictive maintenance activities, DT can identify potential issues before they escalate, thereby reducing downtime and maintenance costs through real-time data and scenario analysis (Hosamo *et al.*, 2023a; Davies *et al.*, 2022; Hosamo *et al.*, 2022b; Mihai *et al.*, 2021). Additionally, BM organisations can collaborate effectively through DT, as it provides a shared platform for all stakeholders, reducing communication gaps and improving alignment on maintenance priorities (Omrany *et al.*, 2023; Marocco and Garofolo, 2022). Specifically, studies have investigated the effectiveness of DT in managing maintenance activities (Jiao *et al.*, 2023; Pomè and Signorini, 2023; Lu *et al.*, 2020a; Peng *et al.*, 2020; Lu *et al.*, 2019). Although these studies have evidently explored the potential of DT for maintenance activities, they fall short of establishing a sustainable avenue for its implementation, particularly at the organisational level (Broo *et al.*, 2022).

For a comprehensive approach to maintenance management, BM organisations need to be strategic in their practices through the use of DT. Such a need arises from their engagement in multidisciplinary activities, including technical, managerial, and administrative practices, to preserve buildings and assets in their initial functional state, ensuring they can efficiently serve their designated purposes (Emoh and Ndulue, 2021; BS 15331, 2011). Meanwhile, previous studies have established that poor organisational practices are among the leading causes of maintenance-related issues (Aghimien *et al.*, 2019; Ismail and Motawa, 2019; Olanrewaju and Abdul-Aziz, 2015), and if BM organisations optimise their practices using DT, other maintenance-related issues can be effectively managed (Jiao *et al.*, 2023; Pomè and Signorini, 2023).

For this reason, without further studies on utilising DT for organisational practices, little will be known about how BM organisations can implement it for maintenance management. Hodavand *et al.* (2023) emphasise that a clear roadmap and process for DT's implementation in organisations is necessary due to its complex setup. Bello *et al.* (2024) corroborate that understanding DT's potential is limited, particularly in developing countries, and understanding its perceived complexity and implementation barriers would assist organisations in utilising it. Therefore, this study aims to fill this gap by rationalising the implementation of DT to support BM organisations' maintenance activities, focusing on Nigeria as a developing country for contextual insights.

1.2 Statement of the Research Problem

The maintenance management of buildings is a worldwide issue that has been studied across various countries. Such studies have been conducted in both developing (Aghimien *et al.*, 2019; Onyili *et al.*, 2020; Osuagwu *et al.*, 2021b) and developed countries (Fateh and Nikmat, 2023; Pomè and Signorini, 2023; Dahal and Dahal, 2020; Lu *et al.*, 2020a), revealing a convergence in the types of maintenance challenges encountered; however, the approaches to managing these issues differ significantly across countries (Annunen *et al.*, 2024; Fateh and Nikmat, 2023; Bajic *et al.*, 2021; Osuagwu *et al.*, 2021b; Dahal and Dahal, 2020; Onyili *et al.*, 2020; Aghimien *et al.*, 2019). Studies have demonstrated that technologies and systems have the potential to assist BM organisations in managing maintenance-related issues (Marocco and Garofolo, 2021; Cheng *et al.,* 2020; Kameli *et al.,* 2020); nevertheless, they have certain limitations due to their static nature, which could be addressed using DT (D'Amico *et al.,* 2022; Marocco and Garofolo, 2022). Therefore, investigating how DT could support BM organisations in managing maintenance-related issues is crucial (Ebiloma *et al.,* 2023; Xie *et al.,* 2023), and understanding its implementation process is vital for effective utilisation (Elyasi *et al.*, 2023; Broo *et al.*, 2022; Gulewicz, 2022).

To investigate the potential of DT in supporting BM management, its implementation process could be explored from the perspective of a developing country, which would make the findings useful to both developing and developed countries. For this reason, Nigeria has been chosen, considering its status as a developing country where the adoption of technology is progressing, though at a gradual pace (Arowoiya *et al.*, 2024; Ebiloma *et al.*, 2023). In the past, technologies such as BIM have been underutilised; however, recent trends indicate an increase in its adoption among various organisations in Nigeria (Eromonsele, 2021; Olapade and Ekemode, 2018).

Therefore, this study focuses on maintenance-related issues within the Nigerian context due to organisational inefficiencies, data limitations, and insufficient utilisation of technological advancements, aiming to explore how DT can be effectively integrated to support BM organisations in the management of buildings and assets (Ebiloma *et al.*, 2023; Emoh and Ndulue, 2021; Aghimien *et al.*, 2019). The implementation of DT offers significant advantages, particularly its capability to provide real-time data updates and conduct scenario analyses, which are crucial for BM operations, capabilities that are often lacking in conventional systems and technologies (Hodavand *et al.*, 2023; Madubuike and Anumba, 2021). As maintenance activities become increasingly complex, dependence on static data stored in digital models such as BIM may be inadequate (Jiao *et al.*, 2023; Hosamo *et al.*, 2022b). In contrast, real-time data acquisition can equip BM organisations with richer informational resources for improved decision-making and strategic planning (Lu *et al.*, 2022; Deng *et al.*, 2021). Therefore, studying DT's implementation, especially at the organisational level, is important (Broo *et al.*, 2022).

Specifically in Nigeria, maintenance-related issues are persistent problems that necessitate effective management. Studies have attributed the causes of these issues to organisational-related causes (e.g., organisational practices and lack of maintenance policies) (Emoh and Ndulue, 2021; Osuagwu *et al.*, 2021a; Adeniyi *et al.*, 2020; Onyili *et al.*, 2020; Aghimien *et al.*, 2019; Faremi *et al.*, 2019) and building user-related causes (e.g., misuse of building assets and lack of a maintenance culture) (Ndulue and Ifeanyiemoh, 2021; Osuagwu *et al.*, 2021b; Izobo-Martins *et al.*, 2018; Aliyu *et al.*, 2016; Waziri and Vanduhe, 2013). Others include technical-related causes (e.g., faulty design and construction, as well as the use of substandard materials) (Lekan *et al.*, 2021; Chidi *et al.*, 2017; Ajetomobi and Olanrewaju, 2015; Olanrewaju and Anifowose, 2015; Okuntade, 2014a, 2014b), human-related causes (e.g., inexperienced maintenance personnel) (Emoh and Ndulue, 2021; Osuagwu *et al.*, 2021a; Aghimien *et al.*, 2019; Chidi *et al.*, 2017; Waziri and Vanduhe, 2013), financial-related causes (e.g., insufficient funds for maintenance) (Emoh and Ndulue, 2021; Osuagwu *et al.*, 2021a; Waziri and Vanduhe, 2013), and natural-related causes (e.g., wear and tear, and unforeseen circumstances) (Emoh and Ndulue, 2021; Aliyu *et al.*, 2016). Although these studies have examined various maintenance-related issues and underscored the necessity for effective BM management, clear avenues for managing these issues have been found to be lacking (Ebekozien, 2021; Aghimien *et al.*, 2019).

Moreover, several prominent issues recognised from these studies include faulty designs and poor construction materials, which cannot be rectified during building usage. Building users represent another serious cause of maintenance-related issues recognised, as their attitudes towards the use of building assets are often uncontrollable. For example, in office buildings, users may not adhere to guidelines for operating Heating, Ventilation, and Air Conditioning (HVAC) systems, lighting, or other utilities. Overriding automatic settings on HVAC systems or unnecessarily leaving lights on can result in increased wear and tear, energy consumption, and premature system failures (Adepoju *et al.*, 2017; Aliyu *et al.*, 2016). In managing these maintenance complexities, several studies have recommended adopting a more proactive maintenance strategy through the use of technological advancements for BM management (Ebiloma *et al.*, 2023; Ndulue and Ifeanyiemoh, 2021; Osuagwu *et al.*, 2021b; Aghimien *et al.*, 2019). In this context, few studies have attempted to manage some of these maintenance complexities with the integration of technological advancements such as CMMS, BIM, and Archibus (Musa *et al.*, 2021; Osuji *et al.*, 2020; Afolabi *et al.*, 2019). Although these studies have revealed the benefits and usefulness of technological advancements for maintenance activities, research on how these complexities could be effectively managed remains insufficiently explored.

Globally, studies have continued to explore avenues for utilising technological advancements and digital innovations to support BM management. These studies have focused on CMMS, CAFM, and BIM utilisation, among others (Ermenyi *et al.*, 2020; Ismail *et al.*, 2020; Kameli *et al.*, 2020; Ismail and Motawa, 2019; Ofide *et al.*, 2015). Despite the valuable assistance these technological advancements provide to BM organisations in their maintenance activities, challenges have been identified, particularly regarding real-time data updates that are crucial for BM. They often lack the capacity to effectively manage maintenance activities and complexities as standalone solutions. To mitigate these challenges, several studies have proposed the integration of digital innovations, such as big data analysis, IoT, cloud computing, and AI, among others, to enhance these technological solutions for effective maintenance management (Jiao *et al.*, 2023; Bouabdallaoui *et al.*, 2021; Villa *et al.*, 2021; Ruiz-Sarmiento *et al.*, 2020; McArthur *et al.*, 2018). Some studies emphasise that real-time monitoring of buildings and assets can significantly improve maintenance management (Villa *et al.*, 2021; Osuji *et al.*, 2020; Antonino *et al.*, 2019; McArthur *et al.*, 2018). Thus, it is evident from these studies that the incorporation of digital innovations for maintenance management makes its processes and activities seamless.

Furthermore, several studies recommend that DT, which encompasses different digital innovations such as IoT, AI, AR, and VR, have the potential to effectively manage maintenance-related issues, including maintenance documentation (Hosamo *et al.*, 2023b; Brunone *et al.*, 2021), maintenance requests (Lu *et al.*, 2022), and maintenance decision-making processes (Zhao *et al.*, 2022; Lu *et al.*, 2020a), among others. This potential is realised through asset monitoring, real-time data updates, and predictive capabilities enabled by scenario analysis. Essentially, BM organisations can now adequately monitor the utilisation of buildings and assets, allowing for effective maintenance strategies in their practices. Several studies have attempted to utilise DT as an effective digital solution for managing maintenance complexities. Such studies have focused on maintenance inspection (Coupry *et al.*, 2021; Lu *et al.*, 2020c), defect detection (To *et al.*, 2021; Zhang *et al.*, 2021a), anomaly detection (Xie *et al.*, 2023; Lu *et al.*, 2020b), data management (Lu *et al.*, 2020a; Peng *et al.*, 2020), and maintenance optimisation (Jiao *et al.*, 2023; Pomè and Signorini, 2023), among others. Although these studies reveal DT's substantial potential for managing maintenance complexities, its implementation process has been found lacking.

Meanwhile, some studies have attempted to explore how DT can be technically implemented by deploying various technologies (Broo *et al.*, 2022; Rassõlkin *et al.*, 2021; Lin and Low, 2019). However, the available literature indicates that there is no clear evidence regarding how DT can be implemented at the organisational level (Broo *et al.*, 2022). While technical implementation encompasses the technicality of deploying technology, organisational implementation addresses the organisational changes necessary for integrating technology within an organisation (Elyasi *et al.*, 2023; Lundell *et al.*, 2022; Ahmad and Rasid, 2021). Broo *et al.* (2022) argue that the organisational implementation of DT is as crucial as its technical implementation. Supporting this argument, a review by Arisekola and Madson (2023) underscores that most studies on DT have primarily focused on its technical implementation, creating confusion for its new users. These studies underline a knowledge gap and the necessity to unravel how DT can be implemented at the organisational level. Therefore, this study aims to fill this gap by exploring how DT can be implemented organisationally for the management of maintenance-related issues, using Nigeria as a focus.

Research Question:

Following the exploration of the research scope, the overarching research question this study addresses is:

- How can digital twin be implemented at the organisational level for building maintenance management, focusing on Nigeria to provide contextual insights?

1.3 Aim and Objectives

This study aims to develop a framework for the organisational implementation of digital twin for building maintenance management. It focuses on Nigeria as a developing country to provide contextual insights and an overarching view of building maintenance-related issues and management for organisations where maintenance activities are inadequate, using technologies and systems.

The specific objectives are to:

a) Identify the challenges of building maintenance management in Nigeria.

This objective seeks to understand the current challenges encountered in BM management in Nigeria, as well as the prominent issues and potential avenues for improvement. This will involve reviewing literature and collecting primary data through surveys with BM professionals. The analysis of data will result in an outcome categorising the prominent challenges of maintenance-related issues that hinder effective maintenance management.

b) Explore the current technologies and systems used for building maintenance management in Nigeria.

This objective focuses on investigating the current technological advancements in BM management in Nigeria. This will be achieved by reviewing literature and conducting surveys to collect data on the technologies and systems currently in use. The outcome will be a comprehensive overview that examines the effectiveness and support offered by these technologies and systems for BM management, thereby identifying areas where improvements or upgrades are necessary, such as the use of DT.

c) Explore the applicability of digital twin for building maintenance management.

Under this objective, the research will explore how DT has been utilised in BM management in other countries and identify its potential applicability in Nigeria. This will involve analysing existing studies to evaluate the benefits and limitations of DT. The expected result is an outcome that identifies how DT could support Nigerian BM practices, highlighting potential enhancements in efficiency, accuracy, and overall effectiveness.

d) Determine the organisational requirements for implementing digital twin for building maintenance management.

This objective seeks to identify the necessary organisational changes required to implement DT successfully. This includes analysing the need for adjustments in human resources, process re-engineering, and upgrades to technological infrastructures. By reviewing literature and consulting with both academic and industry experts, the research will produce a strategic implementation guide that outlines specific organisational requirements essential for implementing DT in BM management. The implementation guide will subsequently be used to assess the readiness of the BM organisation in Nigeria for DT implementation.

e) Develop a framework for the organisational implementation of digital twin for building maintenance management.

This objective seeks to develop a practical and actionable framework that BM organisations can systematically adopt to implement DT effectively. The framework will be developed based on best practices and industry standards, detailing each phase of implementation, key activities, stakeholder roles, and metrics for monitoring progress. The outcome will be a comprehensive implementation guide, facilitating a smooth transition to DT-supported maintenance management.

f) Evaluate the developed framework for its applicability to support building maintenance management.

This objective seeks to evaluate the developed framework and determine its efficacy and applicability in supporting BM management. The evaluation will be carried out through a focus group discussion session, assessing the framework using some organisational implementation metrics. Feedback will be elicited from participants involved in the focus group session. This evaluation will help identify gaps or shortcomings in the framework and provide valuable insights into its practical implementation challenges and benefits.

1.4 Scope of the Study

DT is a relatively recent technology compared to other AEC digital technologies. Hence, this study focuses on identifying the organisational requirements for implementing DT for BM organisations. The context of this study is Nigeria, as it is a developing country, and the findings derived can be useful in other developing and developed countries for DT implementation.

1.5 Thesis Outline

This study is organised into eight chapters: introduction, literature review, methodology, presentation and discussion of results, framework development, and conclusion. Chapter one presents the background of the study, the statement of the research problem, the overarching research question, the aim and objectives, and the scope of the study. Chapter two reviews the literature on building maintenance management and its related concepts, followed by empirical studies on the causes of maintenance-related issues. Next, chapter three reviews the literature on DT and its related concepts, followed by empirical studies on the application of DT for BM activities, its development processes, and the research lens to guide the study.

Chapter four discusses the methodology of the study, including the research philosophy, design, and data collection methods.

Chapter five presents the results of the quantitative data and analyses them in relation to research objectives one and two. The discussions of the results reference the literature review in chapter two. Chapter six presents the results of the qualitative data, followed by its thematic analysis in relation to research objectives one, two, three, and four. The discussions of the results also reference the literature reviews in chapters two and three. Next, chapter seven discusses the development of the study's framework. The concluding chapter, which is eight, summarises the study's findings in relation to its aim and objectives and then highlights the research limitations and contributions to knowledge.

1.6 Summary

This chapter introduces the purpose of the study. It begins with the background of BM, the causes of maintenance-related issues, and the need for a more strategic approach to managing them using DT. Next, the chapter presents the statement of the research problem and question, followed by the study's aim, objectives, and scope. The chapter concludes with an outline of the thesis.

Chapter Two – Literature Review on Building Maintenance

2.0 Introduction

The review of the literature focuses on maintenance, specifically in the built environment. In conducting a narrative literature review for this chapter, a systematic search is employed to ensure comprehensiveness and relevance. Relevant literature is sourced from journals on maintenance management and related fields. Academic databases such as Scopus, Web of Science, JSTOR, IEEE Xplore, and Google Scholar are searched using targeted keywords, such as "Building Maintenance", "Facility Management", "Maintenance Operations", "Asset Management", "Systems in Maintenance", "Digital Technologies in Maintenance", and "Building Maintenance Management or Practices". The review focuses on peer-reviewed literature and documents from 2000 to 2024, emphasising works relevant to BM in both developing and developed countries, with a spotlight on Nigeria. Forward and backward searches are further employed to identify more literature, ensuring that relevant literature is reviewed. Inclusion criteria ensure sources directly address the research objectives, while exclusion criteria filter out unrelated studies and those not written in English.

The process includes an initial screening of titles and abstracts, full-text reviews, and critical analysis to identify relevant trends and gaps. The review aims to pinpoint the gaps present in previous studies that this study seeks to address. This chapter is divided into the following major sections. First, it examines the historical evolution of maintenance. Second, BM and related concepts are explored. The last section provides information on Nigeria's maintenance situation and establishes the need for this study.

2.1 History of Maintenance

Maintenance can be traced back to the early days of the Bible, when God instructed Adam to tend to and maintain the Garden of Eden. Currently, a wide range of research has focused on maintenance. Figure 2.1 illustrates that maintenance research has spanned over 80 years, with a gradual progression towards the use of digital technologies.

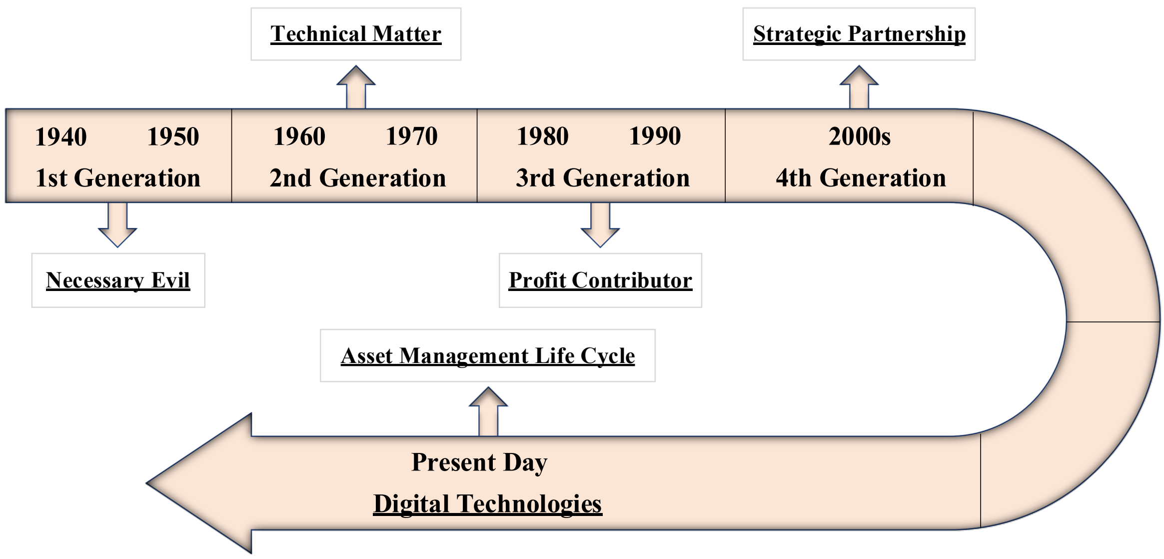


Figure 2.1: Evolution of Maintenance (Adapted from Jiao *et al.*, 2023; Ruiz-Sarmiento *et al.*, 2020; Kobbacy and Murthy, 2008; Moubray, 1997)

The first generation (1940s and 1950s) of maintenance activities revolved around the principle that if a system is functioning, there is no need to repair it (Pintelon and Parodi-Herz, 2008). All maintenance procedures during this era were corrective and took place only after the breakdown or failure of a system or asset (Kobbacy and Murthy, 2008). This approach typically led to unavoidable costs associated with repairing malfunctioning or broken systems. Consequently, this generation can be referred to as the era of a necessary evil, as all maintenance activities centred on repairing broken-down systems (Pintelon and Parodi-Herz, 2008).

The second generation (the 1960s and 1970s) witnessed a transition in maintenance activities from corrective to preventive maintenance. Maintenance organisations observed that certain mechanical system breakdowns resulted from age-related fatigue and usage (Pintelon and Parodi-Herz, 2008). These observations prompted them to adopt precautionary measures for mechanical systems by establishing scheduled maintenance plans aimed at reducing costs and extending the lifespan of these systems. While this led to a reduction in system failures, unnecessary maintenance issues arose due to a lack of understanding of failure patterns and limited data on the systems. As a result of these issues, maintenance activities began to incorporate statistical methods to gain insights into the operating conditions of systems and assets.

In the late 1970s, various methodologies were developed to provide technical maintenance management solutions through science, engineering, and statistics, aiming to prevent the over-maintenance of systems and assets stemming from preventive practices (Kobbacy and Murthy, 2008; Pintelon and Parodi-Herz, 2008). These practices initiated a progressive transition from preventive to predictive and condition-based maintenance. For example, industries such as aviation reaped the benefits of the technical solutions linked to predictive maintenance, which facilitated the introduction of the Boeing 747 (Pintelon and Parodi-Herz, 2008). In the early 1980s, industries such as manufacturing started to leverage predictive maintenance strategies as monitoring equipment became more affordable and accessible (Ahmad and Kamaruddin, 2012; Pintelon and Parodi-Herz, 2008).

The third generation (1980s and 1990s) of maintenance management is characterised by a general increase in system lifespan, reliability, performance, and quality. During this era, awareness regarding maintenance risk became critical (Brown and Sondalini, 2015). Consequently, organisations like Shell and DuPont established strategies focusing on life cycle engineering development, encompassing the analysis of design, construction, operation, maintenance, and demolition costs (Kobbacy and Murthy, 2008; Pintelon and Parodi-Herz, 2008). The goal of these strategies was to enhance systems' availability, reliability, performance, quality, and safety. As a result of this development, organisations began establishing specialised offices to address maintenance activities at the early stages of system design and commissioning (Pintelon and Parodi-Herz, 2008). This transition resulted in an internal recognition of maintenance activities as profit contributors. During the 1990s, the United Kingdom (UK) government established 'The Institute of Asset Management' to promote best practices and knowledge concerning cohesive and strategic maintenance of systems (Brown and Sondalini, 2015).

The fourth generation of maintenance activities ushered in the adoption of various technological innovations (Industry 4.0). These innovations encompassed big data processing, AI, IoT, and cloud computing, among others (Jiao *et al.*, 2023; Ruiz-Sarmiento *et al.*, 2020). Studies indicate that the implementation of these technologies has enhanced predictive maintenance activities (Jiao *et al.*, 2023; Bouabdallaoui *et al.*, 2021; Mihai *et al.*, 2021; Lu *et al.*, 2020b). These technologies are employed in diagnostic and prognostic analysis, cost optimisation, and intelligent decision support systems, among other applications. Consequently, the reliability of systems improved, resulting in reduced costs and a robust return on investment (Gustavsson *et al.*, 2014; Al-Najjar, 2012). While these technologies have the potential to refine maintenance strategies and practices, challenges related to the reoccurrence of maintenance activities persist.

In summary, the evolution of maintenance management has been marked by an upward trajectory, reflecting not just a trend but a significant transformation in how organisations approach asset reliability and operational efficiency. Initially, maintenance was reactive, characterised by simple repairs as issues arose (first generation). This approach evolved into preventive maintenance, where regular inspections aimed to prevent issues before they occurred (second generation). As the field matured, the focus shifted to condition-based maintenance, utilising comprehensive data to address issues as they emerged, thereby optimising resources and minimising downtime (third generation). With advancements in technology, predictive maintenance gradually became prevalent, employing advanced analytics and machine learning to anticipate potential failures before they occur, and ensuring maximum equipment effectiveness (fourth generation). This historical progression highlights a journey towards increased sophistication in maintenance strategies, driven by the need for efficiency and cost-effectiveness in increasingly complex environments. Moreover, in recent years, the integration of digital technologies has revolutionised maintenance practices, enabling organisations to function with precision and foresight for improved management of asset life cycles (Figure 2.1). This evolution not only enhances reliability but also signifies a broader transition towards proactive management in today's dynamic maintenance landscape.

2.2 Definition of Building Maintenance

BM is a branch of maintenance that focuses on preserving and optimising building facilities, assets, and systems (Dahal and Dahal, 2020). Moreover, a building is a structure consisting of interconnected components, such as walls, roofs, doors, and windows, alongside mechanical and electrical systems. It requires maintenance to ensure comfort and convenience for its occupants (Drobnyi *et al.*, 2023; Osuagwu *et al.*, 2021b). Therefore, to understand BM properly, it is crucial to comprehend what maintenance entails. According to Imai (1997, p.3), maintenance encompasses "*activities directed toward maintaining current technological, managerial and operating standards and upholding such standards through training and discipline*". In addition, BS 3811 (1984) highlights that maintenance is a combination of activities conducted to sustain or restore an asset/system to its functional state. Ajetomobi and Olanrewaju (2015) corroborate that maintenance preserves an asset's qualities and extends its lifespan for optimal performance. It can be inferred that maintenance management involves both the physical execution of maintenance activities and the initial planning alongside financing processes. Thus, the primary aim of maintenance management is to optimise an asset/system life cycle, which pertains to safety, availability, functionality, and reliability (Pintelon and Parodi-Herz, 2008).

Similar definitions of BM are presented in the literature, most of which revolve around those provided by the BSI (Bouabdallaoui *et al.*, 2021; Emoh and Ndulue, 2021; Aghimien *et al.*, 2019; Chua *et al.*, 2018; Waziri and Vanduhe, 2013; Hamid *et al.*, 2007) and Chartered Institute of Building (CIOB) (Yasin *et al.*, 2019; Hamid *et al.*, 2007). According to BSI EN 15331 (2011, p.5), BM is defined as the "*combination of all technical, administrative and managerial actions during the lifecycle of a building (or a part of it), intended to retain it, or restore it to, a state in which it can perform the required function*". Additionally, maintenance activities incur certain costs and resource implications. In this context, CIOB (1990) defines BM as the work undertaken to maintain, restore, or enhance every facility or part of a building, including its services and surroundings, to an agreed-upon standard determined by the balance between need and available resources.

It can be inferred from both definitions that BM management is essential for preserving a building and its assets or systems. This includes recognising a building as a tangible asset, the necessity for its continuous preservation, effective collaboration among all BM stakeholders, and adequate financial management of maintenance activities. However, a slight variation exists between the two definitions; the BSI definition places greater emphasis on performance and functionality, whereas the CIOB focuses on balancing needs and resources.

Furthermore, some researchers have defined BM according to certain parameters. To identify and select these definitions beyond those provided by the BSI and CIOB, a forward and backward search approach is employed. Initially, a comprehensive literature review is conducted across key academic databases mentioned in Section 2.0 to gather a range of definitions. These definitions are then evaluated against strict inclusion and exclusion criteria, focusing on source credibility, relevance, and specificity. This rigorous selection process aims to ensure diverse representation of perspectives within the field. Ultimately, six definitions are selected based on their relevance to the research context, their ability to provide distinct insights, and their contribution to a refined understanding of BM management. Table 2.1 summarises these definitions.

Table 2.1: Summary of Some Definitions of Building Maintenance

Authors	**Definition**	**Keywords**
Arumsari *et al.* (2021)	BM encompasses all activities that enhance the functionality and restoration of building facilities' reliability.	Functionality, restoration, and reliability
Plebankiewicz and Gracki (2021)	Building maintenance encompasses any activity that guarantees a structure remains both visually appealing and technically robust throughout its lifecycle.	Aesthetic and technical
Pratama *et al* (2020)	BM refers to activities that ensure a building asset is reliable and functional.	Functionality and reliability
Chen and Tang (2019); Yasin *et*	BM refers to any action undertaken on a building asset to restore or maintain it in an acceptable condition	Restoration and performance

al. (2019)	for adequacy performance.	
Puķite and Geipele (2017)	BM refers to any activity that involves restoring and improving a building asset to enhance its performance and maintain the overall value of the building.	Restoration, improvement, performance, and preservation
Wood (2009)	BM involves maintaining or restoring a system to a certain standard of usable acceptability.	Restoration and acceptability

Drawing inferences from Table 2.1, BM encompasses any activities that assist in the restoration of building assets or systems aimed at enhancing performance, functionality, and reliability. Despite the similarities in these definitions, Chudley (1981) argues that maintenance is an action to prevent a repair (restoration) and not the misconception that it corresponds to repair. Eti *et al.* (2006) corroborate that maintenance is focused on preserving and keeping the condition of an asset in good condition. Therefore, this study defines BM as a process that incorporates all administrative and technical procedures to manage, enhance, and retain the functional capabilities of a building and asset/system lifecycle (BS 15331, 2011), thereby improving its performance, value, and reliability (Arumsari *et al.*, 2021; Puķite and Geipele, 2017). This definition stems from the understanding that buildings and assets/systems require periodic monitoring to avert total breakdown due to excessive use, which leads to repairs and unplanned costs.

2.3 Importance of Building Maintenance

The importance of BM is numerous and cannot be overlooked. Firstly, BM supports the preservation and enhancement of buildings and systems to ensure their effective functioning. For example, BM improves the appearance of building fabric by preventing its deterioration (Osuagwu *et al.*, 2021b). Osuagwu *et al.* (2021a) emphasise that BM is an operational strategy for organisations and building owners to preserve their properties and facilities in order to achieve their goals and objectives. In essence, building owners or organisations should ensure the adequate maintenance of their buildings and assets, as this is an operational strategy that optimises their preservation.

Economically, BM reduces the need for major repairs or restorations of building systems. In some cases, restoring systems such as lifts and HVAC can be more costly than maintaining them (Chanter and Swallow, 2007). According to Mydin (2016), appropriate monitoring and maintenance management of building assets minimises or prevents unforeseen substantial repairs. Therefore, such maintenance management can economically sustain building assets and systems in the long term.

In terms of safety, adequate maintenance ensures the protection of building users and their assets. For example, maintaining fire installations in buildings is critically important. Fire safety installations, such as fire doors, extinguishers, hydrants, and smoke detectors, among others, must be readily available at standard levels to ensure the safety of the buildings and their users (Arumsari *et al.*, 2021). Thus, BM activities are vital for the long-term viability of buildings and assets, and the strategy adopted is crucial to their success (Chua *et al.*, 2018).

2.4 Types of Maintenance

Maintenance is categorised into several types in literature. For example, Djonli *et al.* (2020) categorise them as corrective, condition-based, preventive, and predictive maintenance.

Similarly, Chua *et al.* (2018) divide them into proactive, preventive, corrective, predictive, and emergency maintenance. BS 3811 (1984) classifies maintenance into planned (preventive, scheduled, and condition-based) and unplanned (corrective and emergency). While these studies have labelled maintenance approaches into various categories, they all fall under planned or unplanned maintenance strategies (Chua *et al.*, 2018). Therefore, this study defines these maintenance strategies based on BS 3811 (1984).

• Planned maintenance: This is an organised type of maintenance carried out using a well-thought-out process, with records and documents used in performing the maintenance.

• Preventive maintenance: This is carried out at predetermined intervals, based on specific criteria, aimed at reducing the likelihood of failure or performance degradation of an asset.

• Condition-based maintenance: This is executed with the anticipation that a system will degrade based on observed evidence.

• Scheduled maintenance: This type of maintenance is conducted according to an established routine schedule.

• Unplanned maintenance: This is undertaken without any predetermined plan and is the opposite of planned maintenance.

• Corrective maintenance: This is carried out after a fault has been identified, with the aim of restoring an asset or system to a condition where it can fulfil its required function.

• Emergency maintenance: This is an unforeseen task conducted to avert an asset's total failure and prevent serious consequences.

Figure 2.2 illustrates these different maintenance types. Figure 2.3 elaborates on how to choose the appropriate maintenance strategy for a specific maintenance activity.

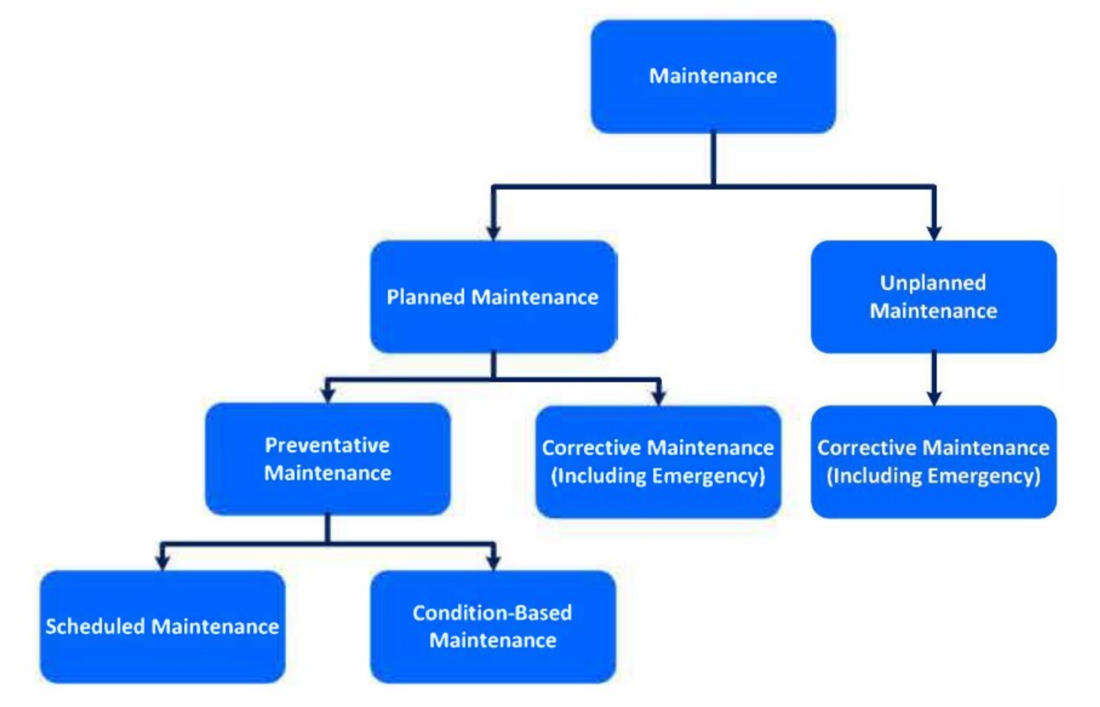


Figure 2.2: Types of Maintenance Strategies (Chanter and Swallow, 2007)

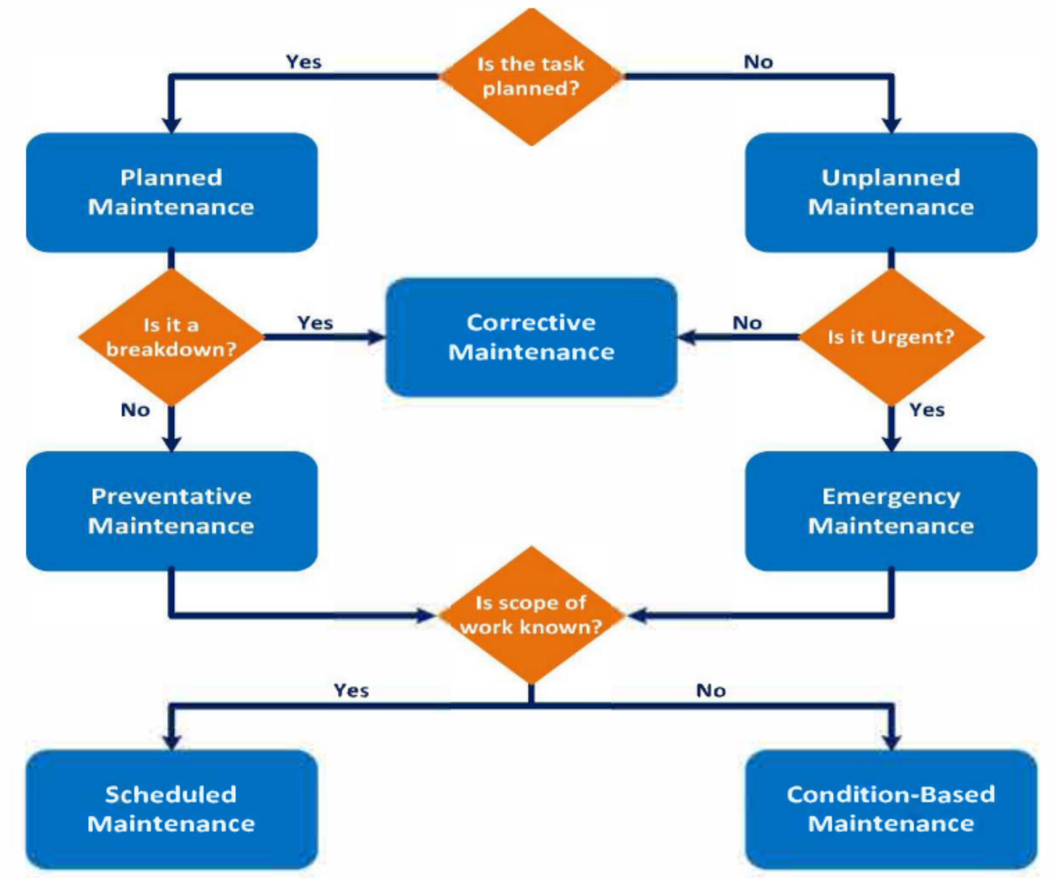


Figure 2.3: Decision-based Types of Maintenance (Chanter and Swallow, 2007)

2.5 Building Maintenance Organisations, Processes, and Stakeholders

BM organisations engage in multi-disciplinary activities, such as technical, managerial, and administrative functions, to preserve buildings and assets in their original functional state, thereby efficiently serving their designated purposes (Emoh and Ndulue, 2021; BS 15331, 2011). The processes that BM organisations adopt for maintenance activities are crucial to their operational success (Musa *et al.*, 2021). According to studies, the management of maintenance activities is fragmented and complex (Bortolini and Forcada, 2020; Wetzel and Thabet, 2015). Hence, a well-mapped-out process and the involvement of relevant stakeholders are vital in addressing this issue (Wong *et al.*, 2018; Au-Yong *et al.*, 2017). Meanwhile, Corrie (2004, p.3) defines a process as a "*set of interrelated or interacting activities which transform inputs to outputs*". The use of a process by BM organisations ensures that maintenance activities are structured to achieve the organisational objectives for a particular task (Annunen *et al.*, 2024; Ermenyi *et al.*, 2020). Chanter and Swallow (2007) point out that BM organisations rely on their BM department for the technical skills and expertise necessary for managing maintenance activities. Thus, adequate processes and guidelines are required for BM organisations to optimise their operations comprehensively.

A maintenance planning process is crucial for maintenance activities. As highlighted by BS 8210 (2012), the maintenance planning process commences with a clear definition of the asset requirements, as well as service delivery, performance requirements, asset audits, maintenance scope identification, maintenance strategy selection, assessment of resource needs, maintenance plan preparation, formulation of a delivery plan, provision of maintenance resources, implementation of maintenance, and ultimately concludes with the performance assessment of the work to be conducted. Figure 2.4 illustrates this process. Therefore, maintenance activities need to follow a suitable process established by the maintenance team or stakeholders to achieve optimum performance and mitigate the reoccurrence of maintenance-related issues.

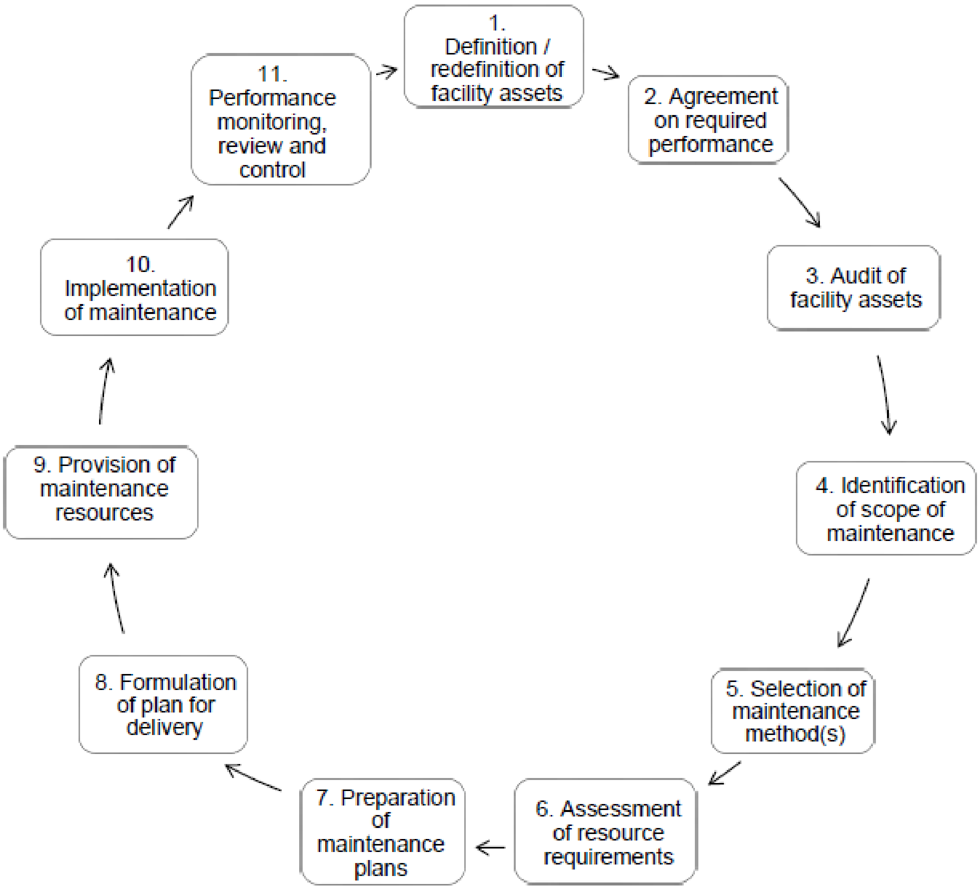


Figure 2.4: Maintenance Planning Process (Adopted from BS 8210, 2012)

Furthermore, BM organisations consist of team members and stakeholders (managers, in-house staff, and contractors) who are responsible for conducting maintenance activities (Olanrewaju and Abdul-Aziz, 2015; Kobbacy and Murthy, 2008). Yik *et al.* (2010) highlight that work orders and approvals affect the overall performance of maintenance activities, varying according to project scope and organisational practices. While BM organisations strive to preserve buildings and assets, other stakeholders, such as the building owner/client and building user, play a crucial role in executing maintenance activities (Au-Yong *et al.*, 2017; Hua *et al.*, 2005). The attitudes and commitments of these stakeholders greatly influence the processes and execution of maintenance activities. Thus, proper communication and coordination among these stakeholders are essential to achieving the deliverables of BM management (Au-Yong *et al.*, 2017). It is, therefore, imperative to highlight the distinct roles of these stakeholders in maintenance activities.

The building owner is the primary coordinator of any BM operations and significantly influences the propagation of maintenance activities (Ali *et al.*, 2006). Such coordination concerns the final approvals and performance monitoring of maintenance tasks. According to Chanter and Swallow (2007), the building owner leads the maintenance management team, communicating the work scope, resources, and budgets to the team. However, resource and budget constraints have occasionally posed challenges for building owners, as they favour lower quotations at the expense of quality work (Ogunbayo *et al.*, 2022; Ali *et al.*, 2002). As a result, contractors may engage incompetent subcontractors or unskilled personnel to undertake maintenance activities, leading to numerous maintenance and ethical issues (Abisuga *et al.*, 2017; Hua *et al.*, 2005). In an effort to mitigate the acceptance of low quotations, De Silva *et al.* (2004) argue that maintenance activities should be assessed based on the lifecycle cost rather than the initial cost. Therefore, building owners need to establish a proper maintenance work policy for transparency, which can be achieved with the assistance of a maintenance manager (Chanter and Swallow, 2007).

The maintenance manager oversees all maintenance operations and is responsible for planning, budgeting, and managing all aspects of BM complexities (Au-Yong *et al.*, 2017). This individual is experienced in BM management and works directly with the maintenance department of any establishment or building owner to coordinate plans and resolve maintenance issues (Kobbacy and Murthy, 2008). The maintenance manager’s duties include conducting meetings involving all stakeholders and auxiliary personnel to brainstorm effective approaches to managing maintenance-related issues (Au-Yong *et al.*, 2017). Thus, the maintenance manager's responsibilities are vital to the success of BM management.

The maintenance staff consists of personnel who carry out maintenance activities, either as in-house employees or contractors (service providers) (Olanrewaju and Abdul-Aziz, 2015). On one hand, the maintenance staff are based within an organisation and function under the supervision of a maintenance manager, ensuring that maintenance activities are executed within a defined budget (Au-Yong *et al.*, 2017). However, the lack of technical skills and expertise often presents a major barrier to the execution of maintenance tasks by these staff members (Au-Yong *et al.*, 2017). Kangwa and Olubodun (2004) corroborate that the inability of maintenance staff to detect avoidable mistakes made during maintenance operations indicates incompetence. To mitigate this issue, Hauashdh *et al.* (2020) suggest that staff participation in regular and relevant training workshops will enhance their technical skills and expertise. Thus, the maintenance staff are the field executors of maintenance activities in BM organisations.

On the other hand, a building owner or organisation may consult contractors to provide specific maintenance services that the in-house maintenance staff cannot perform. According to Au-Yong *et al.* (2017), maintenance activities undertaken by contractors are likely to prolong the lifespan of equipment due to their expertise. However, Osuagwu *et al.* (2021a) argue that contractor-executed maintenance activities have issues, such as using substandard materials to cut costs, thereby undermining the overall purpose of the activity. Ali *et al.* (2002) underscore that in maintenance activities, while building owners seek to conserve costs, contractors aim to maximise profit. For this reason, a proper assessment is necessary after a contractor completes maintenance work (Au-Yong *et al.*, 2017).

Furthermore, users are the individuals who utilise a building and its facilities daily to achieve their tasks (Au-Yong *et al.*, 2017). Their cooperation is crucial for the effective performance of any maintenance activity. Such cooperation pertains to their behaviour in using building assets and the timely reporting of maintenance-related issues (Almarshad *et al.*, 2010). Douglas (1996) emphasises that users' misuse of building facilities hinders the actual performance of a building. Although building users may impede the efficiency of building assets, their feedback is vital for effective maintenance management (Au-Yong *et al.*, 2017). This feedback aids in understanding their behaviour when using a building asset and evaluating the efficacy of any maintenance activities provided. Myeda *et al.* (2011) suggest that BM organisations should encourage building users to voice their opinions, as this serves as a checkpoint for maintenance personnel's performance on executed tasks. Thus, building users play a crucial role in evaluating maintenance activities, both positively and negatively.

In summary, it can be deduced that the processes adopted by BM organisations and various stakeholders of BM management, such as clients and maintenance teams, contribute positively or negatively to the overall performance of any maintenance activity. While building owners or maintenance organisations strive to conserve costs, contractors aim to maximise profit, and building users may misuse building assets, thereby complicating the effective management of maintenance activities. Therefore, all stakeholders need to be proactive in mitigating the reoccurrence of maintenance-related issues.

2.6 Building Maintenance Sector in Nigeria

The BM sector in Nigeria has been engaged in a variety of activities over the years, as the O&M stage is the longest in a building's life cycle, overshadowing other stages (Aghimien *et al.*, 2019). The maintenance of a building constitutes approximately 50% of its operational or management costs (Ebekozien, 2021; Abdul Lateef *et al.*, 2011). Therefore, adequate monitoring and maintenance of a building and its assets are crucial. Nigeria's National Building Code (NBC) (2006), a regulatory guide for building projects, specifies certain requirements for the maintenance of buildings. These include a certificate of fitness for habitation, as-built drawings, a BM manual, and a building condition survey report. Emoh and Ndulue (2021) point out that these requirements support maintenance activities in preserving a building and its assets in their initial and functional state to serve their intended purpose efficiently. However, certain factors hinder BM activities. According to Osuagwu *et al.* (2021a), the lack of adequate funding is one of the major contributors to poor BM activities in Nigeria. Supporting this view, the United Nations researches countries' per capita income rates, identifying Nigeria as the fifty-seventh poorest country (UNDESA, 2022).

Furthermore, the government's nonchalant attitude towards maintaining public buildings has led to issues such as the deteriorating condition of structural defects and decorative damages (Ajetomobi and Olanrewaju, 2015). Such issues arise because authorities prefer to allocate enormous amounts of money to construct new buildings rather than to maintain existing ones (Ogunbayo *et al.*, 2022). Adeniyi *et al.* (2020) underscore that this phenomenon stems from corruption, as funds are not available for the maintenance of existing buildings compared to new constructions. To address this issue, a more proactive and technical approach will reduce the financial bottlenecks associated with maintenance activities (Emoh and Ndulue, 2021; Osuagwu *et al.*, 2021b; Waziri and Vanduhe, 2013). Thus, examining other causes that lead to the reoccurrence of maintenance activities in Nigeria is imperative.

2.6.1 Causes of Maintenance-related Issues

There are numerous causes of maintenance-related issues that lead to BM reoccurrences and activities. Adepoju *et al.* (2017, pp.18–19) categorise these causes as "*building characteristics (location and age), technical (design, materials, workmanship, and construction methods),* *the building user (wilful damages, vandalism, and overpopulation), biological (bacteria or fungi attack), and climate/weathering (radiation, rain, temperature and air constituents)"*. While human activities impact the technical and user-related causes (Waziri and Vanduhe, 2013), biological and weathering factors are associated with natural occurrences (Aliyu *et al.*, 2016). Therefore, it is imperative to investigate the human-induced root causes of the reoccurrence of BM, particularly in Nigeria.

Some studies have attempted to evaluate the causes of maintenance-related issues arising from poor BM practices in certain building contexts. For example, Aghimien *et al.* (2019) examined BM practices in tertiary institutions, and Osuagwu *et al.* (2021a) evaluated BM practices in public buildings. The findings from these studies indicated that factors such as management, usage, staff inexperience, communication among staff, building design, building materials, policies, and funding contribute to poor BM practices. Additionally, Faremi *et al.* (2019) investigated the factors influencing the practices of insourcing and outsourcing maintenance services in universities. The results showed that management influences the insourcing of maintenance activities by in-house maintenance staff, whereas contractors are engaged for specialised maintenance tasks. Regarding insourcing maintenance services, Onyili *et al.* (2020) assessed BM practices in public institutions, and their findings revealed that management approval for building inspections was the primary barrier to effective BM practices. Therefore, these studies (Table 2.2) suggest that the managerial aspect of maintenance activities is central to their effective management.

Furthermore, Emoh and Ndulue (2021) examined the managerial strategies employed for maintaining hostel buildings. The study revealed a poor maintenance culture, insufficient funding, a lack of a functional operational framework, skilled maintenance personnel, and unfavourable climatic conditions were responsible for poor BM management. Osuagwu *et al.*

(2021b) explored the maintenance issues of public buildings, indicating that the poor maintenance culture among building users and management regarding plumbing systems, walls, and ceiling finishes were the prominent maintenance-related challenges. Thus, it can be inferred from these studies that a poor maintenance culture, which is an attitudinal issue, significantly contributes to the reoccurrence of maintenance activities.

Moreover, the absence of an appropriate maintenance culture represents a major attitudinal problem in Nigeria (Adeniyi *et al.*, 2020). Aliyu *et al.* (2016) observe that the "I do not care" attitude is a deeply entrenched mindset affecting the average Nigerian. This detrimental attitude has manifestly resulted in the deterioration of buildings. Some studies have attempted to investigate the factors responsible for the poor maintenance culture in buildings. For example, Chidi *et al.* (2017) examined the maintenance culture of public buildings. The study revealed that maintenance personnel lacked a formal organisational structure in their tasks and recommended that architects provide their clients with "Maintenance-Free Buildings." Similarly, Lekan *et al.* (2021) evaluated the maintenance culture of building occupants in a low-cost housing estate. The study discovered that the use of substandard materials contributed to defects in building assets. Likewise, Waziri and Vanduhe (2013) assessed building users' perceptions of maintenance-related issues. The study revealed that faulty design, workmanship, and substandard materials significantly contributed to such issues. From these studies (Table 2.2), it can be inferred that the incompetence of building professionals is a key factor leading to the deplorable state of buildings.

Table 2.2: Factors Responsible for Maintenance-Related Issues in Nigeria

Causes	Emoh and Ndulue (2021)	Lekan *et al.* (2021)	Ndulue and Ifeanyie moh (2021)	Onyili, *et al.* (2020)	Osuagwu *et al.* (2021a)	Osuagwu *et al.* (2021b)	Aghimien *et al.* (2019)	Ibitayo *et al.* (2019)	Faremi *et al.* (2018)	Izobo-Martins *et al.* (2018)	Chidi *et al.* (2017)	Olanrewaju and Anifowose (2015)	Okuntade (2014a)	Okuntade (2014b)	Waziri and Vanduhe (2013)	Aliyu *et al.* (2016)
Management																
Organisational practices	X		X	X			X		X	X						
Substandard building materials		X				X						X	X	X	X	
lack of maintenance policy						X	X		X							
Technical																
Maintenance consideration at the design stage							X	X			X			X	X	
Faulty construction								X					X	X		
Use of poor-quality assets / faulty procurement												X		X		

Human resources																
Inexperienced maintenance personnel	X					X	X				X				X	
Financial																
Insufficient funds to maintain buildings	X					X									X	
Building user																
Misuse of building assets					X											X
Lack of maintenance culture	X	X			X											
Others																
Wears and tears due to the constant usage																X
Natural factors from unforeseen circumstances	X															X

Buildings need to be in good condition to be habitable for their users. Therefore, adequate maintenance is essential for them to remain habitable. In this context, Ugwu *et al.* (2018) examined the maintenance status of public buildings concerning defects and decay. The study revealed that the condition of the building assets was deplorable. Such a deplorable condition results from various factors, including faulty designs, substandard building materials, poor managerial practices, and occupants' attitudes toward using the assets. Consequently, some studies have attempted to uncover the root causes of this deplorable condition of buildings. For example, Ibitayo *et al.* (2019) assessed the factors that hinder the effective maintenance of public buildings, which led to defects. The study emphasised that faulty design and construction are the primary hindrances to BM. This study substantiated Okuntade's (2014a, 2014b) findings, which explored the potential effects of faulty design and construction on maintenance activities. Although these studies highlighted that the severity of defects could be attributed to faulty design and construction, with non-compliance to specifications as the main cause, other factors also contribute to building defects. Therefore, Olanrewaju and Anifowose (2015) investigated the challenges of BM, which include physical inspection and defect identification. Their study revealed that poor building materials were a significant cause of these defects.

Regarding the deplorable state of buildings due to usage, Aliyu *et al.* (2016) examined the problems and prospects of maintenance management in hospital buildings. Similarly, Ndulue and Ifeanyiemoh (2021) explored the factors affecting the effective maintenance of hostel buildings. These studies found that users' misuse of building features, normal wear and tear, and natural factors arising from unforeseen circumstances and building abandonment were among the primary causes of maintenance-related issues. Although building users were identified as key contributors to the deplorable condition of buildings, their feedback on the state of these buildings is crucial for effective maintenance management. In this context, Izobo-Martins *et al.* (2018) examined users' perceptions of the deplorable physical state of public school buildings. The study highlighted that the management's nonchalant attitude toward BM management significantly contributed to the poor condition of the buildings. Based on these findings, BM organisations need to be proactive in their maintenance activities to ensure that buildings remain habitable.

In summary, it can be concluded that numerous factors contribute to the reoccurrence of BM activities in Nigeria. The most prominent factors include faulty designs, substandard building materials, poor managerial practices, and occupants' attitudes toward using building assets. These causes have led to the deteriorating condition of buildings and assets, creating an uncomfortable living and working environment for their occupants. While most studies address the causes of maintenance-related issues, very few attempt to tackle them. Some studies recommend a more proactive maintenance strategy, particularly through the adoption of technologies and systems for building maintenance management, as the current strategy is predominantly reactive (Ndulue and Ifeanyiemoh, 2021; Osuagwu *et al.*, 2021b; Aghimien *et al.*, 2019). Therefore, it is imperative to investigate further how technologies and systems can enhance building maintenance management.

2.7 Technology and Systems in Building Maintenance

Technology and systems are essential tools during the O&M phase of a building's life cycle. This phase is the longest in a building's life cycle and generates a substantial amount of information that needs to be documented, such as work orders, maintenance requests, and asset performance, among others (Lu *et al.*, 2020a; McArthur *et al.*, 2018; Mohanta and Das, 2016). Documented information is crucial for overall maintenance processes, as it aids BM organisations by providing the necessary details required to perform maintenance activities. Ismail and Motawa (2019) highlight that inadequate management of documentation systems presents a significant challenge to the recording, diagnosis, and analysis of maintenance information. Ismail *et al.* (2020) further argue that the use of conventional methods (paper-based reports) has certain setbacks, as there is a lack of coherence in the documentation of maintenance-related activities. Kameli *et al.* (2020) stress that the reliance of maintenance personnel on paper and two-dimensional drawings adds another burden to their work tasks. Therefore, an effective maintenance management system is crucial for managing the dynamic information generated from various activities requiring documentation. A range of commercial systems and technologies has been developed to support the maintenance of buildings. These include CMMS, Enterprise Asset Management (EAM), Building Automation Systems (BAS), CAFM, IWMS, and BIM, among others (Mohanta and Das, 2016; Kobbacy and Murthy, 2008; Hosamo *et al.*, 2022b).

In recent years, digital technologies have transformed the AEC industry, supporting its professionals in streamlining their activities (Alwashah *et al.*, 2024; Brozovsky *et al.*, 2024; Luo *et al.*, 2022). According to Luo *et al.* (2022), digital technologies encompass a variety of intelligent solutions aimed at optimising work efficiency and automation. They include BIM, IoT, AR, VR, drones, and DT, among others (Dou *et al.*, 2023; Pomè and Signorini, 2023; Luo *et al.*, 2022). Thus, the effective utilisation of these technologies can optimise activities, including maintenance.

2.7.1 Technologies and Systems Used for Building Maintenance Globally

1 Computerised Maintenance Management Systems

According to various studies, CMMS is one of the most prominent systems employed for maintenance activities (Besiktepe *et al.*, 2020; Peng *et al.*, 2020; Mohanta and Das, 2016; Parsanezhad and Dimyadi, 2014; Ismail and Kasim, 2013). CMMS facilitates the documentation of daily work orders, service requests, and maintenance information (Hosamo *et al.*, 2022b; Peng *et al.*, 2020), enabling maintenance personnel to maintain records of their activities (Osuji *et al.*, 2020). It aids maintenance organisations in planning their activities, identifying issues in advance, and coordinating the efficient utilisation of organisational resources to manage emerging issues (Besiktepe *et al.*, 2020; Ofide *et al.*, 2015). Musa *et al.* (2021) point out that CMMS plays a critical role in managing large volumes of maintenance data, enabling maintenance personnel to perform their functions effectively. These functions are achieved through mediums such as paper documentation and Excel spreadsheets (Hosamo *et al.*, 2022b). However, while conducting maintenance activities, personnel expend considerable time and effort retrieving information from the CMMS (Hosamo *et al.*, 2022b; Lu *et al.*, 2020b). To address these shortcomings, Hosamo, Svennevig, *et al.* (2022c) recommend that a BIM system with a level of detail between 400-500 offers greater support for maintenance activities compared to a CMMS.

2 Integrated Workplace Management Systems

IWMS serves as an enterprise solution for managing building assets and related services within the scope of workplace management (Mohanta and Das, 2016). It encompasses several technological solutions (Wetzel and Thabet, 2015). However, Mohanta and Das (2016) argue that IWMS cannot provide specialised solutions comparable to those of other systems, such as CMMS and CAFM. Hanley and Brake (2016) assert that the IWMS's scope of reference resembles that of a jack of all trades, but a master of none. It possesses the ability to combine different application datasets into a cohesive database (Marocco and Garofolo, 2022). Thus, IWMS facilitates the accurate creation of reference data for buildings, their assets, and contract terms for easier management of business processes, such as organisational maintenance activities (Hanley and Brake, 2016).

3 Computer-Aided Facility Management

CAFM plays a crucial role in enhancing planning capabilities for facility and BM organisations by assisting them in various activities, thereby improving workplace management (Marocco and Garofolo, 2022; Mohanta and Das, 2016). These activities include asset management, operational services, procurement, and both reactive and preventive maintenance management. Supporting this viewpoint, Mohanta and Das (2016) point out that CAFM enables organisations to understand the spaces within a building and the corresponding activities of its users. In terms of BM, CAFM supports the operational and strategic management of building facilities and assets by integrating Computer-Aided Design (CAD) for effective maintenance planning (Ismail and Kasim, 2013). Some studies suggest that organisations can maximise CAFM's potential by combining CAD modules and relational database platforms to manage various building spaces and facilities/assets (Wetzel and Thabet, 2015; Parsanezhad and Dimyadi, 2014).

Furthermore, CAD is often used to design digital models for asset management. However, the designed model and the actual built structure frequently do not align in measurement and placement (Angjeliu *et al.*, 2020). This discrepancy can make CAD-generated models challenging to utilise for maintenance purposes due to information update distortions, which could be critical for decision-making (Parsanezhad and Dimyadi, 2014). BIM is regarded as a solution to mitigate this issue (Yang, 2021; Zhang *et al.*, 2020; Guo *et al.*, 2019). Mohanta and Das (2016) corroborate that BIM offers more accurate information, assisting facility management and BM organisations in executing their activities more effectively.

4 Building Information Modelling

BIM can provide a comprehensive digital representation of a building and its assets, including both their physical and functional characteristics (Chang *et al.*, 2018). It has the potential to integrate various construction information, encompassing designs from different building professionals, procurement, scheduling, and asset installation data (Dou *et al.*, 2023; Coupry *et al.*, 2021). BIM can accommodate both graphic and non-graphic information. With these capabilities, BM organisations can visualise and plan their maintenance activities more effectively and precisely (Alwashah *et al.*, 2024; Pomè and Signorini, 2023). The visualisation potential of BIM enables BM organisations to explore three-dimensional (3D) models for better insights into the spatial relationships among building assets, identify access points, and effectively plan inspection and repair routes (Gao and Pishdad-Bozorgi, 2019). However, while BIM has been effective in a building project's design and construction phase, its usage in the O&M phase has not been fully maximised (Coupry *et al.*, 2021; Bolshakov *et al.*, 2020). A possible reason for this shortfall is BIM's lack of automatically maintaining precise building models, resulting from changes in building conditions over time (Jiao *et al.*, 2023; Hosamo *et al.*, 2022b). These changes arise from buildings' dynamic nature and asset upgrades (Moretti *et al.*, 2020). Keeping these models up to date requires a conscious effort.

Meanwhile, interoperability is an increasing concern when integrating data into building models (Hosamo *et al.*, 2022a; Parsanezhad and Dimyadi, 2014). Such concerns arise from the lack of a standardised data format and protocol from other digital tools and maintenance databases (Moretti *et al.*, 2020). As a result, data losses or inaccuracies are encountered when integrating BIM and the existing maintenance workflow (Chen and Tang, 2019). If this issue is addressed, BIM can transform BM management through visualisation, leading to a better understanding of buildings and assets (Zhao *et al.*, 2022; Ermenyi *et al.*, 2020). Thus, BIM aids BM organisations in integrating data from diverse sources, visualising them, and planning their maintenance activities more effectively.

5 Internet of Things

IoT has ushered in an innovative era for better management of buildings through the smart connectivity of their assets (Mouha, 2021). Such innovation is made possible by using IoT devices such as sensors, which play an active role in connecting systems/assets like lighting and HVAC systems (Zhao *et al.*, 2022; Kang *et al.*, 2018). IoT devices, whether embedded or attached to various building systems, provide a continuous collection of real-time data on operational performance and environmental conditions (Pomè and Signorini, 2023). The collected data can then be analysed to predict potential faults (Hosamo *et al.*, 2023b; Cheng *et al.*, 2020).

With this potential, BM organisations can proactively execute maintenance activities to avert fault escalation. This will result in reduced downtime, improvements in asset lifespan, and significant cost reductions in asset operations (Hosamo *et al.*, 2022b; Brunone *et al.*, 2021). Although IoT has revolutionised the AEC industry, particularly for maintenance activities, certain challenges persist, such as data security in its usage (Mouha, 2021; Fuller *et al.*, 2020). The collection and transmission of data through IoT devices involve sensitive information, and this infringes on the rights of the systems/assets users (Fuller *et al.*, 2020). In mitigating this issue, Mouha (2021) suggests that data breaches and unauthorised data access should receive considerable attention when using sensors for data collection. Hence, clear and ethical policies should be established to foster trust in the use of sensors for maintenance activities.

While data infringement poses a challenge in sensor usage, the reliability and accuracy of the collected data persist. According to Khajavi *et al.* (2019), erroneous sensor readings can mislead BM organisations in planning and decision-making for maintenance activities. Such readings could negatively impact the operational efficiency of building systems/assets. To address this issue, studies recommend proper calibration of sensors to ensure accurate data is provided (Arisekola and Madson, 2023; Khajavi *et al.*, 2019; Yang *et al.*, 2018). Thus, IoT devices offer BM organisations the leverage to access the conditions of buildings and their assets in real-time, enabling them to plan their maintenance activities better.

6 Drone

Drones, also referred to as unmanned aerial vehicles, are useful monitoring technologies with the potential to assist BM organisations in maintenance activities, particularly building inspections (Kung *et al.*, 2021; Razali *et al.*, 2019). They are equipped with cameras and sensors to capture high-resolution images and videos in hard-to-reach areas of buildings for maintenance inspections (Ermenyi *et al.*, 2020). Drones facilitate the inspection of elevated building elements, such as roofs and facade conditions (Ermenyi *et al.*, 2020; Razali *et al.*, 2019). With drones, BM organisations can easily cover large areas of a building promptly for inspections compared to conventional approaches (Chen *et al.*, 2019).

Although drone technology is advantageous for maintenance activities, it presents certain challenges. Such challenges include the quality of data collection, which hinges on the sensor quality attached to the drone, weather conditions, and the skill sets of the drone handler (Liang *et al.*, 2023; Kung *et al.*, 2021). Privacy is another challenging issue in using drones, as sensitive data is collected, which infringes on the rights of building occupants (Vattapparamban *et al.*, 2016). To address the privacy issue, Liang *et al.* (2023) recommend that clear and ethical policies be established for using drones for construction-related activities, such as maintenance. Thus, drone technology offers BM organisations the capability to conduct their maintenance inspection activities more efficiently.

7 Virtual Reality

VR is one of the most useful digital technologies for BM management. It can create realistic and immersive simulations of buildings, enabling BM organisations to visualise spaces and inspect assets for maintenance purposes virtually (Fang *et al.*, 2022; Ke *et al.*, 2019). VR technology offers an opportunity for the maintenance team to practice maintenance procedures in a controlled virtual environment. Such an opportunity benefits the maintenance team, allowing them to gain practical experience without needing physical access to the building (Dzulkifli *et al.*, 2021; Heesom *et al.*, 2003).

While VR has the potential to support maintenance activities, transitioning tasks from the virtual environment to the actual physical workspaces presents a challenge for maintenance procedures (Ke *et al.*, 2019; Lee and Akin, 2011). According to studies, a possible reason for this challenge is that VR's realistic virtual simulation may not accurately reflect the actual building conditions and environment (Goyeneche *et al.*, 2022; Lee and Akin, 2011). Studies suggest that addressing this issue requires careful calibration and validation of VR models to align with real-world environments (Cárdenas-Robledo *et al.*, 2022; Alrabadi, 2020). Another challenge in using VR is the cost associated with acquiring VR hardware and software (Lee and Akin, 2011). Although these challenges may seem like obstacles, VR technology allows BM organisations to virtually simulate the environment of a physical building and its assets for effective maintenance management.

8 Augmented Reality

AR is another valuable technology for BM activities, as it provides real-time visualisation of data overlaid on physical structures (Dzulkifli *et al.*, 2021; Gao and Pishdad-Bozorgi, 2019; Mourtzis *et al.*, 2017). It assists BM organisations in collecting maintenance data during building inspections (Goyeneche *et al.*, 2022; Gao and Pishdad-Bozorgi, 2019; Lee and Akin, 2011). With AR devices, the on-site maintenance team can easily connect with their superiors in real-time for expert guidance (Dzulkifli *et al.*, 2021; Mourtzis *et al.*, 2017; Lee and Akin, 2011). This AR potential is particularly beneficial when specific maintenance-related issues require more technical and expert knowledge. However, varying environmental conditions in buildings, such as lighting or physical obstacles, may affect the accuracy of AR data overlays (Chen *et al.*, 2020).

To address this challenge, studies recommend implementing mechanisms to reduce these obstacles, as the success of AR technology hinges on its precise mapping of virtual data onto the building environment (Dzulkifli *et al.*, 2021; Mourtzis *et al.*, 2017). The cost of acquiring AR devices, like smart glasses, is another determining factor in their use (Lee and Akin, 2011). Furthermore, the maintenance team's adaptation to using AR devices is crucial, as it facilitates seamless usage (Chen *et al.*, 2020). To address this concern, studies suggest employing suitable techniques to alleviate discomfort and fatigue during prolonged usage of AR devices, especially during maintenance tasks (Chen *et al.*, 2020; Aukstakalnis, 2017). Overall, the use of AR technology supports BM organisations in better understanding building systems and assets, enabling effective diagnosis and planning of their maintenance activities.

9 Digital Twin

DT is an innovative technology that has the potential to transform how buildings and assets are monitored and managed. Its unique strength lies in its capability to create a dynamic replica of buildings and assets (Brunone *et al.*, 2021). It serves as a virtual representation of a physical structure, with bi-directional data connectivity between them (Kritzinger *et al.*, 2018). By leveraging real-time data from IoT devices and other sources, DT allows for comprehensive optimisation of a building's operational performance through scenario analysis (Coupry *et al.*, 2021). With these capabilities, BM organisations can effectively monitor the status of buildings and assets, promptly detect anomalies, and predict potential failures to minimise downtime (Hosamo *et al.*, 2022b; Lin and Low, 2019). These capabilities will significantly enhance the overall effectiveness of maintenance management and ultimately reduce unforeseen costs associated with emergency repairs or system failures.

However, while DT appears promising for optimising maintenance activities, there is no clear evidence of its implementation for BM management, particularly at the organisational level. Most available studies have focused on the technical aspects of its implementation (Broo *et al.*, 2022; Rassõlkin *et al.*, 2021; Lin and Low, 2019). Supporting this view, Arisekola and Madson (2023) assert that most studies on DT have focused on its technical implementation, creating confusion for aspiring users. To address this issue, further studies are needed to explore how organisations, such as those involved in BM, can implement DT for their maintenance activities. Thus, DT presents a promising solution to assist BM organisations in their maintenance activities, and its transformative potential and application for BM management are comprehensively discussed in Chapter Three.

2.7.2 Technologies and Systems Used for Building Maintenance in Nigeria

In Nigeria, some studies have attempted to explore the utilisation of technologies and systems for BM management. These attempts primarily focus on the use of CMMS for maintenance activities. For example, Ofide *et al.* (2015) examined the BM practices of institutional buildings. The study revealed that maintenance manuals were lacking for these activities, with the predominant strategies being the non-utilisation of CMMS and corrective maintenance. In light of this non-utilisation of CMMS, Osuji *et al.* (2020) evaluated the readiness of public institutions to implement CMMS for maintenance activities. Although the study's findings indicated some evidence of readiness concerning processes, personnel, and technology adoption for utilising CMMS, organisational management needs to cultivate an environment that fosters its proactive usage. Eti *et al.* (2006) emphasise that for the Nigerian maintenance sector to attain best-in-class status, it needs to operate with an 80% proactive approach compared to 20% reactive strategies in its maintenance activities. Hence, employing CMMS can facilitate a transition in maintenance activities from reactive to preventive strategies for BM organisations.

Furthermore, Musa *et al.* (2021) highlight that advancements in CMMS have led to the integration of technologies such as BIM and Archibus, which provide supporting solutions for maintenance activities. These technologies are essential for integrating pre- and post-construction project information while enabling mobile solutions for maintenance activities (Osuji *et al.*, 2020). This integrative approach has brought several advantages to the organisational processes related to maintenance activities. A significant outcome of this integration is the establishment of an e-maintenance system (Osuji *et al.*, 2020). In this context, Afolabi *et al.* (2019) developed an e-maintenance system for asset management in tertiary institutions. The study's results indicated that the proposed e-maintenance system proved more effective in collecting maintenance requests and feedback compared to traditional paper-based approaches. These studies have underscored the benefits and necessity of utilising technology for maintenance activities. However, gaps exist in the utilisation of technologies and systems, particularly concerning predictive maintenance strategies. Thus, there is a pressing need to explore how BM organisations in Nigeria can harness the proactive potential of technological advancements, such as DT, for effective maintenance management.

Overall, it can be inferred that the reoccurrence of maintenance issues can be managed through various technologies and systems. However, some studies argue that BIM, Computer-Aided Facility Management (CAFM), and CMMS, among others, lack the capability for real-time data monitoring (Deng *et al.*, 2021; Madubuike and Anumba, 2021). Osuji *et al.* (2020) emphasise that real-time monitoring of buildings and assets would enhance maintenance activities. To mitigate these shortcomings, Halmetoja (2022) pointed out that software vendors have introduced certain digital solutions to BIM, referred to as DT; however, these are merely 3D graphical user interfaces that visualise building spaces and conditions. Pomè and Signorini (2023) assert that BIM can serve as a starting point for developing DT. Supporting this assertion, Xie *et al.* (2020a) stress that the concept of DT is more elaborate than BIM due to its data enrichment and analytical capabilities, which integrate and simulate data from various sources. Based on findings from these studies, investigating how DT can be utilised for BM management is expedient.

2.8 Summary

This chapter reviewed the literature on BM, its related challenges, and possible avenues to address some of them. Following the literature review, it can be deduced that maintenance-related issues are worldwide, stemming from human activities and natural phenomena. Signs of these issues encompass building defects/deterioration, which, in turn, lead to maintenance activities. However, these issues can be managed through various avenues, which vary across countries. Technologies and systems such as CMMS, CAFM, BIM, IoT, VR, and AR have been employed by BM organisations in different ways to enhance their maintenance activities.

In Nigeria, the prominent causes of human-related issues include faulty designs, poor construction materials, misuse of building assets by users, and ineffective managerial practices. Some studies have demonstrated the effective utilisation of technologies and systems such as BIM and CMMS in managing maintenance activities. Although these technologies and systems provide BM organisations with substantial support in managing maintenance activities, they have certain limitations, particularly the lack of real-time data updates.

Therefore, exploring more proactive technological solutions, such as DT, to manage these maintenance-related issues, which lead to BM activities, is imperative. The call for such a proactive solution is underscored by the fact that issues like faulty designs and the use of poor construction materials cannot be rectified during a building's lifecycle, nor is it likely that building users will change their attitudes towards the use of building assets. Thus, buildings and assets need to be monitored and optimised through effective BM management to ensure users' comfort and well-being.

Chapter Three – Literature Review on Digital Twin

3.0 Introduction

The literature review focuses on DT, specifically its application for BM management. In conducting a narrative literature review for this chapter, a systematic search was conducted using keywords such as “Building Maintenance”, “Facility Management”, “Digital Twin”, “Digital Twin for Building Maintenance”, “Digital Twin Implementation”, “Organisational Implementation”, and “Organisational Change Management”. Searches were conducted across databases, such as Scopus, Web of Science, JSTOR, IEEE Xplore, and Google Scholar, prioritising publications from the last 24 years. Forward and backward searches were also employed to uncover additional literature, ensuring that relevant studies are reviewed, given that DT is a relatively recent technology compared to other digital technologies in the AEC industry. The review focuses on peer-reviewed articles and documents that specifically address the study’s research question, emphasising the pathway towards achieving the study’s aim. Inclusion criteria ensure that selected literature directly relates to the research objectives, while exclusion criteria eliminate unrelated studies and those not written in English.

The review process follows a stepwise flow, involving initial screenings of titles and abstracts, full-text reviews, and critical synthesis of selected literature to ensure a comprehensive understanding of the study topic. The review will highlight trends, benefits, and challenges associated with DT implementation, providing valuable insights for its integration into organisational BM management. The chapter is organised into the following major sections: First, it reviews the historical evolution of DT and its attributes. Second, studies on the utilisation of DT for BM purposes are discussed. Third, it reviews DT model development and implementation. The final section explores a strategic approach for DT implementation in BM organisations. The review aims to identify the gaps inherent in previous studies, which this study seeks to fill.

3.1 History of Digital Twin

DT is an innovative and dynamic technology with the potential to optimise the interoperability of processes and provide adequate information for decision-making (Coupry *et al.*, 2021). Its utilisation aims to enhance the asset design process, execution, and O&M by incorporating data and information throughout its lifecycle (Jiao *et al.*, 2023; Hosamo *et al.*, 2022a). Moreover, the evolution of DT can be traced back to the early 1990s when the idea of mimicking reality emerged (Singh *et al.*, 2022). In this context, DT was first deployed by the National Aeronautics and Space Administration (NASA) in the public domain to develop a technological blueprint for modelling, simulation, information technology (IT), and processing (Jiao *et al.*, 2023; Opoku *et al.*, 2021).

This technological blueprint was evident in the NASA Apollo programme, where models of two identical space artefacts were constructed to facilitate adequate mirroring of the artefact during the space mission (Singh *et al.*, 2022; Boschert and Rosen, 2016). The artefact on Earth represented the twin of the other on exploration in space (Coupry *et al.*, 2021). Furthermore, a review conducted by Singh *et al.* (2022) indicates an exponential increase in the application of DT between 2016 and 2022 across agriculture, smart cities, disaster management, personalised medicine, and smart manufacturing (Figure 3.1). This study highlights DT as becoming one of the proponent drivers of Industry 5.0.

In the context of scientific research, DT was first introduced by Michael Grieves in 2002 during his presentation on the concept of a virtual representation model of a physical product in a product lifecycle management course for manufacturing (Zhou *et al.*, 2021). It was officially named DT in 2011, and researchers from various disciplines have significantly contributed to its expansion (Liu *et al.*, 2021a). Moreover, some studies indicate that DT gained worldwide attention in 2016 due to its inclusion in the top 10 strategic technological advances for 2017 by Gartner's research firm (Fang *et al.*, 2022; Perno *et al.*, 2022). Similarly, DT was regarded as one of the six key technologies that influenced the military industry in 2018 by Lockheed Martin (Fang *et al.*, 2022). Thus, drawing inferences from the literature, the practical applications of DT technology commenced in 2017 (Fang *et al.*, 2022; Perno *et al.*, 2022).

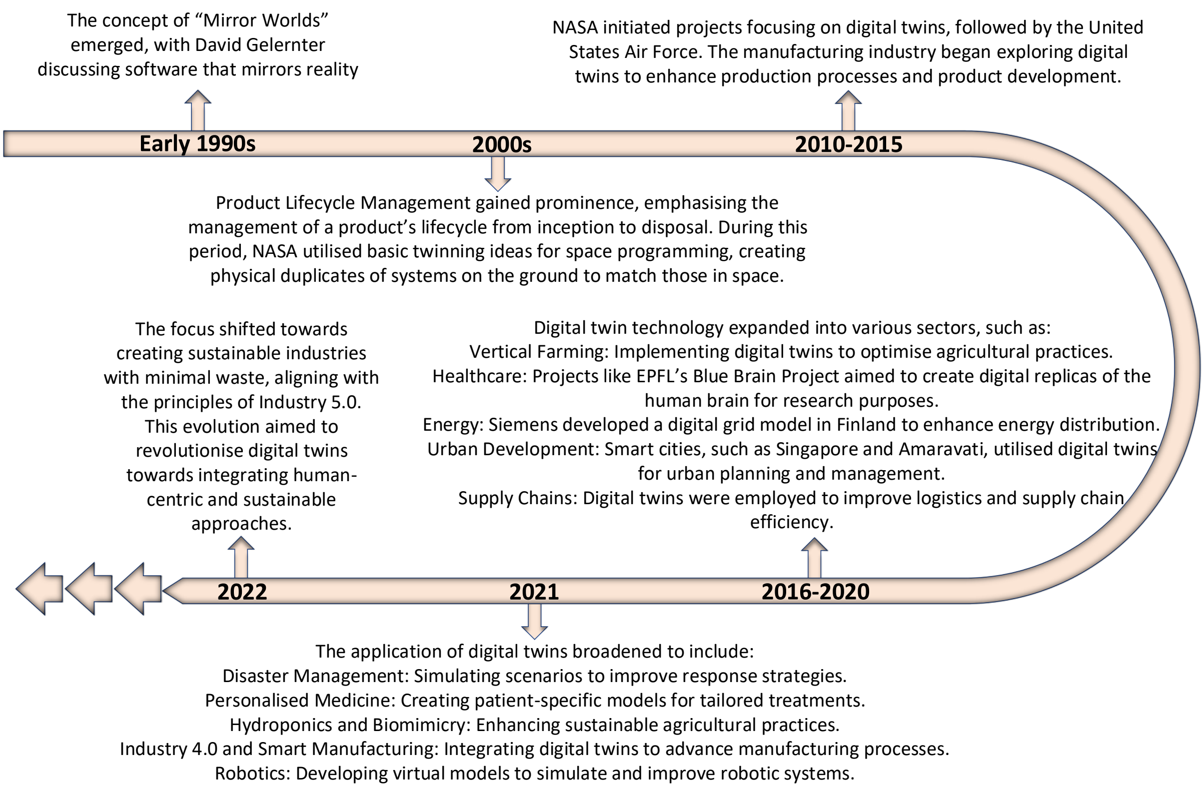


Figure 3.1: Evolution of Digital Twin Application (Adapted from Fang *et al.*, 2022; Perno *et al.*, 2022; Singh *et al.*, 2022; Zhou *et al.*, 2021; Boschert and Rosen, 2016)

In recent years, DT has been adopted by various industries to enhance the operational efficiency of their facilities and equipment. Figure 3.1 summarises the evolution of DT from the early 1990s until the commencement of this study. A scientometric analysis was conducted on literature from 2011, the year it was officially termed DT (Liu *et al.*, 2021a), to

2022, when this study commenced. The Scopus database was explored to obtain relevant literature using the following keywords: (TITLE-ABS-KEY ("Digital Twin*" OR "Virtual Twin" OR "Digital Clone" OR "Virtual Mirror" OR "Virtual Model" OR "Digital Copy" OR "Mathematical Counterpart" OR "Digital Couple") AND TITLE-ABS-KEY ("Building Maintenance" OR "BM" OR "Maintenance*" OR "Operation and Management" OR "O&M" OR "Facility Management" OR "Asset Management" OR "Facility Maintenance") AND TITLE-ABS-KEY ("Built Environment" OR "Architectural, Engineering, and Construction" OR "AEC" OR "Construction" OR "Building*")) The results indicate a gradual increase in studies on DT (from 0.7% in 2011 to 55.5% in 2022), its application in maintenance (from 0.5% in 2011 to 34.7% in 2022), and its use for maintenance in AEC (from 0.0% in 2011 to 42.3% in 2022). These findings are presented in Table 3.1 and Figure 3.2.

Table 3.1: Summary of Scientometric Analysis of Literature on Digital Twin for Maintenance Activities in the Architectural, Engineering, and Construction Industry

	Digital Twin		Digital Twin and Maintenance		Digital Twin, Maintenance, and AEC Industry	
Year	Articles	Percentage	Articles	Percentage	Articles	Percentage
2011	6	0.7	2	0.5	0	0.0
2012	14	1.5	7	1.8	1	0.0
2013	8	0.9	4	0.0	3	0.8
2014	10	1.1	6	0.1	4	1.0
2015	4	0.4	3	0.0	2	0.5
2016	10	0.1	4	0.4	1	0.3
2017	34	0.4	19	2.1	8	2.1
2018	122	1.3	38	4.1	13	3.4
2019	368	4.0	118	12.8	43	11.2

2020	1010	11.0	154	16.7	52	13.6
2021	2511	27.5	226	24.6	86	22.5
2022	5072	55.5	319	34.7	162	42.3

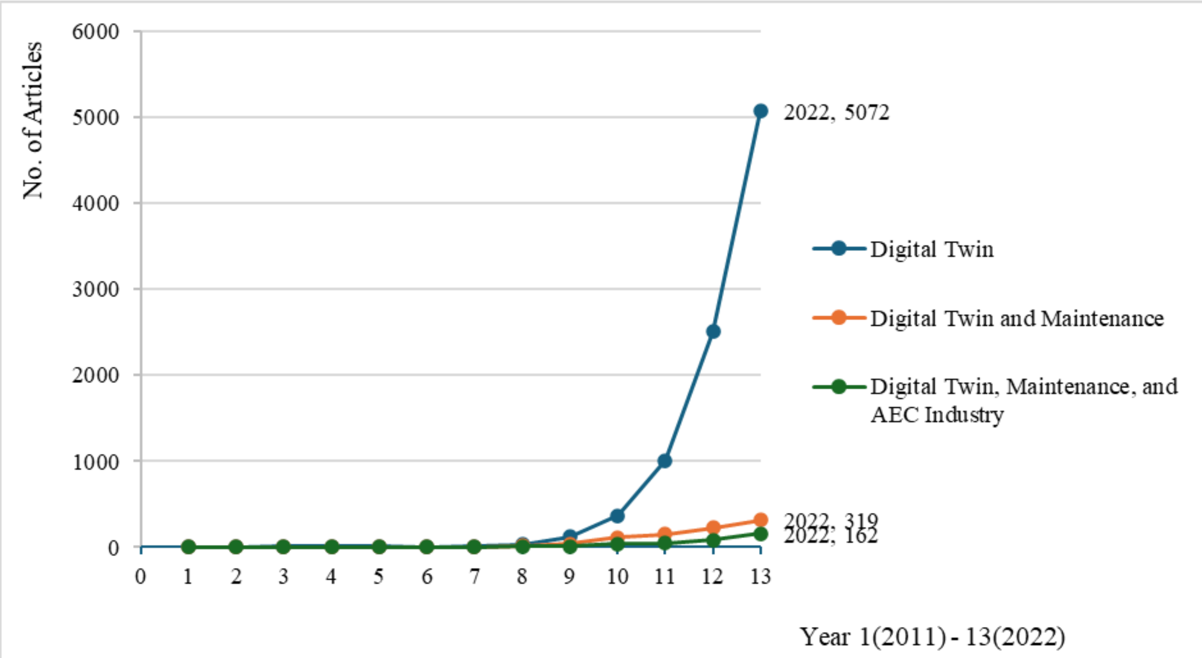


Figure 3.2: Comparison of Scientometric Analysis of Literature on Digital Twin for Maintenance Activities in the Architectural, Engineering, and Construction Industry

According to Figure 3.2, a comparison of the literature on DT application across all industries shows significant progress from 2018 (9) to 2022 (13). A review by Errandonea *et al.* (2020) reveals that the manufacturing industry is at the forefront (Figure 3.3). Such trends may be attributed to substantial investments in high-tech machinery, which must be adequately monitored and managed for optimal productivity (Hosamo *et al.*, 2022c). The energy industry follows, encompassing infrastructure such as offshore facilities, wind turbines, and oil and gas equipment. The third category is construction, which includes bridges and buildings. Aerospace and naval engineering, among others, follow next, respectively. Errandonea *et al.* (2020) further summarise DT application across different work functions, which include design, lifecycle, process/logistics, maintenance, and prognostic health management (PHM) (Figure 3.3).

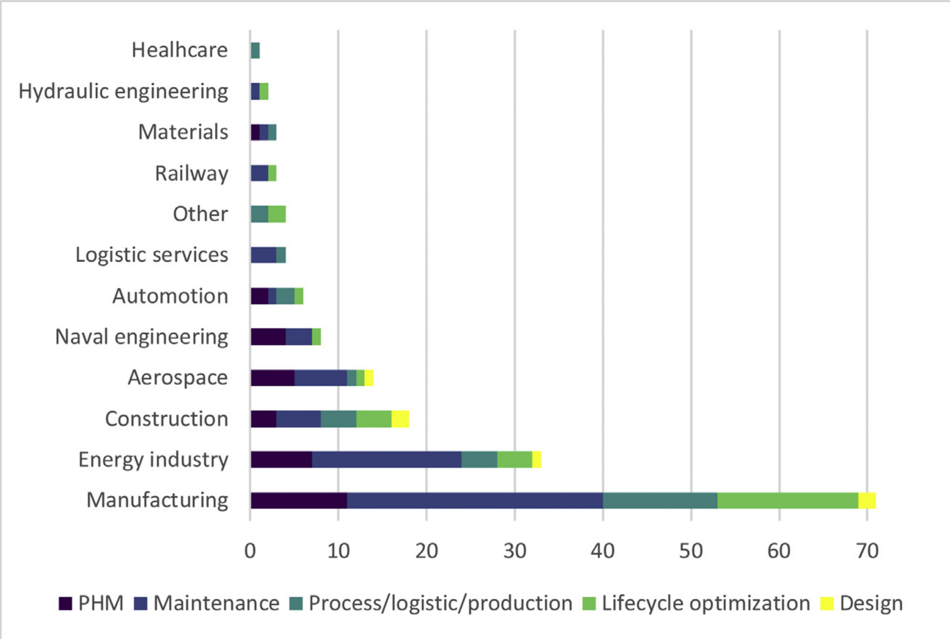


Figure 3.3: Exploration of the Digital Twin in Industrial Sectors (Adopted from Errandonea *et al.*, 2020)

In the context of DT application for maintenance activities, Table 3.1 reveals that literature from 2011 (0.5%) to 2022 (34.7%) has also experienced an increment. Such an increment signifies an ongoing research effort to explore the potential of DT in managing maintenance-related issues. Errandonea *et al.* (2020) highlight that studies on the use of DT for maintenance remain prevalent within the manufacturing industry. This prominence is subsequently followed by the energy, aerospace, and construction industries (Figure 3.4). Furthermore, a common trajectory across these studies is the application of Industry 4.0 technology, which has, in turn, brought to fusion the concept of Maintenance 4.0 or smart maintenance (Madubuike *et al.*, 2022; Mihai *et al.*, 2021). According to Jasiulewicz-Kaczmarek *et al.* (2020), smart maintenance utilises the proactive strategies of Industry 4.0 technology to predict faults in facilities/assets and facilitate their subsequent optimisation.

However, regarding the AEC industry, which encompasses construction, some studies indicate that DT has not been fully explored to support its activities. One of the inhibiting factors is its level of digitalisation compared to other industries (Arowoiya *et al.*, 2024; Elyasi *et al.*, 2023; Pomè and Signorini, 2023; Coupry *et al.*, 2021). Hence, based on these studies, the utilisation of DT technology in the AEC industry is still evolving.

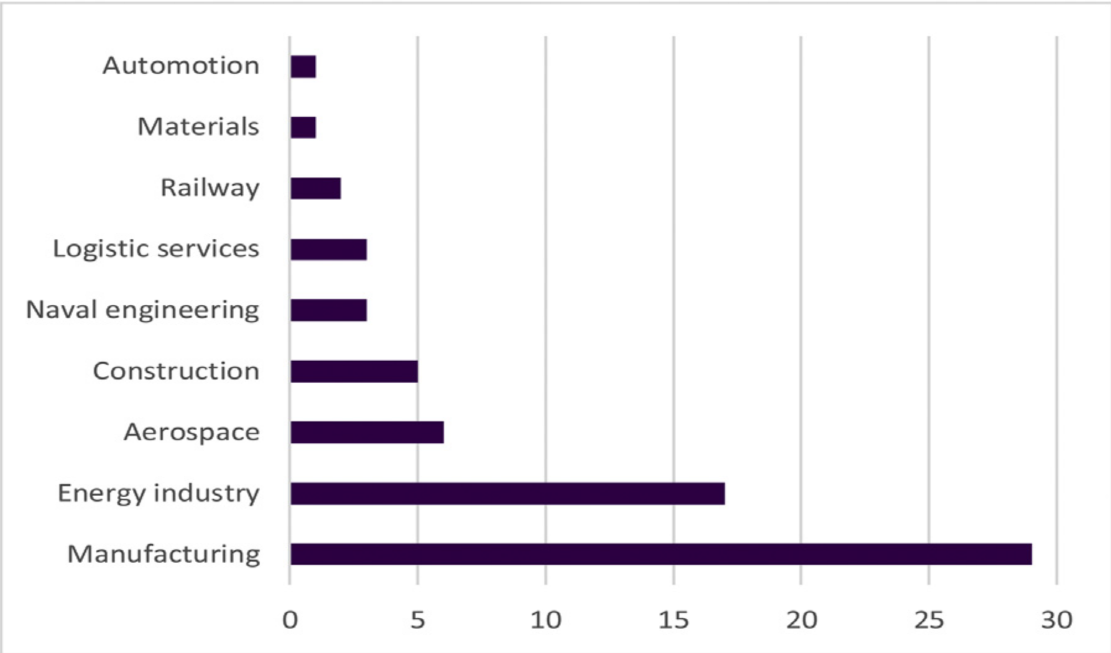


Figure 3.4: Maintenance Application of the Digital Twin in Industrial Sectors (Adopted from Errandonea *et al.*, 2020)

3.2 Definition of Digital Twin

The definition of DT as an innovation varies across industries, reflecting its broad applicability and adaptation to specific needs. In manufacturing, it focuses on real-time optimisation of machine processes, while in aerospace, it integrates complex simulations for aircraft maintenance and performance prediction. The evolution of DT, highlighted in the previous section, underscores its dynamic nature to evolve alongside advances in various industries, making each definition tailored to optimise outcomes and address challenges unique to each industry. Moreover, the core concept in DT's definition revolves around creating a virtual replica of a physical structure and the transfer of data between them (Brunone *et al.*, 2021; Coupry *et al.*, 2021). The most widely accepted definition of DT, presented by several authors (Jiao *et al.*, 2023; Davies *et al.*, 2022; Coupry *et al.*, 2021; Villa *et al.*, 2021; Angjeliu *et al.*, 2020), comes from Glaessgen and Stargel (2012, p.7), who define DT as "*an integrated multiphysics, multiscale, probabilistic simulation of an as-built vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its corresponding flying twin*". This definition emphasises that DT functions as a data management system, facilitating real-time synchronisation of data between a physical structure and its virtual model to ensure data reliability.

Furthermore, some other researchers have also defined DT based on certain related parameters beyond those of Glaessgen and Stargel (2012, p.7). By conducting a systematic search with keywords related to virtual and physical systems, models, and real-time data integration, the databases highlighted in Section 3.0 are explored. The literature selection process involved an initial screening of titles and abstracts, followed by a full-text review of relevant literature. The definitions of DT are then thematically grouped and evaluated for comprehensiveness and clarity based on the searched keywords. This approach ensured a balanced representation and understanding of DT's theoretical and practical perspectives, resulting in the selection of seven distinct definitions. Table 3.2 provides a summary of these definitions.

Table 3.2: Summary of Some Definitions of Digital Twin

Authors	Definition	Keywords
Brunone *et al.*(2021)	DT is a cloned digital replica model of an existing physical system. The digital model reveals the present status of the physical system and aids its future behavioural predictions.	Digital replica model and physical system
Coupry *et al.* (2021)	DT is a multiscale representation of a physical object that consists of an existing system in a real environment and its virtual counterpart, in which the exchange of data is carried out in real-time using simulation algorithms or smart sensors to predict future responses to a certain phenomenon.	Physical object, virtual counterpart, and real-time
To *et al.* (2021)	DT refers to the digital replication of a physical structure using real-time data interaction.	Virtual model and physical structure
Zhou *et al.* (2021)	DT involves creating a digital model that accurately represents a physical structure, which can be utilised to simulate the future and predict various outcomes of the physical structure.	Digital model and physical structure
Angjeliu *et al.* (2020)	DT serves as a dynamic digital counterpart to a physical structure and system, employing IoT devices	Digital counterpart and physical structure.

	to collect data from the users of the physical structure.	
Lu *et al.* (2020)	DT is a dynamic virtual representation of a physical structure, process, and system that utilises IoT devices to capture data and corresponding feedback from its users.	Virtual model and physical structure
Xie *et al.* (2020)	DT is a virtual representation of a physical asset and system, with the intention of mimicking its real-world counterpart attributes.	Virtual representation, physical assets, and real-world

It can be inferred from Table 3.2 that the definition of DT deals with a physical structure and its digital model with a corresponding bi-directional real-time data update. Such a bi-directional real-time synchronisation of data facilitates scenario analysis on the digital model, with the outcomes being actioned back on the physical structure. Angjeliu *et al.* (2020) emphasise that the primary components of DT include a physical reality, the collection of data that describes the physical reality, and a corresponding virtual reality.

In the context of the built environment, Camposano *et al.* (2021, p.27170) define DT as "*an integrated software solution to manage static and dynamic information of a built asset across its lifecycle phases. It usually provides a realistic digital representation of the physical asset, generated by enriching the geometric or graphical data with support from building automation systems (BAS), sensors, Internet of Things (IoT) components, and other feedback systems informing about the asset, its occupants, or its environment*". Similarly, Al-Sehrawy and Kumar (2021, p.930) describe DT as "*an approach for connecting a physical system to* *its virtual representation via bidirectional communication (with or without human in the loop) using temporally updated Big Data (primary data collected from this physical system and supplementary data from the surrounding environment interacting with it for the purpose of contextual awareness) to allow for exploitation of Artificial Intelligence and Big Data Analytics by harnessing this data to unlock value through optimisation and prediction of future state"*.

These definitions suggest that DT is the virtual replica of a physical structure, system, process, and environment, with or without human intervention, for its bidirectional communication (Pomè and Signorini, 2023; Heaton and Parlikad, 2020; Bolton *et al.*, 2018). Moreover, Hosamo *et al.* (2022b) emphasise that DT provides a comprehensive solution for managing, planning, predicting, and demonstrating a building and its asset status. DT mirrors a system's physical and social processes by mimicking its operations in real-time (Broo *et al.*, 2022). This study, therefore, will define DT as the virtual representation of a physical entity, system, or process (Pomè and Signorini, 2023; Bolton *et al.*, 2018), with data exchange and human intervention (Al-Sehrawy and Kumar, 2021) actioning scenario analysis results from the virtual model to the physical structure, thus enabling closure for its bidirectional data communication.

3.3 Classification of Digital Twin

The classification of DT varies across literature and depends on certain criteria. These criteria encompass DT creation time, levels of integration, DT application, hierarchy, and maturity level. Therefore, understanding DT based on these criteria is essential for its effective usage.

3.3.1 DT Creation Time

Time is a crucial factor in the creation of DT. Grieves and Vickers (2017) point out that types of DT can be categorised based on when an artefact is developed. Such creation may occur either before the design phase of the artefact (prototype) or after the artefact has been developed and is ready for use (Singh *et al.*, 2021a). Thus, these types of DT are referred to as the digital twin prototype (DTP) and the digital twin instance (DTI), both of which operate on a digital twin environment (DTE) platform (Singh *et al.*, 2021b).

1. **Digital Twin Prototype (DTP):** This type of DT is developed prior to the creation of the physical twin. It includes various sets of information, such as design documents and a bill of materials, among others, which are essential for creating a physical twin from its virtual replica (Barabanova *et al.*, 2023; Singh *et al.*, 2021a). The artefact development cycle begins with the creation of a DTP, which undergoes a series of evaluations through testing before its physical twin is constructed in the real world (Barricelli *et al.*, 2019). Therefore, DTP aids in identifying and avoiding unpredictable phenomena that would be challenging to discern through traditional prototyping.

2. **Digital Twin Instance (DTI):** A DTI is a form of DT that connects a virtual replica to its physical twin throughout its lifecycle. Its development commences at the creation stage of a physical system (Barabanova *et al.*, 2023; Grieves and Vickers, 2017). With its unique creation perspective, the synchronisation of data from the real world to the virtual replica assists in monitoring and predicting the physical system's behaviour upon completion (Singh *et al.*, 2021a). Basically, a collection of DTIs makes up a Digital Twin Aggregate (DTA), as illustrated in Figure 3.5. Therefore, by employing this type of DT, undesirable activities can be eliminated from the physical system when identified within the virtual replica (Delgado and Oyedele, 2021; Singh *et al.*, 2021a).

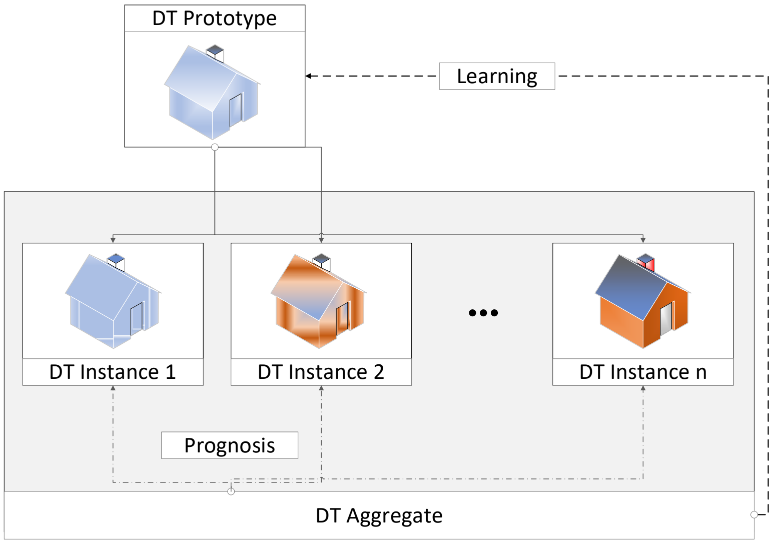


Figure 3.5: A Pictorial Description of the Digital Twin Prototype, Instance, and Aggregate (Adapted from Delgado and Oyedele, 2021; Singh *et al.*, 2021a)

3.3.2 Level of Integration

DT can be classified according to the level of data transmission between a physical object or structure and its digital counterpart (Singh *et al.*, 2021a; Kritzinger *et al.*, 2018). According to Kritzinger *et al.* (2018), DT is categorised into three subcategories: digital model, digital shadow, and digital twin. The digital model, which may consist of a combination of BIM and SQL database, lacks self-driven data synchronisation between the physical and digital objects (Opoku *et al.*, 2021; Antonino *et al.*, 2019). The digital shadow has a self-driven real-time unidirectional synchronisation of data flow solely from the physical to the digital objects (Sharma *et al.*, 2022; Schroeder *et al.*, 2016) and can be characterised as a static digital model (Singh *et al.*, 2021a; Lamb, 2019). In contrast, the digital twin, also referred to as a dynamic digital model, enables a bi-directional synchronisation of data flow between the physical and digital objects (Lamb, 2019; Kritzinger *et al.*, 2018). Figure 3.6 illustrates the level of data transmission between these objects or structures. Based on this review, DT represents a dynamic digital technology that facilitates real-time data transmission, thereby addressing the limitations of other static technologies, such as BIM.

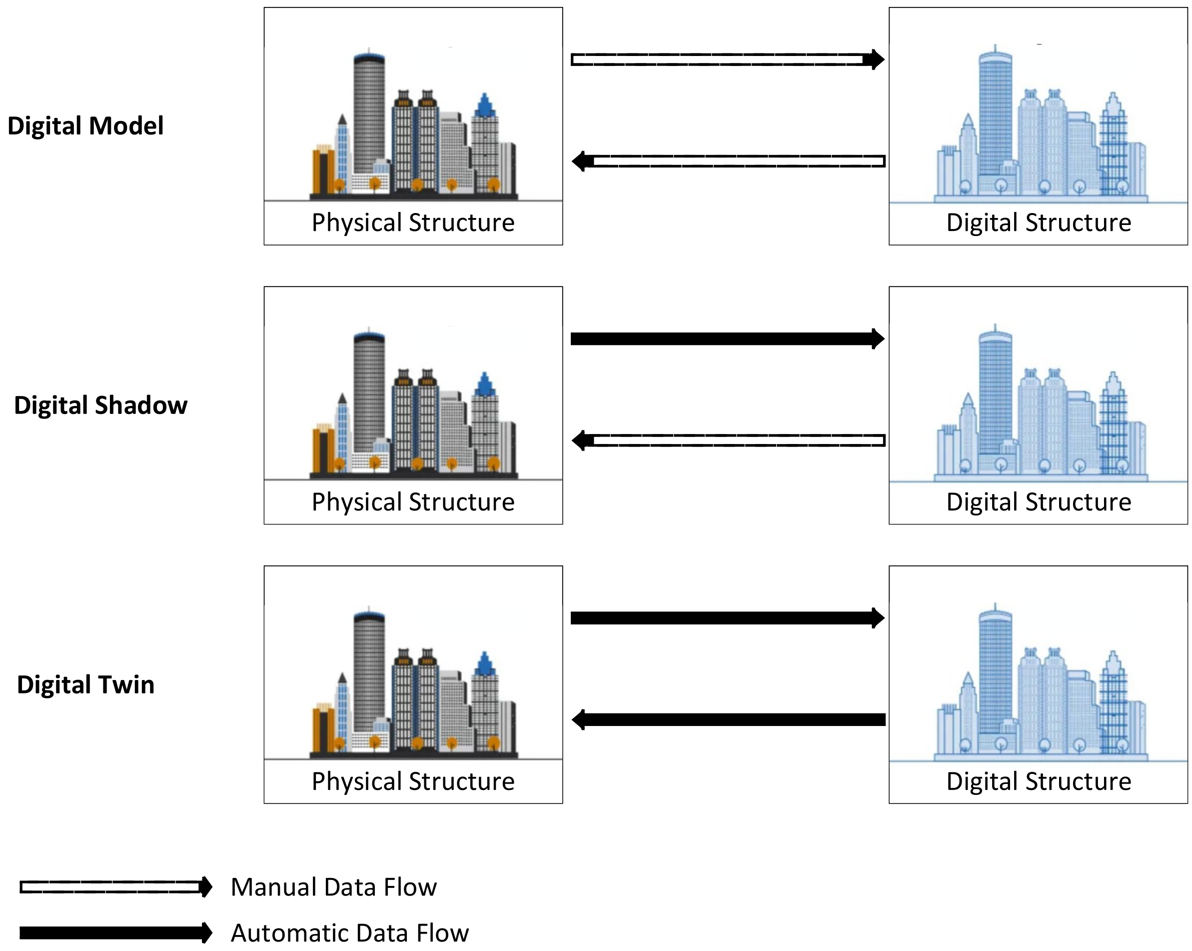


Figure 3.6: Types of Digital Twins Based on the Level of Data Integration Between Objects or Structures (Adapted from Singh *et al.*, 2021a; Kritzinger *et al.*, 2018)

Furthermore, according to Al-Sehrawy and Kumar (2021), the bi-directional data communication between a physical structure and its virtual replica of DT can be classified as either "Passive" or "Active". A “Passive DT” facilitates seamless data exchange through an open-ended feedback loop that allows humans to implement recommendations derived from the virtual model onto the physical structure. Conversely, an “Active DT” can alter the physical structure using technologies such as actuators, operating through a closed-ended feedback loop without human intervention (Al-Sehrawy and Kumar, 2021).

3.3.3 Hierarchy

DT can be categorised into different levels, ranging from its simplicity of use to its complexity. In this context, Segovia and Garcia-Alfaro (2022) categorise DT into three levels: unit, system, and system of systems.

1. **Unit level:** This is the smallest DT unit in a building and can serve as a standalone component that forms part of a system (Al-Sehrawy and Kumar, 2021). It includes items such as windows, blinds, and lighting fittings, among others (Singh *et al.*, 2021a).

2. **System level:** This level consists of combinations of unit-level DTs that share a common environment within a building. The interconnections among several unit levels create a broader data pool for adequate resource utilisation (Segovia and Garcia-Alfaro, 2022; Singh *et al.*, 2021a). For instance, a system that controls indoor environmental quality may include air-conditioning units, light fittings, windows, and blinds (Al-Sehrawy and Kumar, 2021).

3. **System of Systems (SoS) level**: This level integrates multiple system-level DTs to create a complex, independent system (Singh *et al.*, 2021a). An example of SoS DT is that of smart buildings (Segovia and Garcia-Alfaro, 2022).

In conclusion, it can be deduced that DT exists in various forms. It is classified by factors such as creation time, data integration levels, and hierarchical levels, among others. Reviewing the classifications of DT enables the development of a suitable type that can support its intended activities, such as maintenance activities. Therefore, the intended purpose of DT usage will determine the type to be developed, which is influenced by its scale, complexity, functionality, and level of model details, among other factors.

3.4 Characteristics of a Digital Twin

Certain characteristics must be present for a system to be classified as a DT. According to studies, these consist of a physical structure, its virtual replica, and a data connection between them (Hosamo *et al.*, 2022b; Segovia and Garcia-Alfaro, 2022; Madubuike and Anumba, 2021). Barricelli *et al.* (2019) highlight that connection processes, such as networking devices, are essential to equip both the physical structure and its virtual replica for seamless and continuous data transfer, which can occur through either direct physical connections or indirect cloud-based methods. Such data connection processes should be designed to ensure effective communication between the physical structure and its virtual replica (Sharma *et al.*, 2022; Delgado and Oyedele, 2021). In this context, Barricelli *et al.* (2019) categorise the connection processes in DT into three types: the connections between the physical structure and its virtual replica, DT and other DTs within the system environment, and DT and domain experts. Therefore, a DT must comprise a physical structure, its virtual replica, and a seamless data connection between them.

3.5 Importance of Digital Twin

The importance of DT is enormous. Firstly, DT has the potential to utilise collected historical and real-time data for scenario analysis, which can predict the future condition of a system or asset, thereby optimising its maintenance operations (Coupry *et al.*, 2021). IoT devices are employed to monitor the physical structure and generate valuable real-time data effectively. Such generated data is analysed using AI to diagnose faults in a system or asset, facilitating improved planning and scheduling of maintenance activities (Rasheed *et al.*, 2020). Mihai *et al.* (2021) emphasise that DT is a dynamic system capable of continuously analysing a system or asset's current state and providing intelligent recommendations, such as process optimisation and effective predictive maintenance activities, to enhance its overall performance. Thus, DT optimises the maintenance activities of a system or asset.

Secondly, DT supports the visualisation of a system or asset environment, analyses data irregularities, and optimises their service life (Villa *et al.*, 2021). Its potential in remote monitoring facilitates easy access to the system or asset from any location, and performance metrics are established for adequate optimisation (Rasheed *et al.*, 2020). According to Shahzad *et al.* (2022), DT provides a platform for conducting a “what if” analysis of an asset during the O&M phase, as opposed to building management systems (BMS) or other traditional building management technologies. Consequently, DT aids in remote monitoring and data analysis for maintenance purposes.

Thirdly, DT enhances documentation and communication among building management stakeholders through the availability of real-time data. Shahzad *et al.* (2022) emphasise that DT can foster better collaboration among stakeholders, including facility managers, asset managers, and maintenance professionals, to manage spaces and digitise O&M activities. Such collaboration increases the transparency of documented reports, leading to improved communication and decision-making (Rasheed *et al.*, 2020). Thus, disputes among these stakeholders can be resolved more easily with the availability of robust data.

Lastly, DT assists in the prototyping of maintenance interventions. According to Agostinelli (2021), BM managers currently invest considerable time assessing the benefits and costs of any intervention before its actual implementation. With the support of DT, BM managers can conduct scenario analysis on available data, as discussed in Section 3.3.1, and evaluate the intervention's success rate before its implementation.

3.6 Digital Twin Application for Building Maintenance

Some studies have explored DT for managing building assets and system maintenance. These studies have focused on defect detection, anomaly detection, maintenance inspections, maintenance conservation, and data management, among others, as summarised in Table 3.1.

Table 3.3: Summary of Some Studies on Digital Twin for Building Maintenance

Author(s)	**Year**	**Key Issue/Focus**	**Maintenance**
Villa *et al.*	(2021)	Data Integration	Preventive
Heaton and Parlikad	(2020)	Data Interoperability	Preventive
Lu *et al.*	(2020a)	Data Management	Predictive
Peng *et al.*	(2020)	Data Management	Predictive
Lu *et al.*	(2019)	Data Management	Predictive
Stojanovic *et al.*	(2018)	Data Management	Preventive
Lu *et al.*	(2020b)	Anomaly Detection	Condition-based
Xie *et al.*	(2020a)	Anomaly Detection	Condition-based
Xie *et al.*	(2020b)	Anomaly Detection	Condition-based
Xie *et al.*	(2023)	Anomaly Detection	Condition-based
To *et al.*	(2021)	Defect Detection	Condition-based
Zhang *et al.*	(2021b)	Defect Detection	Condition-based
Angjeliu *et al.*	(2020)	Defect Detection	Condition-based
Marra *et al.*	(2021a)	Maintenance Conservation	Condition-based
Marra *et al.*	(2021b)	Maintenance Conservation	Condition-Based
Zhou *et al.*	(2021)	Maintenance Efficiency	Predictive
Jiao *et al.*	(2023)	Maintenance Optimisation	Predictive
Pomè and Signorini	(2023)	Maintenance Optimisation	Predictive
Coupry *et al.*	(2021)	Maintenance Inspection	Preventive
Lu *et al.*	(2020c)	Maintenance Inspection	Preventive

Defect detection is crucial for maintaining building assets and systems because a fault in one asset may impact another. Consequently, several studies have proposed methods for defect detection. For example, To *et al.* (2021) proposed a drone-DT augmentation model that employs AI and 3D reconstruction. The evaluation of this model demonstrated its effectiveness in defect detection, resulting from the information fusion derived from the 3D reconstruction of BIM using a drone. Similarly, Zhang *et al.* (2021b) developed a BIM-Unity 3D-Hololens model, integrating DT and Mixed Reality (MR) technology for defect detection in electromechanical equipment. Although this model proved effective in identifying failures in gear systems, it requires evaluation in other contexts, such as electromechanical equipment. Likewise, Angjeliu *et al.* (2020) developed a digital model that integrated the experimental physical reality of a structural system using the DT concept for historic masonry buildings. The findings of this study highlighted the model's effectiveness in assessing structural defects.

From these studies, it can be inferred that defect detection technologies will significantly enhance the maintenance of building assets and systems. However, the reoccurrence of building defects stems from various factors, including user influence, material deficiencies, force majeure, and design choices, among others, and some of these factors are unavoidable. Therefore, it is essential to effectively monitor building assets and systems to prevent unforeseen defects.

Inadequate inspection and monitoring during routine maintenance can sometimes lead to building defects. Several studies have attempted to utilise DT for the inspection and monitoring of buildings. For example, Lu *et al.* (2020c) developed an AR-supported inspection system to examine temperature anomalies in building facilities. Similarly, Xie *et al.* (2020b) proposed an AR-based anomaly detection system to assist facility/maintenance managers with fault isolation and to address issues affecting the thermal comfort of building users. In both studies, the developed systems enabled maintenance teams to visualise and detect failed facilities unnoticed behind walls and ceilings.

Furthermore, Lu *et al.* (2020b) and Xie *et al.* (2020a) developed a DT-supported anomaly detection system for monitoring and diagnosing centrifugal pumps in HVAC systems. This system demonstrated efficiency in detecting pump anomalies through a Bayesian change point methodology. These studies have underscored the importance of adequate and effective monitoring of building assets and systems. Thus, employing DT will aid in the effective monitoring of buildings and their assets, enhancing their preservation and longevity.

The preservation and conservation of building assets and systems can reduce maintenance needs. According to Chudley (1981), maintenance is often construed as repair (restoration), and this misconception has contributed to the reoccurrence of maintenance activities. Consequently, several studies have suggested methods for conserving buildings and their assets and systems through technology. Marra *et al.* (2021b) developed a digital model of a historical architectural asset using an integrated informative system for maintenance and preservation. Similarly, Marra *et al.* (2021a) presented a historical DT model, combining an integrated informative system for the maintenance and preservation of artefacts in a museum. Results from both studies underscored the potential of the DT-integrated informative system in enhancing the value of architectural assets through maintenance activities, as well as integrating cultural artefacts and digital models with other databases for scenario analysis. Extracts from both studies indicate that employing DT will effectively conserve and preserve a building and its assets. Therefore, the full potential of DT needs to be explored to facilitate the management of maintenance-related issues in buildings.

Some studies have attempted to utilise DT to maintain buildings and their assets. For instance, Lu *et al.* (2019) developed a DT system at the building level to integrate heterogeneous data. This study revealed the potential of DT for building maintenance management. However, the potential user's interaction with the DT system for decision-making was underexplored. Against this backdrop, Lu *et al.* (2020a) developed a dynamic DT system using Industry 4.0 technologies such as big data, IoT, and AI, among others, at both the building and city levels. This study corroborates the findings of Lu *et al.* (2019), highlighting DT's potential in maintenance management. It further revealed these potentials in the integration of heterogeneous data, efficient data analysis, and effective decision-making processes.

Similarly, Peng *et al.* (2020) proposed a continuous life cycle integration DT system from the design phase to the O&M of a hospital building. This study confirmed the effectiveness of DT in fault diagnosis and routine maintenance within the hospital complex. Expanding on the effectiveness of DT, Pomè and Signorini (2023) explored its advantages through case studies for building management. Their study highlighted several benefits of DT in minimising energy consumption and optimising maintenance. However, they also noted that the significant cost of its implementation could hinder its utilisation. While these studies have evidently demonstrated the potential of DT for maintenance activities, they lack a sustainable approach to its implementation. In addressing this shortfall, Jiao *et al.* (2023) developed a sustainable DT model applicable to the O&M phase of building infrastructures. Although this model adds to existing frameworks regarding sustainability, effectiveness, and improved security at the operational level, it does not provide a clear process path for implementing DT, particularly at the organisational level. Therefore, this study aims to address this gap.

Drawing inferences from these studies, DT can potentially manage certain reoccurring maintenance-related issues, such as maintenance documentation, requests, and decision-making processes, among others. This potential relies on the real-time updating of data and scenario analysis. Consequently, BM organisations can effectively monitor building assets and develop an efficient maintenance strategy for specific activities. Meanwhile, existing studies conducted in Nigeria have identified the causes of maintenance-related issues as faulty design, the use of substandard construction materials, misuse of building components by users, and poor managerial practices. Although some of these issues originate from activities prior to a building's use and cannot be rectified during its operation, literature evidence suggests that DT presents a promising strategy for assisting BM organisations in managing these maintenance-related issues. The capability of DT to monitor and perform scenario analysis can provide real-time data on the misuse of building assets by users and the actual condition of the buildings. Such capability enables BM organisations to effectively plan their maintenance activities. Thus, understanding how DT can assist in asset monitoring for maintenance activities is noteworthy.

3.6.1 Continuous Monitoring of Building Assets

Asset monitoring is a crucial aspect of DT in identifying potential faults, which facilitates the planning and execution of effective maintenance activities (Delgado and Oyedele, 2021). Rassõlkin *et al.* (2021) highlight that DT offers flexibility in data visualisation through efficient monitoring of a building and its assets. Effective monitoring is central to the continuous updating of information, which hinges on the efficiency of the digital twinning of the physical structure (Jiao *et al.*, 2023). In this context, sensors are employed to monitor non-geometric information about a building and its assets (Jiang *et al.*, 2021). Delgado and Oyedele (2021) emphasise that structural health monitoring (SHM) and building services monitoring (BSM) are primarily conducted in the built environment. While SHM identifies structural faults in building structures, BSM focuses on faults in HVAC, mechanical, electrical, plumbing, and lighting systems, among others (Hodavand *et al.*, 2023; Delgado and Oyedele, 2021). To elucidate the processes of conducting SHM and BSM, Delgado and Oyedele (2021) developed a DT asset monitoring process model (Figure 3.7), which is relevant to this study.

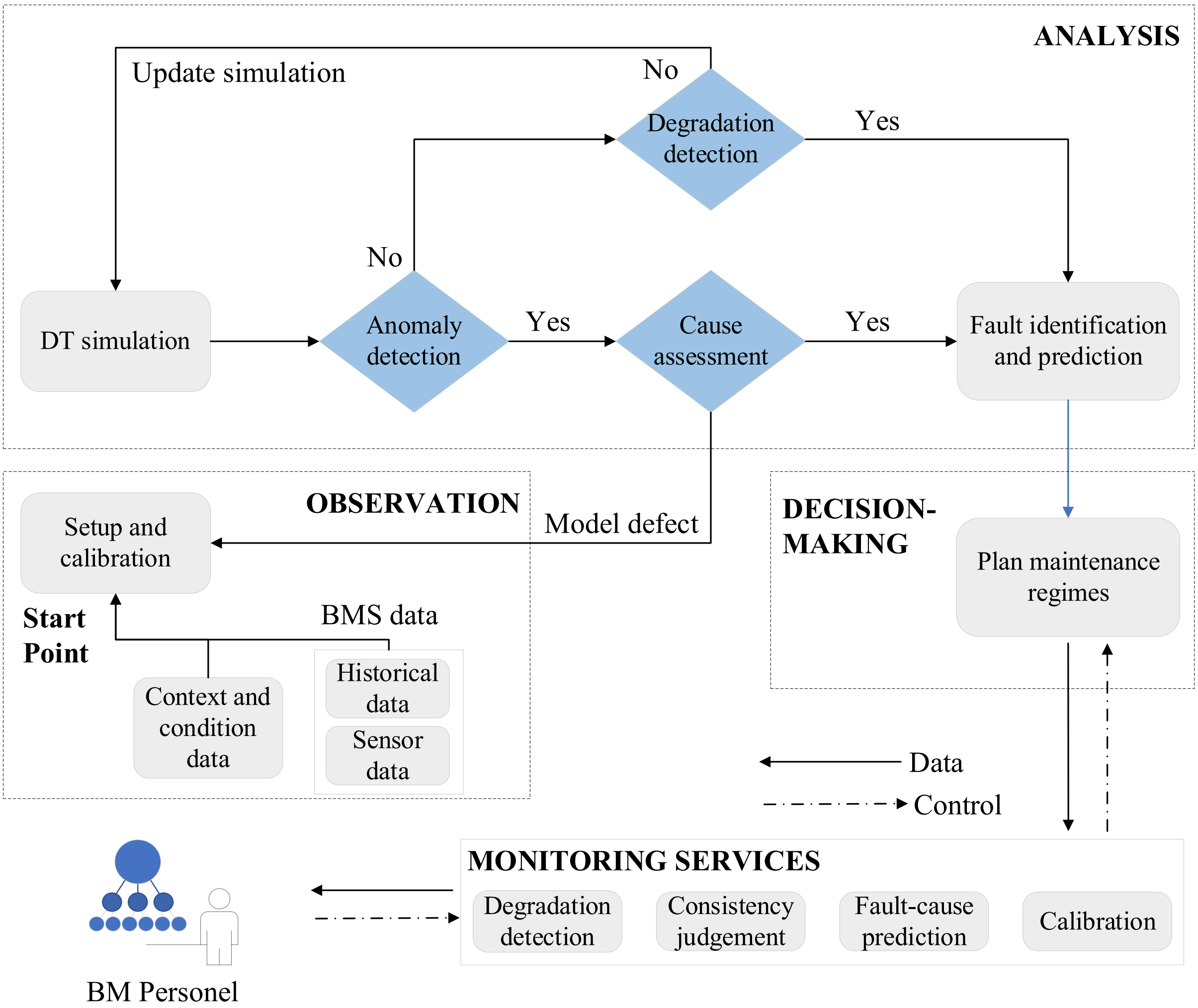


Figure 3.7: Digital Twin Monitoring Process Model for Structural Health Monitoring and Building Services Monitoring (Adopted from Delgado and Oyedele, 2021)

The model comprises four components: observation, analysis, decision-making, and monitoring services, as illustrated in Figure 3.7. The process begins with the calibration of the DT using data from the physical structure. In-depth data analytics becomes possible and more accurate through real-time data support (Xie *et al.*, 2023; Lin and Low, 2019). Meanwhile, in cases where there is insufficient data from the historical and sensor data pool for prediction, intelligent algorithms are employed to generate data from the data pool for the optimisation of maintenance activities (Jiao *et al.*, 2023). Such data is then simulated to detect anomalies, which are procedural activities geared towards identifying faults within a building asset (Hosamo *et al.*, 2022b). If an anomaly is detected, the potential cause is investigated. Furthermore, anomaly patterns can be categorised into point and contextual anomalies (Lu *et al.*, 2020c). A point anomaly arises when the data set deviates from its normal state, whereas contextual anomalies pertain to deviations in the data set occurring within a specific context.

Furthermore, when the anomaly is attributed to a model defect, a re-calibration of the DT is repeated (Delgado and Oyedele, 2021). Performing the re-calibration serves as a springboard for more responsive predictive analysis (Lin and Low, 2019). In instances where the cause does not relate to the model, a prediction of the likely cause is carried out. If no anomaly is detected from the predictive actions, a simulation is performed using available data (Xie *et al.*, 2023). Such a simulation aims to investigate the root cause of the anomaly further. Should any sign of degradation appear in the model, further predictions regarding its probable cause are made as it pertains to a contextual anomaly (Lu *et al.*, 2020). Hence, extrapolating these processes into practical applications for building assets will enable BM organisations to detect anomalies and signs of degradation promptly, thereby optimising them efficiently.

A recent study by Xie *et al.* (2023) further illustrates building fault detection and diagnosis by employing an AI model to analyse sensory data through its corresponding labelled time series. The model proved beneficial in managing dynamic data and detecting faults. Segovia and Garcia-Alfaro (2022) corroborate that utilising sensors to monitor building assets aids in anticipating unforeseen events. Drawing from these studies, BM organisations can discover new opportunities to enhance their processes and optimise building assets and systems. Furthermore, through the analytical capabilities of DT, potential issues can be identified before disrupting operational services (Xie *et al.*, 2023). Essentially, this contributes to an improved level of the asset's functional status, thus reducing chokepoints and unplanned downtime, among others (Lin and Low, 2019). Consequently, the remaining useful life (RUL) of the building asset can then be calculated to avert unforeseen asset breakdown (Talamo *et al.*, 2019).

3.6.2 Remaining Useful Life of a Building Asset

The RUL of an asset refers to the uptime during which the asset can be utilised for operations. According to Bondoc *et al.* (2022), DT can assist in determining the RUL of an asset using a data-driven historical approach. However, in a situation where maintenance files and records for a building asset are absent or inadequately documented, predicting the asset's future state becomes challenging (Mihai *et al.*, 2021). Therefore, real-time data from IoT devices can accurately provide the current state of an asset (Madubuike *et al.*, 2022). DT can be employed for fault detection and predicting asset failures by replacing outdated data with information generated by IoT devices (Agostinelli, 2021). This approach allows for the functional patterns of an asset to be replicated, achievable through AI analysis of the available data to identify the most appropriate time to conduct its maintenance (Davies *et al.*, 2022; Agostinelli, 2021). Thus, real-time data can facilitate the determination of a building asset's RUL.

Some studies have illustrated the use of DT in determining the RUL of assets and systems. For example, Aivaliotis *et al.* (2019) introduced a DT-based method for mirroring a device's physical attributes and generating virtual sensor data for prognostics and health management. Likewise, Davies *et al.* (2022) demonstrated the effectiveness of DT-based simulation models for maintenance optimisation. Both studies indicated that an asset's RUL could be readily estimated from fault history, maintenance history, and asset conditions (sensor data). Furthermore, Mihai *et al.* (2021) highlight that RUL is influenced not only by time but also by cycles or orders. For instance, during the simulation of an asset, it might encounter failures in specific cycles, influenced by a series of cycles predetermined before the predictive activity. Therefore, understanding the RUL of a building asset or system will enable BM organisations to improve their maintenance planning. Based on these studies, it is evident that DT has the potential to support BM management; however, it is crucial to recognise the factors hindering BM organisations from utilising it for maintenance activities.

3.6.3 Factors Affecting the Digital Twin Application for Building Maintenance Management

Factors and barriers exist in applying or implementing DT for BM management. However, in the literature, these factors are not expressly detailed in the context of BM management. Some studies have attempted to identify these factors using parameters that encompass different industries of application (Perno *et al.*, 2022; Singh *et al.*, 2021b). A review by Perno *et al.* (2022) points out that these factors and barriers to DT implementation are related to system integration, security, performance, organisational, environmental, and data quality. Consequently, some of these factors and barriers are discussed in the context of BM management.

1 Data-Related Issues

Data is central to the functioning of a DT. Nevertheless, data ownership and privacy issues severely limit DT utilisation (National Infrastructure Commission, 2017). Data and models have to be shared among stakeholders. Furthermore, data sharing is susceptible to concerns regarding data security and the intellectual property rights of different stakeholders (Broo *et al.*, 2022). Such data is frequently subject to the mindset of the stakeholders and an organisation's policies (Arowoiya *et al.*, 2024). These factors often result in data silos and inconsistencies in data synchronisation (D'Amico *et al.*, 2022; Singh *et al.*, 2021b). Additionally, security threats are inevitable in cyber processes but can be managed with appropriate measures (Perno *et al.*, 2022). Edge computing devices represent one strategy that can be deployed for data acquisition as they enhance data security within their purview, thereby mitigating cyber attacks or breaches during data transmission (Omrany *et al.*, 2023; Fang *et al.*, 2022). Other strategies for managing these data issues are discussed in Section 3.9.1.2.

Technically, data exists in various formats, which can be unstructured (such as Portable Document Format, Microsoft Word format), semi-structured (files from field personnel), or structured (Excel spreadsheets) (Singh *et al.*, 2021b). The sources of this data include BMS, asset management systems (AMS), space management systems (SMS), and sensors, among others (Hosamo *et al.*, 2022c; Lu *et al.*, 2020a, 2020c, 2019). However, data from most existing built assets may not be structured and often lack detailed design specifications in digital formats that are readable or compatible with DT (Camposano *et al.*, 2021). The lifecycles of most buildings span many years, and changes in technologies make it more challenging to manage the data of these buildings. Perno *et al.* (2022) emphasise that transitioning information from old technology to new can be problematic due to the compatibility of data from diverse sources and their structures into a common data environment. Some studies argue that data standardisation is one significant inhibiting factor impacting DT's application in the AEC industry (Arowoiya *et al.*, 2024; Elyasi *et al.*, 2023; Hosamo *et al.*, 2022a). Therefore, data needs to be adequately integrated through avenues such as ontology to allow seamless exchange between a physical structure and its virtual replica.

2 Financial Resources

Cost is one of the primary challenges in the implementation of DT (Qoseem *et al.*, 2024). The acquisition of new devices and technological infrastructure often requires financial investment, along with the recruitment of new personnel (Pomè and Signorini, 2023; Gulewicz, 2022). DT requires substantial computational resources to create and operate high-fidelity computer models and simulation processes (Singh *et al.*, 2021b). Such resources vary depending on the scope and objectives of the DT application for an asset. According to Opoku *et al.* (2021), the cost of DT applications can differ based on sophistication, type, and hierarchy (Opoku *et al.*, 2021). Madubuike and Anumba (2022) underscore that huge funding is required to set up a DT solution, emphasising that its benefits outweigh its setup costs. Thus, financial resources are crucial for implementing DT.

3 Organisational Dynamics

The adoption of DT by organisations is still in its infancy within the AEC industry (Arowoiya *et al.*, 2024; Pomè and Signorini, 2023; Delgado and Oyedele, 2021). While studies have focused on the technical challenges of DT implementation, research on its organisational aspects is lacking (Rassõlkin *et al.*, 2021; Lin and Low, 2019). As highlighted by Broo *et al.* (2022), organisations need to establish suitable mechanisms, such as financial backing and technical expertise, to bridge the knowledge gap among stakeholders regarding DT implementation, thereby fostering a collaborative working environment. They further emphasised that this issue is as critical as the technological challenges impacting DT's implementation. Moreover, advancements in technology are often met with resistance from an organisation's internal structures. Shahzad *et al.* (2022) point out that both employees and the organisational structure significantly impact the implementation of DT. Such an impact is associated with employees feeling threatened by the use of new technologies due to fears of job loss (Perno *et al.*, 2022). Gulewicz (2022) emphasises that a lack of technical know-how among employees regarding DT functions undermines its implementation. Furthermore, other organisational challenges persist, including conservative attitudes, technological literacy, and top management commitment to the adoption of digital technologies, which encompass DT (Elyasi *et al.*, 2023; Tripathi *et al.*, 2023a; Maganga and Taifa, 2022; Ern *et al.*, 2017; Love *et al.*, 1996). In addressing these challenges, Section 3.9.1.1 discusses various avenues.

4 Communication-Related Issues

Seamless data transmission between a physical structure and its virtual replica is crucial in DT application (Section 3.4). According to Barricelli *et al.* (2019), DT requires high-end, reliable internet connectivity for data exchange between a physical structure and its virtual replica. Hence, an appropriate communication framework is essential for successful DT implementation.

5 Technical Resources

DT is an emerging technology, one of the key Industry 4.0 technologies, and relies on various associated technologies, such as big data, IoT, and AI, among others, for its operations (Elyasi *et al.*, 2023; Hosamo *et al.*, 2022a; Madubuike and Anumba, 2021). DT has been widely applied in manufacturing and robotic industries compared to the AEC industry. As highlighted by Broo *et al.* (2022), the low maturity of DT within the AEC industry stems from limited technological advancements. Stakeholders in AEC may be unaware of the potential offered by Industry 4.0 technologies, which serve as a springboard for DT operations (Lu *et al.*, 2022; Karmakar and Delhi, 2021). To address this shortcoming, studies recommend that the AEC industry should maximise the potential of other Industry 4.0

technologies to increase the maturity level necessary for implementing DT, which would benefit maintenance purposes (Arowoiya *et al.*, 2024; Jasiulewicz-Kaczmarek *et al.*, 2020). Hence, BM organisations need to collaborate with other industries and researchers to become acquainted with Industry 4.0 innovations.

From an organisational standpoint, the absence of adequate infrastructure also hinders DT implementation. High-performance IT infrastructures, including hardware and software, are essential for exchanging, storing, and processing data within a DT system (Singh *et al.*, 2021b). Gulewicz (2022) recommends that organisations upgrade their infrastructure by purchasing new equipment to realise the full benefits of DT.

In summary, this section has attempted to highlight several factors affecting DT implementation, particularly from an organisational perspective. These factors encompass data-related issues, financial resources, organisational dynamics, communication-related issues, and technical resources. While these factors might militate DT implementation, the benefits to be derived from its use outweigh these drawbacks. Given that DT is an evolving innovation, Section 3.9.1 explores how a framework can facilitate its implementation at the organisational level.

3.7 Awareness of Digital Twin Application in Nigeria

The quest to utilise DT remains in its infancy worldwide, as discussed in Section 3.1. In Nigeria, a developing country, certain studies have explored DT applications in various industries, including agriculture, electricity, banking, construction, and oil and gas. For instance, in agriculture, Elijah *et al.* (2021) examined the application of DT to enable smart agricultural practices in Nigeria. Similarly, Nwaizu *et al.* (2022) investigated the utilisation of DT to evaluate value-chain changes in tomato production quality. Findings from these studies outline the benefits of DT in agriculture, emphasising how its application can significantly enhance the preservation and quality management of perishable goods during transport. In relating DT to the banking industry, Eleonu *et al.* (2020) explored an adaptive simulation model of a centralised locking system for banks in Nigeria, utilising DT technology. The study found that DT can improve security and operational efficiency in banks through real-time monitoring and adaptation of the locking system based on data-driven insights. In the oil and gas industry, Esiri *et al.* (2024) investigated the policy requirements and implementation strategies for DT usage, highlighting the significance of regulatory and strategic frameworks for its adoption. Likewise, Aliyu *et al.* (2021) examined the use of DT in the Nigerian electricity industry, revealing that it could enhance best practices within the study's industrial context. These studies have thus spotlighted the usefulness and benefits of DT in improving work activities across the studied industries.

In the AEC sector, Bello *et al.* (2024) examined the barriers to DT adoption in Nigeria's construction industry. The study noted a limited understanding and awareness of DT's potential, particularly in developing countries, and acknowledged that an understanding of its implementation barriers and interdependencies would assist organisations in its application. In regard to the awareness of DT, Oke *et al.* (2024) investigated the awareness levels of DT among construction professionals in relation to promoting timely project completion. The findings revealed a low level of awareness and utilisation of DT among professionals. Statistically, Eromonsele (2021) assessed the awareness of digital technologies such as BIM and DT, noting that Nigerian AEC professionals, particularly in Lagos State, have very little knowledge about DT technology. The study found that 9.5% of 42 respondents were aware of DT's application within the AEC industry, whereas 90.5% were unaware. Substantiating this finding, Bello *et al.* (2024) indicated that the awareness levels among construction professionals regarding DT were 76% low, 17% moderate, and 7% high. Thus, these studies reveal the evolving awareness of DT in Nigeria in recent years.

On DT's implementation feasibility, Arowoiya *et al.* (2024) investigated the drivers of DT implementation in the Nigerian construction sector. The study identified technological trends, data storage, safety, and customer satisfaction as key drivers of DT applications. Regarding maintenance activities, Ebiloma *et al.* (2023) examined the necessity of maintenance documentation for DT adoption, concluding that such documentation is critical for the effective maintenance management of hospital buildings and for facilitating its adoption. Thus, these studies underscore the importance of a comprehensive understanding of DT implementation requirements to promote its use in enhancing work efficiency.

These studies underscore the advantages, benefits, and applications of DT in enhancing work processes across certain industries in Nigeria. They highlight how DT not only streamlines operations but also fosters innovation and enhances operational efficiency. By integrating DT, organisations can bolster productivity, improve decision-making, and better respond to situational demands. These findings spotlight the necessity of embracing DT to maintain efficiency in an increasingly digital economy, with implications extending beyond immediate operational enhancements, which can broaden strategic advantages. Thus, these studies provide evidence that Nigeria, as a developing country, is progressively embracing technological innovations such as DT. While the pace may be slow, it calls for further research to uncover and harness its full potential, particularly in the AEC industry, which remains the least digitalised (Arowoiya *et al.*, 2024), to enhance work efficiency and productivity.

3.7.1 Suitability of Digital Twin for Building Maintenance Management in Nigeria

DT is a dynamic innovation suitable for managing issues related to data (Peng *et al.*, 2020; Lu *et al.*, 2020a; Antonino *et al.*, 2019). As previously discussed in Section 2.6.1, issues of maintenance reoccurrence include organisational, technical, financial, and user-related, each contributing to the deterioration of buildings and assets. By leveraging DT, these issues could be managed through the following avenues.

1. Centralisation of Data Management

One of the primary organisational issues in BM is the lack of a centralised data system (Ebiloma *et al.*, 2023). DT can effectively address this issue by integrating all building data (structural, operational, and maintenance history) into a single platform (Hosamo *et al.*, 2023b; Jiao *et al.*, 2023). Such integration facilitates better coordination and communication among maintenance teams and stakeholders, as real-time data from DT provides comprehensive insights into the building's status. DT also supports the automation of maintenance processes, ensuring that activities are conducted as scheduled, thereby enhancing organisational efficiency (Omrany *et al.*, 2023; Boje *et al.*, 2020). Studies have established that DT enables strategic and operational planning capabilities by providing stakeholders with richer data necessary for dynamic decision-making, thus overcoming traditional barriers of organisational silos and fragmented data systems (Han *et al.*, 2023; Hosamo *et al.*, 2023b; Marocco and Garofolo, 2022).

2. Predictive Maintenance and Fault Detection

Implementing DT in BM organisations can effectively mitigate technical challenges, such as the lack of technical expertise and outdated maintenance procedures (Marocco and Garofolo, 2021). DT uses IoT devices to continuously collect data, which is then employed to monitor the condition of buildings and predict maintenance needs before failures occur (Pomè and Signorini, 2023; Boje *et al.*, 2020). Such potential for predictive maintenance is crucial for the Nigerian maintenance context, where issues such as faulty design, the use of substandard materials, and users' misuse of buildings are prevalent, coupled with limited technical resources for management. According to studies, DT enhances the precision of maintenance activities by identifying potential issues and addressing them before they escalate into major faults (Hosamo *et al.*, 2023a, 2022b; Davies *et al.*, 2022; Mihai *et al.*, 2021). Thus, such predictive potential of DT extends the RUL of building assets, as discussed in Section 3.6.2.

3. Optimisation of Maintenance Budgets

Finance is one of the constraints hindering regular and proactive maintenance in Nigeria (Ndulue and Ifeanyiemoh, 2021). By leveraging DT, maintenance budgets can be optimised by prioritising activities based on criticality assessed through real-time data analytics (Ebiloma *et al.*, 2023; Gerber *et al.*, 2019). Such prioritisation ensures that limited financial resources are allocated effectively to maintenance activities, focusing on areas that require immediate attention to avoid costly repairs in the future. Studies highlight that DT can reduce maintenance costs through efficient resource management and extend the asset's operational lifecycle through timely interventions (Hodavand *et al.*, 2023; Hosamo *et al.*, 2022c).

4. Improving Maintenance Attitude and User Engagement

In Nigeria, building users' attitudes toward maintaining their buildings often lean toward reactive strategies rather than proactive ones (Adepoju *et al.*, 2017). DT can facilitate a shift in this mindset by visibly demonstrating the benefits of proactive maintenance through detailed simulations and predictive analytics (Enyejo *et al.*, 2024; Tavakoli *et al.*, 2023). BM stakeholders and users can utilise DT for interactive visualisations of building performance, alongside the consequences of neglecting maintenance, which can enhance awareness and promote a more maintenance-conscious attitude (Pomè and Signorini, 2023; Perno *et al.*, 2022; Gerber *et al.*, 2019). Such awareness of DT's interactive capabilities can be showcased at workshops and training sessions to educate stakeholders about the importance of regular maintenance of buildings and assets, thereby changing long-standing attitudinal norms (Tripathi *et al.*, 2023b; Gulewicz, 2022; Parida *et al.*, 2011). While these studies have spotlighted the capabilities of DT to support BM organisations in managing maintenance-related issues, it is essential to understand the requirements for its development.

3.8 Infrastructure and Platforms Requirements for Digital Twin Development

Certain technologies and infrastructure are essential for developing DT in the built environment. However, studies indicate that no standard documents specify the requirements for its development (Hodavand *et al.*, 2023; Lu *et al.*, 2022). Meanwhile, two policy documents exist for digital technology usage in the UK, which have also been adopted in other parts of the world (Lu *et al.*, 2022). These are Data for the Public Good (National Infrastructure Commission, 2017) and the Gemini Principles (Bolton *et al.*, 2018). Data for the Public Good outlines measures for collecting and sharing public data using digital technologies without infringing upon the public's privacy and rights. The Gemini Principles further specify nine principles to guide the use of digital technologies: public good, value creation, insight, security, openness, quality, federation, curation, and evolution.

These documents can be utilised to guide the DT development process, ensuring the right information is available to the right people at the right time, for the purpose of facilitating informed decision-making. Their application will address privacy and rights infringement issues during the DT development process. Moreover, studies have proposed certain technologies and infrastructure for DT development, which are presented in Figure 3.8 (Pomè and Signorini, 2023; Hosamo *et al.*, 2022a; Madubuike *et al.*, 2022; Rasheed *et al.*, 2020; To *et al.*, 2021). These include big data, IoT devices, modelling technologies, communication technologies, computational infrastructures, and extended reality. Big data incorporates data generated from a physical structure and its activities through BAS and sensors, which originate from its entities, information systems, and the internet (Hosamo *et al.*, 2022a; Mokhtari *et al.*, 2022). While BAS collects maintenance data for an asset, sensors monitor its condition and generate operational data (Hosamo *et al.*, 2022c). Thus, the diverse data sources of a building and its assets can be organised into a big data set.

Figure 3.8: Digital Twin Enabling Technologies

As discussed previously in Section 2.7.1.5, IoT represents a comprehensive network of smart devices that can autonomously organise and share data and resources to adapt to various situations and environmental changes (Khajavi *et al.*, 2019). It facilitates communication between the physical and virtual domains by configuring smart devices through ubiquitous technologies (Sharma *et al.*, 2022; Agostinelli, 2021). Such communication is achieved using wireless sensor networks (WSN), which consist of interconnected sensors (Agostinelli, 2021). These sensors assist in collecting non-geometric data from a physical structure, contributing to the development of intelligent assets and environments (Lu *et al.*, 2020b).

Additionally, tags such as quick response (QR) codes, barcodes, and radio-frequency identification (RFID) have been employed to connect dispersed assets or building components into a unified entity (Lu *et al.*, 2020b). These tags can link physical components with technologies such as BIM for effective utilisation (Hosamo *et al.*, 2022c). In recent years, IoT has been integrated into smart buildings. Given its ubiquitous computing potential, physical structures can be controlled through data analysis from sensors, which, in turn, are actioned using actuators (Agostinelli, 2021; Khajavi *et al.*, 2019). Actuators, similar to starters in a mechanical system, execute necessary actions in the components of a physical structure (Agostinelli, 2021). Thus, IoT devices assist in collecting data from a physical structure for maintenance activities, with data transmitted to its virtual replica through communication frameworks.

Communication frameworks and protocols are essential for seamless connections in DT. They facilitate data transmission between a physical structure and its virtual replica. Examples include Message Queue Telemetry Transport (MQTT), Constrained Application Protocol (CoAP), Advanced Message Queuing Protocol (AMQP), and mobile data (Segovia and Garcia-Alfaro, 2022). Additionally, the technologies employed for data transmission comprise both data transfer formats and transmission methods: wired or wireless (Fang *et al.*, 2022). As highlighted by Fang *et al.* (2022, p.4305), data transfer formats include "*Extensible Markup Language (XML), Standard for the Exchange of Product Model Data (STEP), Asset Administration Shell Format (AAS), Computer Aided Exchange (CAEX), JavaScript Object Notation (JSON), and Yet Another Markup*".

Wired transmission methods include optical fibre and cable (Fang *et al.*, 2022). Wireless methods encompass Bluetooth, fifth-generation wireless cellular networks (5G), Wireless Personal Area Networks, IPv6 over Low-power Wireless Personal Area Networks, Wireless Local Area Networks, Worldwide Interoperability for Microwave Access, near-field communication (NFC), and are used to send and receive data from sensors and actuators (Segovia and Garcia-Alfaro, 2022; Madubuike and Anumba, 2021). According to Segovia and Garcia-Alfaro (2022), optical fibre cabling or 5G technology is predominantly utilised as high-speed network links for seamless connections between a physical structure and its virtual replica. Hence, an appropriate communication framework, transmission format, and method are pivotal for seamless data exchange in DT.

3.8.1 Digital Twin Model Development Architecture

The methods for model development in DT are crucial, due to its high-fidelity modelling technologies that require a sophisticated dynamic approach (Opoku *et al.*, 2021). According to studies, DT development comprises five layers: data acquisition, transmission, digital modelling, data/model integration, and the service layer (Lu *et al.*, 2020a; Xie *et al.*, 2020a; Lu *et al.*, 2019). These layers constitute DT's architecture by acquiring the necessary data, facilitating communication between models, integrating data, analysing data, and executing actions on the physical structure through actuators or other suitable means, including human intervention. Figure 3.9 illustrates a diagrammatic representation of some key technologies and functional system architecture in developing a building DT, integrating various Industry 4.0 technologies to foster a community of practice among them.

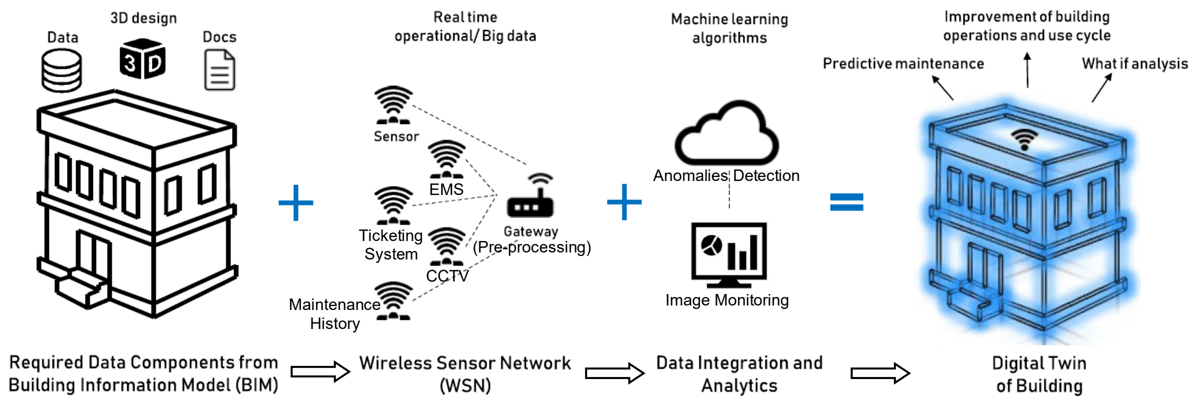


Figure 3.9: Some Essential Components for the Development of a Building Digital Twin (Adapted from Agostinelli, 2021; Khajavi *et al.*, 2019)

1 Data Acquisition Layer

The acquisition of data in the development of DT is essential, as it forms the foundation upon which other layers are built (Jiao *et al.*, 2023). Data pertaining to the operations of the physical structure is collected through various means to create a large data set. Data acquisition may involve technological devices such as IoT devices (WSN), random collection devices, cameras, scanners, and historical building/asset management data (Jiao *et al.*, 2023; Opoku *et al.*, 2021; Lu *et al.*, 2020a). Dynamic data from sensors includes temperature, pressure, air volume, and space occupancy information related to a building asset and its environment, which aids in understanding asset operations (Hellenborn *et al.*, 2023; Tavakoli *et al.*, 2023; Hosamo *et al.*, 2022c). This type of data is referred to as online data. Pomè and Signorini (2023) highlight that sensors are crucial for monitoring the status and performance of a building and its assets. As noted in studies, maintenance information such as design criteria, asset/facility status, maintenance histories, and geometrical parameters is classified as offline or historical data (Hodavand *et al.*, 2023; Wang *et al.*, 2022).

Jiao *et al.* (2023) categorise these data sources (dynamic and historical data) as measurement data and introduce another type called simulation data, which is derived from physics-based models using tools such as DeST, TRNSYS, Ecotect, and eQuest, among others. Furthermore, contactless technologies like bar codes, QR codes, RFID, and image-based techniques are employed for data tracking and connecting building components into a cohesive unit (Madubuike and Anumba, 2021; Lu *et al.*, 2019). AR, which supports real-time visualisation of physical structure information, assists in the collection of maintenance inspection data (Hosamo *et al.*, 2022a, 2022c). Section 2.7.1.8 explores AR's relevance for maintenance activities. Thus, obtaining the appropriate data set is vital for the development of DT.

2 Transmission Layer

This layer facilitates the transmission of acquired data, enabling its transfer from the acquisition layer to the modelling layer. In the development of DT, physical facilities and spaces within a building are equipped with devices such as tags and sensors to capture data (Lu *et al.*, 2020a, 2019). The captured data, which may be unstructured, semi-structured, or structured, is organised into data sets using technologies such as Zigbee base stations (Wang *et al.*, 2022). Edge computing is employed to pre-process time-sensitive data for temporary storage in edge devices such as IoT sensors and smart cameras, which eliminates issues related to transmitting data to a non-time-driven cloud server (Segovia and Garcia-Alfaro, 2022; Opoku *et al.*, 2021).

Moreover, data is transmitted through various mediums, depending on the transmission range, type (wired or wireless), data speed, and volume (Omrany *et al.*, 2023; Fang *et al.*, 2022). These mediums encompass short-range wireless network systems like Wi-Fi, Bluetooth, and NFC, as well as ultra-wideband and long-range wireless network systems, such as spread spectrum, fourth/fifth generation (4G/5G), and long-range wide-area networks (Omrany *et al.*, 2023; Lu *et al.*, 2019). Wired network systems include coaxial, fibre optic, and twisted pair cables (Omrany *et al.*, 2023). According to Fang *et al.* (2022), wireless transmission technologies are more cost-effective and easier to implement, while wired transmission is highly stable. Lu *et al.* (2019) emphasise that wireless transmission is predominantly utilised for data exchange in DT. Therefore, based on the later study, wireless connectivity is expected to facilitate more seamless data transfer from the physical structure to the virtual model.

3 Digital Modelling Layer

A digital model is central to the development of DT. According to Liu *et al.* (2021b), DT models are categorised into physical and semantic data. Physical models require a detailed representation of their physical structure alongside a replica identity. Conversely, semantic data models are generated using AI. In the built environment, as indicated by studies (Drobnyi *et al.*, 2023; Camposano *et al.*, 2021), such digital models are employed to create a building's digital representation, encompassing “as-planned”, “as-designed”, and “as-built” situations, aiding in understanding various stages of the building lifecycle. Angjeliu *et al.* (2020) highlight that accurate geometrical information within a digital model is a critical component of DT. This model can be developed through two approaches (Barabanova *et al.*, 2023): it may originate from construction professionals using BIM, CAD, and CAE or be reconstructed directly from an existing building. According to Xie *et al.* (2020a), BIM is the preferred tool among AEC professionals for developing digital models of buildings, due to its capacity to manage building information if consistently updated throughout its lifecycle. Alternatively, the digital model of an existing building can be created using point clouds, segmentation, and geometry reconstruction methods, assisted by measurement technologies such as laser scanners, photogrammetry, and light detection and ranging (LiDAR), among others (Maru *et al.*, 2023; Pan *et al.*, 2022; Angjeliu *et al.*, 2020; Stojanovic *et al.*, 2018).

According to studies, photogrammetry is suitable for scanning the exteriors of building structures, while stereovision (using infrared or RGB cameras) and 3D LiDAR are more appropriate for interior assets and infrastructures that require higher scanning accuracy (Maru *et al.*, 2023; Pan *et al.*, 2022; To *et al.*, 2021; Angjeliu *et al.*, 2020; Stojanovic *et al.*, 2018). Moreover, To *et al.* (2021) emphasise that stereovision provides a more consistent image scan of buildings compared to 3D LiDAR, highlighting that photogrammetry is inadequate for interior scans. Pan *et al.* (2022) corroborate that cameras with high resolutions and a large field of view yield higher-quality point clouds. In contrast, photogrammetric images are produced as laser-scanned point clouds. Angjeliu *et al.* (2020) indicate that the image-based method provides better geometrical scan measurements than laser scanning, as it employs image-processing algorithms to reconstruct geometry. A review by Drobnyi *et al.* (2023) elaborates on various techniques for reconstructing and maintaining existing building geometry using point cloud datasets.

Regarding the cost of capturing 3D point clouds (non-interpreted data with visual interpretation), Stojanovic *et al.* (2018) emphasise that scanning with a mobile phone is less expensive than using laser scanning devices. Angjeliu *et al.* (2020) elaborate that suitable mobile devices with adequate camera pixels can generate affordable, flexible interior images. Meanwhile, Stojanovic *et al.* (2018) argue that the visual details captured in 3D point cloud images using mobile phones may have lower fidelity compared to those obtained from 3D scanners. Thus, based on these studies, a 3D digital building model can be developed at any point in time for the development of DT or any other purpose.

4 Data/Model Integration Layer

This layer serves as the core processing unit of DT, as data must be processed promptly (Fang *et al.*, 2022). All historical data pertaining to physical assets and systems from BMS, AMS, and SMS, along with real-time data from tags and sensors, are analysed and simulated in this layer (Li *et al.*, 2020). These data are stored in various mediums, such as relational databases, data warehouses, MySQL databases, model databases, and JSON databases (Han *et al.*, 2023). Therefore, integrating these data is vital for their application within DT. El Mokhtari *et al.* (2022) identify two approaches used to structure these data: linked data and ontologies. Linked data is employed to store data from discrete points, such as historical information, and relies on software like BIM to integrate data into a cohesive environment.

Conversely, ontologies provide a robust structure for data integration, utilising semantics to offer shared and machine-understandable vocabularies for data exchange across diverse sources such as BAS, CMMS, and sensor data into DT (Hosamo *et al.*, 2023a; Mokhtari *et al.*, 2022; Barricelli *et al.*, 2019). Gispert *et al.* (2023) highlight that ontologies related to building assets include Industry Foundation Classes Web Ontology Language (IFCOWL), Project Haystack, and Green Building XML, among others. Some studies have demonstrated that ontologies simplify and resolve the complexities of data integration and interoperability (Gispert *et al.*, 2023; Hosamo *et al.*, 2022a). According to studies, Industry Foundation Classes (IFC), Brick, and Construction Operation Building Information Exchange (COBie) serve as schemas for ontology (Xie *et al.*, 2023; Hosamo *et al.*, 2022c; Mokhtari *et al.*, 2022).

The IFC schema, which allows for the coding of building data throughout its lifecycle, is used in BIM as an open data format to integrate data from various sources into the BIM environment. Several studies have shown how data from various sources is integrated into the BIM environment using IFC (Hosamo *et al.*, 2022c; Moretti *et al.*, 2020). The Brick schema is lightweight in conceptual structure, using tags, mapping, and classes to describe building elements (Xie *et al.*, 2023). Additionally, COBie is a protocol developed to facilitate the exchange of building information and aids in the integration of digitised data into BIM using spreadsheets (Hosamo *et al.*, 2022c). Moreover, studies suggest that while IFC offers geometric and semantic information within a BIM model, COBie provides details, spatial data, and graphical information about an asset (Xie *et al.*, 2023; Hosamo *et al.*, 2022c). Furthermore, an application programming interface (API) can be employed to link data within the BIM environment (Lu *et al.*, 2020a). Omrany *et al.* (2023) elaborate that APIs assist in standardising data formats from various software sources for seamless integration into a unified unit.

After the data has been integrated with the digital model, it undergoes screening and filtering to eliminate unwanted and erroneous data, which can act as impurities in data analysis (Jiao *et al.*, 2023). In the analysis of the integrated data model, AI, ML, and simulation engines capable of continuously simulating the assimilated data are employed (Pomè and Signorini, 2023; Lu *et al.*, 2020b; Delzendeh *et al.*, 2020). The analysis begins with fault detection and diagnosis, as discussed in Sections 3.6.1 and 3.6.2. Such analysis is followed by simulating potential solutions to the identified faults (Xie *et al.*, 2023). Furthermore, this layer differentiates the simulations performed by DT from those of the design phase (Villa *et al.*, 2021). The former requires a physical asset/system and a sensor network, while the latter exists solely within a virtual domain. Hence, the simulations conducted at this layer can facilitate effective and dynamic data management for DT users to improve decision-making.

5 Service Layer

This layer represents the apex of DT development, where data interpretation obtained from the data/model integration layer becomes usable to end users. This layer enables end users to interact with the developed DT (Zhao *et al.*, 2022; Lu *et al.*, 2020a). Such interaction can occur through portable devices for visualising data and models (Madubuike and Anumba, 2021). According to Hodavand *et al.* (2023), extended reality visualisation tools, such as AR and VR, can enhance the understanding of a building's physical space in the action of analysed data. On one hand, AR assists end users, such as the maintenance team, in taking informed actions based on the analysed data. On the other hand, VR provides a platform that engages human sensory systems with a virtual environment to optimise maintenance activities (Hosamo *et al.*, 2022a, 2022c). Section 2.7.1.7 discusses the usefulness of VR for maintenance tasks. Thus, by leveraging these technologies, the maintenance team will find it easier to act upon the analysed data and manage the identified maintenance-related issues.

In the long run, this layer reveals the technical usability of a developed DT model by its end users (Lu *et al.*, 2020b). Angjeliu *et al.* (2020) underscore that the accuracy of a developed DT is evaluated through verification and validation processes. Verification ensures that a model will be implemented accurately while representing its conceptual idea and proposed solution. In contrast, validation assesses the accuracy of the proposed model from the perspective of its intended users (Angjeliu *et al.*, 2020). Therefore, this layer provides the end users of a developed DT model, such as BM organisations, with the right information to optimise and better plan their maintenance activities through simulation outcomes and scenario analysis of the physical building and its assets.

In summary, developing a DT model starts with collecting the appropriate data, which is then transmitted to a digital model: a model created at the inception of a building or developed during its lifecycle. This acquired data is integrated into the digital model to evaluate the physical structure and identify faults (condition monitoring). Subsequently, incorporating AI or statistical models facilitates the prediction and prescription of suitable solutions for the detected faults in the physical structure. DT can provide BM organisations with more comprehensive information based on these processes to enhance planning and decision-making for maintenance activities.

3.9 Digital Twin Organisational Implementation

The AEC industry is gradually adopting technologies within its processes (Alwashah *et al.*, 2024; Brozovsky *et al.*, 2024; Luo *et al.*, 2022). Evidence of such adoption is found in the use of technologies like BIM, particularly for managing design and construction phases, and in conjunction with other Industry 4.0 technologies for overseeing the O&M phase of a building's lifecycle (Brunone *et al.*, 2021). Moreover, DT has emerged as a promising solution for managing the O&M phase due to its capability to capture real-time data from a physical building and perform scenario analysis (Lu *et al.*, 2022). A review by Madubuike *et al.* (2022) highlights that the practical application of DT is increasing within the construction industry. This increase is evident as several studies have explored how DT can be implemented technically (Broo *et al.*, 2022; Rassõlkin *et al.*, 2021; Lin and Low, 2019).

DT, as defined earlier in Section 3.2, is the virtual representation of a physical entity, system, or process that features data exchange and human interaction, driving the scenario analysis results from the virtual model to the physical structure, and thus enabling bidirectional data communication. Hence, implementing DT necessitates a systematic approach that encompasses several key components involved in its development, as discussed in Section 3.8.1. While DT's capabilities to collect and analyse data through technology focus on computable outputs from the data (Section 3.6) and primarily address the technical aspects of its implementation (Rassõlkin *et al.*, 2021; Lin and Low, 2019), its organisational implementation involves the essential changes within the organisation required for effective integration (Broo *et al.*, 2022). DT's organisational implementation encompasses the adoption of a structured methodology that facilitates its development, allowing organisations to maximise its potential in supporting their operational dynamics (Sharma *et al.*, 2022; Oliveira, 2020; Lu *et al.*, 2019). It includes investment in appropriate technological infrastructure to support organisational digitalisation (Gulewicz, 2022). Such investments encompass not only cutting-edge software and devices, but also essential data management systems that enable effective analytics and decision-making (Enyejo *et al.*, 2024; Han *et al.*, 2023).

Stakeholder engagement, from top management to operational employees, is also pivotal for ensuring that the DT implementation process yields valuable insights and transformation benefits (Enyejo *et al.*, 2024; Gerber *et al.*, 2019). Such engagement not only promotes the capabilities of DT but also facilitates its smoother implementation and adoption. Therefore, DT organisational implementation encompasses not merely the technical deployment of the technology but also the adaptation of organisational structures, processes, and human resources to fully harness its capabilities (Elyasi *et al.*, 2023; Gulewicz, 2022). This includes strategic planning, stakeholder engagement, change management, and capacity-building initiatives (Esiri *et al.*, 2024; Elyasi *et al.*, 2023).

For this study, the organisational implementation of DT refers to the process by which an organisation adopts, integrates, and operationalises DT technology to enhance its operations, processes, and outcomes (Broo *et al.*, 2022; Gulewicz, 2022; Oliveira, 2020). It involves aligning the characteristics of DT (Section 3.4) and its architecture (Section 3.8.1) with the organisation's goals, resources, infrastructures, and structure. Such alignment optimises performance and improves decision-making in achieving specific organisational objectives, such as predictive maintenance, resource management, and operational efficiency (Vieira *et* *al.*, 2022; Oliveira, 2020). Organisational alignment with DT can yield several benefits, including:

1) Improving stakeholder collaboration by centralising data and insights on a single platform (Esiri *et al.*, 2024).
2) Fostering innovation by providing a platform to simulate and optimise processes without disrupting actual operations (Omrany *et al.*, 2023; Xie *et al.*, 2023).
3) Enhancing operational efficiency through the integration of real-time monitoring and predictive analytics of buildings and assets (Broo *et al.*, 2022).
4) Facilitating the organisation's transition towards more data-driven and predictive decision-making processes (Lu *et al.*, 2019).

With these benefits, if BM organisations successfully implement DT, they will be more strategic and efficient in managing maintenance-related issues. While some studies have highlighted the usefulness and benefits of DT for supporting organisations in optimising their operations, there is no clear evidence of a structured framework for its implementation at the organisational level (Broo *et al.*, 2022). Hence, it is imperative to explore the development of a structured framework and gain a deeper insight into the requirements for implementing DT.

Studies have established various models and frameworks for change management in the implementation of innovation within organisations (Bussiglieri, 2023; Tripathi *et al.*, 2023a; Rawat *et al.*, 2022). These include Lewin's model, the Change Acceleration Process (CAP), Kotter's Change Model, the McKinsey Model, the Bridges Transition Model (BTM), the Prosci Model, and the People, Process, and Technology (PPT) framework, among others. Based on reviews of these models and frameworks, the BTM emphasises the people dimension of organisations, while Lewin's, Prosci's, Kotter's, and McKinsey's models and the CAP place greater emphasis on the dimensions of people and processes. Although these models and frameworks are useful for implementing innovation in organisations, they do not fully consider all three dimensions crucial for effective implementation. For this reason, this study employs the PPT framework, which considers all three organisational dimensions. Thus, it is imperative to explore how DT can be implemented at the organisational level, particularly for BM organisations, to support the management of maintenance activities using the PPT framework.

Meanwhile, theoretically, a framework aids in guiding a study towards its desired outcome and can be utilised in the following ways (Maganga and Taifa, 2022; Varpio *et al.*, 2020):

1) To explain a phenomenon that has occurred in nature or within a specific context/event.

2) To establish causality between factors or variables.

3) To help predict the outcomes of a specific problem or scenario.

4) To establish boundary conditions that help challenge or extend existing knowledge.

Therefore, this study employs the PPT framework as a research lens. This choice aims to extend existing knowledge by developing an approach to frame the implementation of DT for BM organisational management. The PPT framework carefully considers an organisation's people, process, and technology dimensions in implementing innovation, which is often overlooked by other organisational models and given less consideration. Subsequently, its application as a research lens to guide this study is discussed.

3.9.1 People Process and Technology Framework

Over the years, the PPT framework has been a cornerstone in studies exploring how innovations can be implemented in organisations to enhance their operational efficiency (Tripathi *et al.*, 2023a; Halim *et al.*, 2020; Ern *et al.*, 2017; Prodan *et al.*, 2015). The framework's strength lies in its comprehensive use of dimensions, which are pivotal to an organisation's structure (Kayikci *et al.*, 2023; Parida *et al.*, 2011). Its comprehensive application equips the organisation's staff with complete control over their work, boosts efficiency, and optimises their activities (Ern *et al.*, 2017). According to Tripathi *et al.* (2023b), the PPT framework is based on a systematic interconnection among its dimensions, creating balance in an organisation's activities.

In brief history, the PPT framework was initially developed by Harold Leavitt in 1964 as a Diamond model of structure, technology, people, and tasks. Bruce Schneier modified it in 1996 to focus on people, processes, and technology (Tripathi *et al.*, 2023a; Prodan *et al.*, 2015). In an organisational context, individuals perform activities, while the process enhances these activities for better efficiency, and technology supports the personnel in executing their tasks, optimising the process (Tripathi *et al.*, 2023a; Parida *et al.*, 2011). In essence, an organisation's staff engage in activities through a well-optimised process, augmented by technology, to improve efficiency. Thus, an organisation can achieve greater work efficiency by optimising the interconnections among its PPT dimensions.

Studies indicate that the PPT framework functions like a tripod, with each dimension holding equal importance (Papic and Cerovsek, 2019; Parida *et al.*, 2011). For instance, if there is going to be a change involving innovative technologies such as DT, modifications to the people and process dimensions are necessary to align with the proposed technology (Tripathi *et al.*, 2023a; Papic and Cerovsek, 2019). Due to advancements in technology, an organisation needs to explore innovations to facilitate its work activities and address client requests (Okereke, 2020; McArthur *et al.*, 2018; Parida *et al.*, 2011). However, such innovations will only be effective if implemented through a structured process and managed by competent personnel (Tripathi *et al.*, 2023a; Hamou-Lhadj and Hamou-Lhadj, 2008; Love *et al.*, 1996). If an organisation does not employ a well-defined and structured process, personnel actions may be inefficient. Hence, an organisation needs to adequately structure its PPT dimensions to implement technological innovations such as DT effectively.

This study, therefore, employs the PPT framework to explore the interconnection, as illustrated in Figure 3.10, for BM organisations regarding how maintenance activities can be conducted using DT. It will explore how the needs and challenges of the maintenance team are addressed to optimise their maintenance activity processes through the diligent use of DT. Thus, exploring how these different dimensions of the PPT framework can be leveraged to situate the implementation of DT for BM management is imperative.

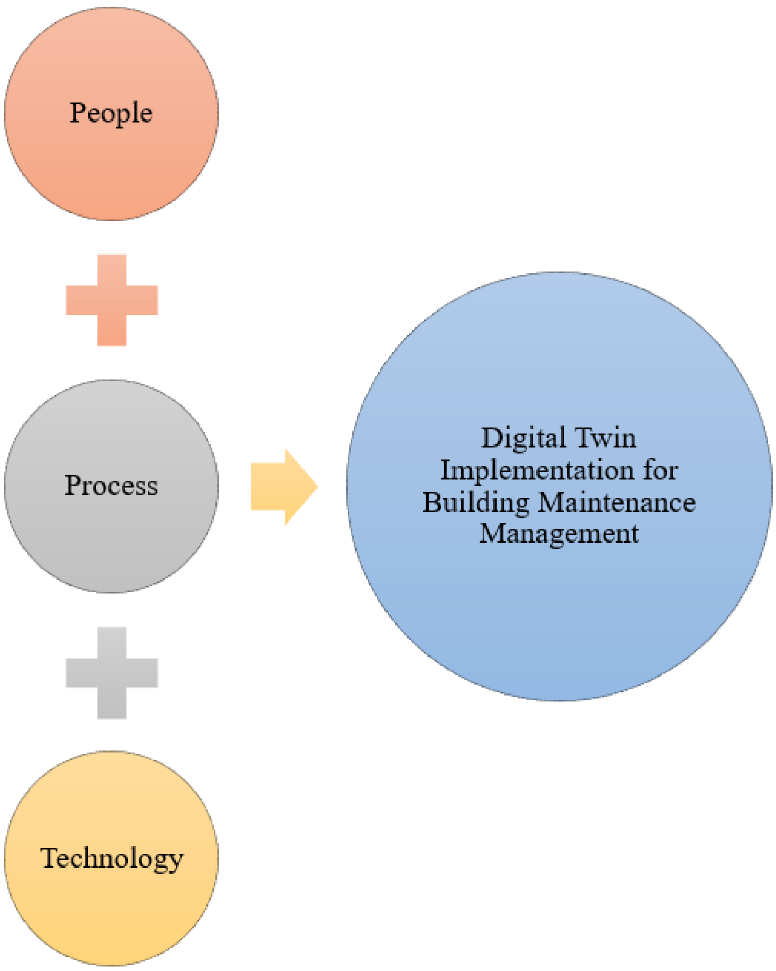


Figure 3.10: Organisational Dimensions of Digital Twin Implementation for Building Maintenance Management

1. **People:**

The people dimension of the PPT framework pertains to the human resources within an organisation, showcasing diverse skills and competencies essential for fostering a collaborative work environment (Maganga and Taifa, 2022; Prodan *et al.*, 2015). According to Ern *et al.* (2017), individuals are the processing units of an organisation, facilitated by their ability to sense, think, and make informed decisions during job execution. Maganga and Taifa (2022) emphasise that an enhanced people-centric process workflow can create a more pleasant work environment, supported by appropriate technological tools for efficient job performance.

Spotlighting DT as a technological innovation to support work activities, studies on its implementation reveal that the focus has often been on its technical aspects while overlooking the importance of people and processes, which are crucial for its organisational application (Broo *et al.*, 2022; Rassõlkin *et al.*, 2021; Lin and Low, 2019). Hamou-Lhadj and Hamou-Lhadj (2008) underscore that without skilled and competent personnel within an organisation, implementing technological innovations will encounter several challenges and barriers. Studies substantiate that employee resistance to change, conservative attitudes, technological literacy, and top management commitment have been barriers to the adoption of technological innovations (Elyasi *et al.*, 2023; Tripathi *et al.*, 2023a; Maganga and Taifa, 2022; Rawat *et al.*, 2022; Ern *et al.*, 2017; Love *et al.*, 1996).

To address these challenges, Maganga and Taifa (2022) suggest that recruiting skilled personnel with knowledge of technological innovations is crucial, as this will assist organisations in effectively leveraging these technologies for their operations. Zizic *et al.* (2022) highlight that the concept of the "operator of the future" is people-centric, revolving around skilled personnel capable of harnessing the potential of technologies or machines for their tasks. However, within the AEC industry, studies indicate that resistance to innovative changes significantly hinders the implementation of digital technologies (Arowoiya *et al.*, 2024; Elyasi *et al.*, 2023). To mitigate this issue, Kumar *et al.* (2022) recommend that a people-centric approach can drive change management in re-engineering organisational operations towards the adoption of digital technologies. Maganga and Taifa (2022) also recommend adequate personnel training in the skills necessary to use the proposed or newly implemented technology. This training can be facilitated through continuous professional development (CPD) initiatives, such as workshops, seminars, and certifications (Tripathi *et al.*, 2023b; Gulewicz, 2022; Parida *et al.*, 2011). Workshops and seminars will help broaden the staff's understanding of the technical aspects of an innovation and its relevance to their workflow.

Certification acquisition serves as another valuable avenue for organisational staff to expand their knowledge, skills, and expertise in innovation (Sachowski, 2018; Ern *et al.*, 2017). This avenue supports the upgrading of staff knowledge and validates previously acquired skills. To implement these solutions effectively, top management can champion their execution within the organisation, maximising the potential of technological innovations (Tripathi *et al.*, 2023a; Maganga and Taifa, 2022). Accordingly, organisations need to invest in human resources and understand what actions need to be taken, why they are necessary, and how they will be advantageous to their operations (Tripathi *et al.*, 2023a; Hamou-Lhadj and Hamou-Lhadj, 2008). Thus, without recruiting the right human resources and training existing staff, organisations will encounter barriers to implementing innovative technologies or processes.

In the context of maintenance activities, the people dimension encompasses BM stakeholders and other parties relevant to its execution, as discussed in Section 2.5. Furthermore, Karmakar and Delhi (2021) note that the involvement of certain individuals is crucial for effectively employing Construction 4.0 during the O&M phase. These individuals include facilities engineers, data analysts, document controllers, and personnel tasked with monitoring and controlling automation. Studies indicate that for an organisation to fully optimise the potential of innovative technology, several actions need to be undertaken, including stakeholder engagement, change management, effective communication strategies, and staff training (Elyasi *et al.*, 2023; Tripathi *et al.*, 2023a; Gulewicz, 2022; Parida *et al.*, 2011).

Organisational stakeholders, such as top management, departmental heads, and operational staff involved in decision-making, are pivotal to the organisation's success (Maganga and Taifa, 2022; Opoku *et al.*, 2022). Their positive or negative decisions will profoundly influence the organisation's overall structure, as measured by task performance (Tripathi *et al.*, 2023a). While the decision to implement an innovation lies with top management, input from other staff is critical, as they are the ones who will actually utilise it in their roles (Agrawal *et al.*, 2022; Parida *et al.*, 2011). Essentially, all organisational stakeholders need to have unanimous buy-in for the implementation of innovation in organisational activities. Additionally, the decision to adopt an innovation can be facilitated through regular meetings to inform stakeholders of its benefits and advantages. These meetings can clarify any uncertainties among stakeholders, such as operational staff, and ensure that the innovation supports their activities (user-centric) rather than rendering them redundant or leading to job loss (Perno *et al.*, 2022).

Change management is another essential strategy for implementing innovative technology (Aliyu *et al.*, 2021; Butt, 2020; Parida *et al.*, 2011; Shelbourn *et al.*, 2007). It involves establishing contingency plans to address unforeseen challenges arising from innovation implementation, ensuring that organisational staff can adapt it accordingly to their activities (Aliyu *et al.*, 2021; Butt, 2020). Shelbourn *et al.* (2007) elaborate that the principles of change management originate primarily with the organisational staff, not the organisation as a whole. Meanwhile, introducing innovation can disrupt workflow, as not all staff may have the same capacity to embrace or adjust to the new processes (Aliyu *et al.*, 2021). In this context, Elyasi *et al.* (2023) emphasise that inadequate change management is a major barrier to implementing innovation within an organisation, particularly concerning diversity and cultural alignment among staff. To effectively implement the change management plan, it is essential to identify key personnel within the organisation, referred to as project champions, change champions, or change agents, who should be trained first on the use of the innovation (Halim *et al.*, 2020; Parida *et al.*, 2011). These individuals will lead others in adopting the innovation and addressing any misconceptions.

Furthermore, developing a robust communication strategy that clearly articulates the benefits of innovations will significantly promote their adoption (Hodavand *et al.*, 2023; Lu *et al.*, 2022). This strategy could incorporate feedback mechanisms to address staff concerns (Halim *et al.*, 2020). Effective execution of activities and the avoidance of data silos can be achieved through collaboration between departments (Tripathi *et al.*, 2023a; D'Amico *et al.*, 2022). Moreover, specialist skilled personnel are necessary to operate technological innovation (Maganga and Taifa, 2022). Such skilled personnel facilitate the successful use of innovations while identifying knowledge gaps that may require further training for other staff. Avenues for this training have been previously discussed in this section. In summary, the right people dimension is crucial for the effective implementation of an innovation, and this can be achieved through a suitable process.

2 Process:

A process is a defined sequence of steps to accomplish a particular task (Kumar *et al.*, 2022; Maganga and Taifa, 2022). It also represents a pathway connecting a series of interrelated activities (Halim *et al.*, 2020). According to studies, "process" defines the "how" dimension of the PPT framework, concerning how people and technology will resolve a specific problem and how the results will be attained (Prodan *et al.*, 2015; Hamou-Lhadj and Hamou-Lhadj, 2008; Love *et al.*, 1996). Such a process can be informal or systematic. An informal process benefits organisations in implementing innovations, as it requires few modifications to existing processes; however, it does not maximise the full potential of innovation, which a systematic process can achieve (Parida *et al.*, 2011). In this context, an informal process implies partial implementation, whereas a systematic process is total.

Furthermore, as noted by Kumar *et al.* (2022), a process involves the integration of horizontal, vertical, and end-to-end activities within an organisation, enhancing effective communication among staff to accomplish their tasks. Vertical integration consists of collaborative functions, such as planning and development, among the various departments. Horizontal integration relates to the workflow of activities within the organisation, whereas end-to-end integration links vertical and horizontal activities across all departments for efficient organisational operations (Kumar *et al.*, 2022; Butt, 2020). Thus, process plays a crucial role in an organisation's functioning, connecting various units to achieve overall efficiency.

The deployment of an appropriate process is pivotal to the utilisation of innovative technology (Parida *et al.*, 2011). However, Love *et al.* (1996) argue that the deployment of technology to enhance organisational activities cannot occur without a clear process. Ern *et al.* (2017) highlight that conventional processes, technical malfunctions, and challenges in integrating existing processes are key barriers to the implementation of new technology. To address these challenges, several studies recommend having a well-structured process for leveraging technologies such as big data, DT, and cloud computing, among others, for organisational activities (Tripathi *et al.*, 2023a; Maganga and Taifa, 2022; Parida *et al.*, 2011). Hamou-Lhadj and Hamou-Lhadj (2008) corroborate that a well-structured process enhances organisational security in terms of ethics and productivity. Thus, a well-structured process facilitates task efficiency within an organisation.

In the context of this study, the process dimension of the PPT framework will focus on the workflow associated with the use of DT. Such a workflow involves how BM organisations will leverage DT for their maintenance activities. Studies underscore that the organisational process dimensions in technology utilisation consist of workflow integration and data management (Caporuscio *et al.*, 2020; Halim *et al.*, 2020). Workflow integration, which is essential for implementing innovations, includes components like process mapping and redesign (Caporuscio *et al.*, 2020). Process mapping facilitates the assessment of existing organisational processes to identify areas where innovations can contribute to improvements. Such mapping can be facilitated by organisational process redesign to accommodate the innovations' effectiveness for activities (Caporuscio *et al.*, 2020). Optimising the use of innovations can enhance work activities through an appropriate process mapping model (Segovia and Garcia-Alfaro, 2022). In this light, Parida *et al.* (2011) suggest the use of stage-gate process models in implementing innovations. For this reason, Section 3.9.2 reviews these highlighted components and some stage-gate process models to develop a suitable model for this study.

Furthermore, data management is crucial for implementing technological innovation, with data central to its operations (Halim *et al.*, 2020). As Section 3.6.3.1 discusses, data-related issues hinder DT implementation. These issues can be managed through various avenues. According to studies, data management can be enhanced through avenues such as data governance, integration, and analysis (Tripathi *et al.*, 2023a; Halim *et al.*, 2020). Data governance assists in establishing the necessary policies required to acquire accurate and high-quality data for innovation operations and to ensure its security (Omrany *et al.*, 2023). Bolton *et al.* (2018) emphasise that data governance in technology usage is vital to prevent infringement upon individuals' privacy during data acquisition. Therefore, data needs to be collected in a manner that does not violate individuals' rights.

Additionally, the centralisation of data and decentralisation of decision-making through effective data management eliminates the presence of data silos within an organisation, which is typical in conventional centralised decision-making organisations (D'Amico *et al.*, 2022; Kumar *et al.*, 2022). In this light, a well-structured organisational process will aid in addressing data silo issues through decentralised decision-making and centralised integration of data within an organisation. Such a process will enable effective data analysis to optimise organisational activities. Thus, an organisation's implementation of a well-structured process for innovative technology can serve as a springboard for interconnecting its people and technology dimensions.

3 Technology:

The technology dimension of the PPT framework depicts the various technological infrastructures available for organisational activities (Halim *et al.*, 2020). It provides the tools for individuals to perform their tasks and achieve their work objectives (Prodan *et al.*, 2015). In this regard, the technology dimension enables an organisation to evaluate its existing technological infrastructure and specify what is required to develop the digital capability needed to implement innovation (Papic and Cerovsek, 2019). However, Love *et al.* (1996)

argue that organisations often invest in technology to gain a competitive advantage while attempting to integrate the people and process dimensions. Maganga and Taifa (2022) emphasise that investing in technology without skilled personnel and appropriate processes will not yield the desired results. To address this challenge, Halim *et al.* (2020) suggest that organisations need to comprehend the business problem before recruiting skilled personnel and identifying the processes to resolve it; thereafter, a suitable technological approach can be considered.

In the context of this study, the technology dimension of the PPT framework involves the effective utilisation of technological resources to implement DT for managing maintenance activities. For organisations seeking to explore technological advancements, Papic and Cerovsek (2019) highlight the need to clarify how technology can be employed to digitise their work processes. Such clarity pertains to considerations of data quality, data security, connectivity, integration capabilities, and scalability, among others (Kayikci *et al.*, 2023; Tripathi *et al.*, 2023a; Kumar *et al.*, 2022; Halim *et al.*, 2020). Connectivity facilitates the integration of different data sources into a cohesive unit, allowing for the sharing of asset data through various communication protocols (Kayikci *et al.*, 2023; Kumar *et al.*, 2022).

Moreover, ensuring adequate security for shared and acquired data is vital for digital technologies (Halim *et al.*, 2020). Bolton *et al.* (2018) underscore that data acquisition from individuals must be secure. Hence, data security is crucial and can be achieved through blockchain technology, employing encryption and access control to prevent silos from arising due to centralisation in decision-making (Tripathi *et al.*, 2023a; Omrany *et al.*, 2023; D'Amico *et al.*, 2022).

Scalability is another essential aspect of digitising organisational work processes (Martell *et al.*, 2023). It enables an organisation to evaluate its structure, determine if the innovation will enhance its organisational profile, and assess the need for additional technological resources (Han *et al.*, 2023; Hamou-Lhadj and Hamou-Lhadj, 2008). Such evaluation is necessary, as the organisation's people and process dimensions must align with the innovation for it to effectively enhance organisational activities (Martell *et al.*, 2023). In this light, Kumar *et al.* (2022) suggest that organisations looking to explore Industry 4.0 technologies can enhance their organisational profile through collaborations and partnerships with others who are already utilising them. Therefore, it is essential for organisations to maintain a balance between the people and process dimensions of their structure and activities when implementing innovative technology.

3.9.2 Approach to Process Modelling and Mapping

Process modelling and process mapping are essential components of organisational process management (Butt, 2020; Van Der Aalst, 2013; Biazzo, 2002). As highlighted in Section 3.9.1.2, these components are crucial for workflow integration. Process modelling provides avenues for connecting and simplifying complex processes into a structured format that can be utilised by individuals within an organisation (Van Der Aalst, 2013). Moreover, modelling a process involves transforming real-world activities and procedures into process models. Vom Brocke and Rosemann (2014) underscore that a process model aims to capture organisational activities and procedures at the appropriate level of detail suitable for an organisation's operations. Al Ahbabi (2014) corroborates that process models are employed for activities such as cost analysis, resource performance assessment, and process automation within an organisation. Thus, the effective design of a process model stimulates an organisation's processes by simplifying complex activities into structures usable by its personnel.

Conversely, process mapping is critical for an organisation to outline its activities. According to Biazzo (2002, p.42), process mapping involves "*constructing a model that shows the relationships between the activities, people, data and objects involved in the production of a specified output*". It facilitates the monitoring and understanding of process flow, aiming for effective utilisation of output once transparency in the process route is achieved, thereby enhancing an organisation's activities. Colquhoun *et al.* (1996) emphasise that one of the successes of organisational re-engineering lies in employing workable and proven methods through process mapping, which aids in restructuring and improving business processes. Hence, process mapping techniques are pivotal for organisational re-engineering to enhance work efficiency through process models.

Based on these studies, organisations willing to implement DT for BM need to strategically re-engineer their operational processes. This necessity arises because the utilisation of DT encompasses the collection of historical data from the conception of a building and its assets, through its design and construction phases, down to its usage during the O&M phase of the building lifecycle. Therefore, creating a process model for DT requires a thorough examination of maintenance activities. Such an examination aims to develop a suitable process mapping technique for DT to support BM management.

As discussed in Section 3.9.1, certain evaluation criteria are deduced, and these are operationalised on the premise that BM organisations consist of different departments and staff (people), who function as a team within their activity zones (vertical integration), through a defined workflow process (horizontal integration) to produce results (Kumar *et al.*, 2022; Karmakar and Delhi, 2021; Butt, 2020). The maintenance requirement is a valuable evaluation criterion for this process development, as the study focuses on BM management and is thus included. These evaluation criteria are presented in Table 3.5. It is, therefore, imperative to examine various process mapping frameworks, models, or codes related to the AEC industry based on these evaluation criteria to adopt or combine the most suitable for implementing DT for BM management.

Table 3.5: Criteria to Evaluate Certain Process Mapping

Process layer	Activity zone	Participant responsibility	Maintenance requirements Specification

1. Nigeria's National Building Code

Nigeria's NBC is "*a set of minimum standards on building pre-design, designs, construction and post-construction stages with a view to ensuring quality, safety and proficiency in the building industry*" in Nigeria (NBC, 2006, p.6). The NBC consists of four parts and fifteen sections. Part one comprises administrative functions across three sections. Part two deals with the technical aspects of buildings in terms of pre-design, design, construction, and post-construction stages, along with their requirements, and encompasses eight sections. Part three focuses on the enforcement of building regulations and has one section, while part four outlines the schedules and references of compliance forms and standards, comprising two sections (NBC, 2006). The development of this building code arose from numerous issues within the built environment, including poor planning in towns and cities, building collapses, non-compliance with design and construction standards, and a lack of maintenance culture, among others (Okonkwo, 2007; NBC, 2006). For these reasons, the NBC was developed to provide guidance on the various aspects of building projects in Nigeria and to specify the requirements for their execution.

The post-construction stage, which involves the maintenance of buildings and their assets, is detailed in part two: section twelve. The NBC further specifies the requirements for this stage, as illustrated in Figure 3.11. As highlighted by NBC (2006), these requirements include: (1) a certificate of fitness for habitation, which serves as a statutory/regulatory requirement issued by the Code Enforcement Officer as a permit under the provisions of the law (code) for the use and occupancy of the building in various sections, including any special conditions of the permit. (2) As-built drawings comprise a set of architectural, structural, mechanical, electrical, and other specialist drawings that depict the building as constructed and prepared by registered architects, engineers, and surveyors. (3) A BM manual, which is a comprehensive guide that includes appropriate forms and logbooks for maintaining a building, prepared by a consortium of registered architects, builders, and engineers. (4) A building condition survey report that provides a detailed account of the actual conditions of all components, elements, and installations. This report is prepared by a consortium of registered architects, builders, engineers, and quantity surveyors.

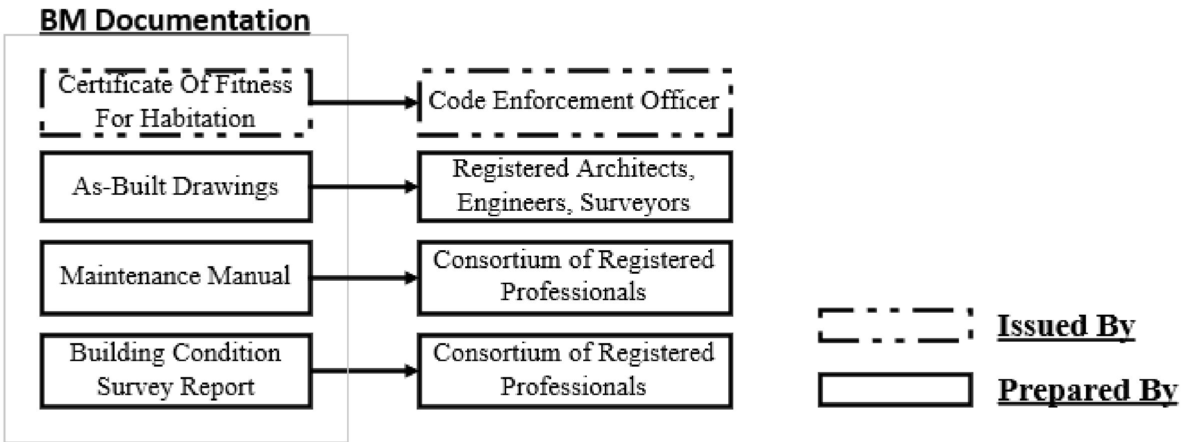


Figure 3.11: Building Maintenance Documentation Requirements (NBC, 2006)

The NBC emphasises that all equipment and assets installed within a building should be properly maintained to ensure the safety of its users. Although the NBC identifies documents such as a certificate of fitness for habitation, as-built drawings, BM manual, and building condition survey report as essentials for maintenance activities, it does not specify how these activities should be conducted. Thus, it is vital to explore alternative methods for mapping out maintenance activities and evaluating their feasibility for implementing DT.

2. British Standards Institution Building Maintenance Process

The BM process is crucial for building performance, which can be influenced by its type and size. As discussed in Section 2.5, maintenance activities are fragmented and complex. BS 8210 (2012) highlights the maintenance planning process for conducting these activities (Figure 2.4). Furthermore, the BSI maintenance guideline specifies that the requirements and records for maintenance activities are twofold (BS 8210, 1986). One set of records is prepared and generated from the initiation of a building project, including the design brief, architectural designs, and construction details, until its handover by the construction contractor. The other consists of records that must be documented during the building's occupancy, such as defect details and maintenance schedules. While the BSI guideline outlines the maintenance planning process (Figure 2.4), it does not specify how the maintenance of buildings should be conducted. Therefore, there is a need to explore alternative construction process models to map out a methodology for conducting maintenance activities using technological innovation, and to identify the building professionals who should be involved in updating maintenance requirements.

3. Construction Project Process Models

The construction process encompasses several phases involving different professionals to successfully deliver a project. According to Karhu *et al.* (1997), the construction of a building is executed as a one-off project form that often generates issues when monitoring its delivery processes. Some authors suggest that the AEC industry should incorporate approaches and techniques from the manufacturing sector to enhance its process management (Koskela, 1999; Egan, 1998; Latham, 1994). In this regard, the Generic Design and Construction Process Protocol (GDCPP) was developed (Aouad *et al.*, 1998; Kagioglou *et al.*, 1998). Moreover, the AEC industry has several guiding models or plans of work, such as the Royal Institute of British Architects (RIBA) in the UK, the Association of Consultancy and Engineering in Europe, and the American Institute of Architects in the United States of America, among others (RIBA, 2020). Thus, understanding the processes underpinning these models and plans, and using the RIBA plan of work as an informative focus, would assist in developing a process model that can support the management of maintenance activities.

1. RIBA Plan of Work

The RIBA plan of work serves as the primary guide or process protocol for designing and constructing buildings in the UK. It has influenced plans of work in many countries, including Nigeria, possibly due to the UK being their colonial father. As RIBA (2013) highlighted, the plan outlines the processes involved in managing and designing building projects by dividing them into stages. Since its initial development in 1963, the plan has undergone several updates. Its primary aim was to organise the construction process, including the brief, design, construction, and operation of a building project. It provides a shared model for organisations and project teams regarding their work processes and serves as a reference point for executing each aspect of work in a building project. In 2007, the RIBA plan of work was updated to simplify and clarify its various stages.

Moreover, in 2013, the RIBA plan of work was further revised with the addition of sustainable design practices, facilitating integration through BIM for all project parties. It comprises eight phases: strategic definition, preparation and briefing, concept design, developed design, technical design, construction, handover and closeout, and in-use. In 2020, it was updated again, incorporating various procurement routes in response to the requirements of BIM and sustainable designs, as illustrated in Figure 3.12 (RIBA, 2020). Although the RIBA plan of work has proven useful for organising and coordinating construction projects, it lacks a clear sequential process and description of the participants' roles and responsibilities at each stage of work. Thus, it only specifies the outcomes that project teams should achieve at each stage of the work.

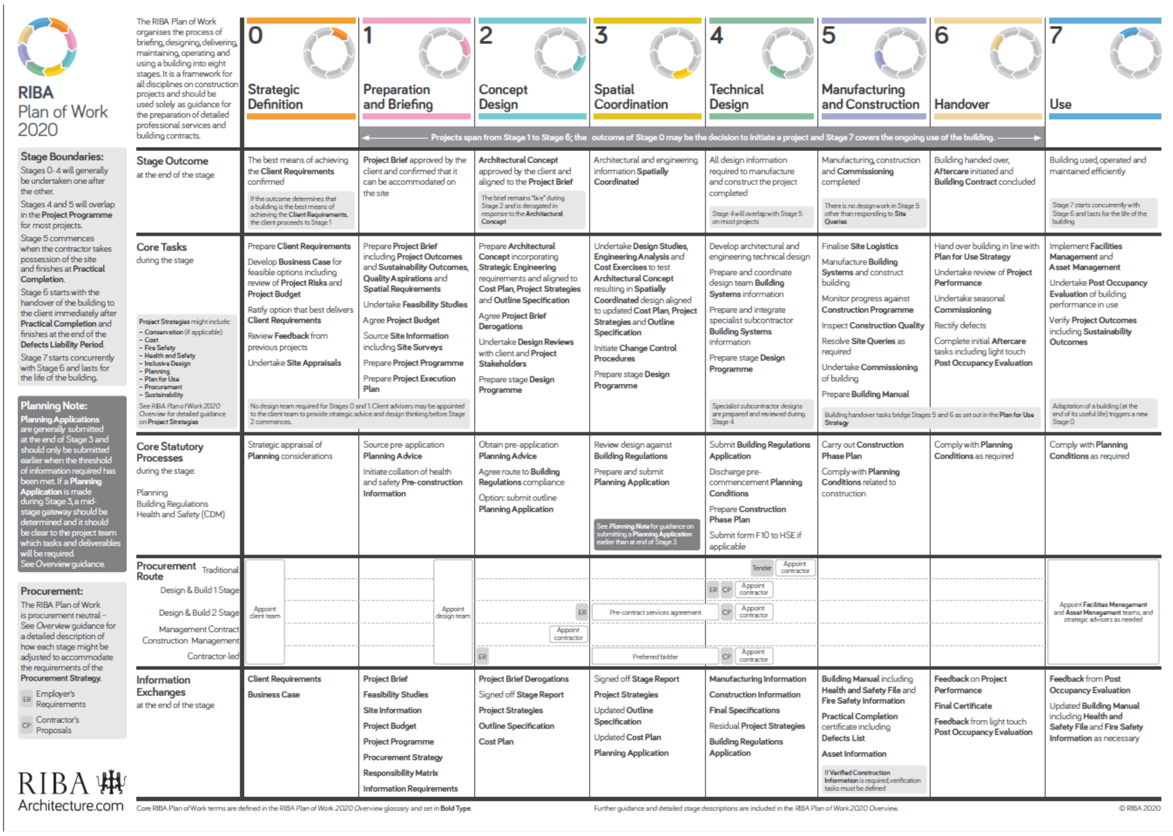


Figure 3.12: Royal Institute of British Architects Plan of Work (Adopted from RIBA, 2020)

2. Generic Design and Construction Process Protocol

The GDCPP concept originated from the manufacturing industry to address the shortfalls of existing construction industry frameworks (Kagioglou *et al.*, 2000). It caters for the interests of various stakeholders involved in a construction project by offering a blueprint for their work functions through a process protocol. As defined by Kagioglou *et al.* (1998), a process protocol is "*a common set of definitions, documentation and procedures that will provide the basics to allow a wide range of organisations involved in a construction project to work together seamlessly", and purposes "to map the entire project process from the client's recognition of a need to operations and maintenance*". The GDCPP was conceived and developed by researchers at the University of Salford in 1998 to challenge existing design, construction, and procurement approaches (Kagioglou *et al.*, 2000). The GDCPP concept seeks to enhance design and construction processes by analysing existing construction practices alongside those of the manufacturing industry and employing IT to develop a model. Moreover, several principles underpin the development of GDCPP (Kagioglou *et al.*, 1998). These are:

1. Whole project view: The entire project lifecycle is taken into account, from recognising a need to the facility's O&M phases. This ensures that all potential issues are captured from both business and technical perspectives.

2. Consistent process: The process protocol aims to reduce ambiguity by consistently using and employing an approach for performance measurements, evaluations, and control.

3. Progressive design fixity: Stage gate methods are utilised, requiring that each process be authorised at each phase before advancing to the next. Phase reviews are conducted to evaluate completed tasks, approval processes, planning, and resource allocation for the subsequent phase. Furthermore, phase gates are categorised as hard or soft, with the hard gate representing the decision point at each stage, while soft gates facilitate the concurrency of processes within phases in a stage.

4. Coordination: The process protocol was developed to improve coordination in construction activities by introducing process and change management activity zones (Figure

3.13). This ensures that all project-related information is communicated to the appropriate participants at each phase.

5. Stakeholder Involvement and Teamwork: The interdependency of tasks is identified for all project participants. This ensures that all parties involved are equipped with the right information at the right time during each process phase. Additionally, multiple workgroups can be created at the project's inception to promote effective collaboration among parties.

6. Feedback: Each stage can be recorded and utilised in subsequent developmental stages and future projects. This is achieved through a legacy archive, a central storage system for information generated at each process phase.

Furthermore, the GDCPP consists of a vertical activity zone and a horizontal process layer, encompassing four key stages and ten phases within these stages, as illustrated in Figure 3.13. The activity zone includes eight groups of participants in management: development, project, resource, design, production, facility, health and safety, statutory and legal, and process management, each involved in various stages of the process protocol. The key stages include the pre-project, pre-construction, construction, and post-construction stages (Aouad *et al.*, 1998; Kagioglou *et al.*, 1998).

At the pre-project stage, an examination of the client's needs and all arrangements related to the project are identified to ensure adequate financial resources are available. This stage includes four phases: (1) demonstrating the need (phase 0), (2) the conception of need (phase 1), (3) outline feasibility (phase 2), and (4) substantive feasibility study alongside an outline of financial authority (phase 3). The pre-construction stage comprises strategies for translating the client's needs into specific phases to ensure sustained financial authority, encompassing an outline of conceptual design (phase 4), full conceptual design (phase 5), coordinated design, procurement, and full financial authority (phase 6).

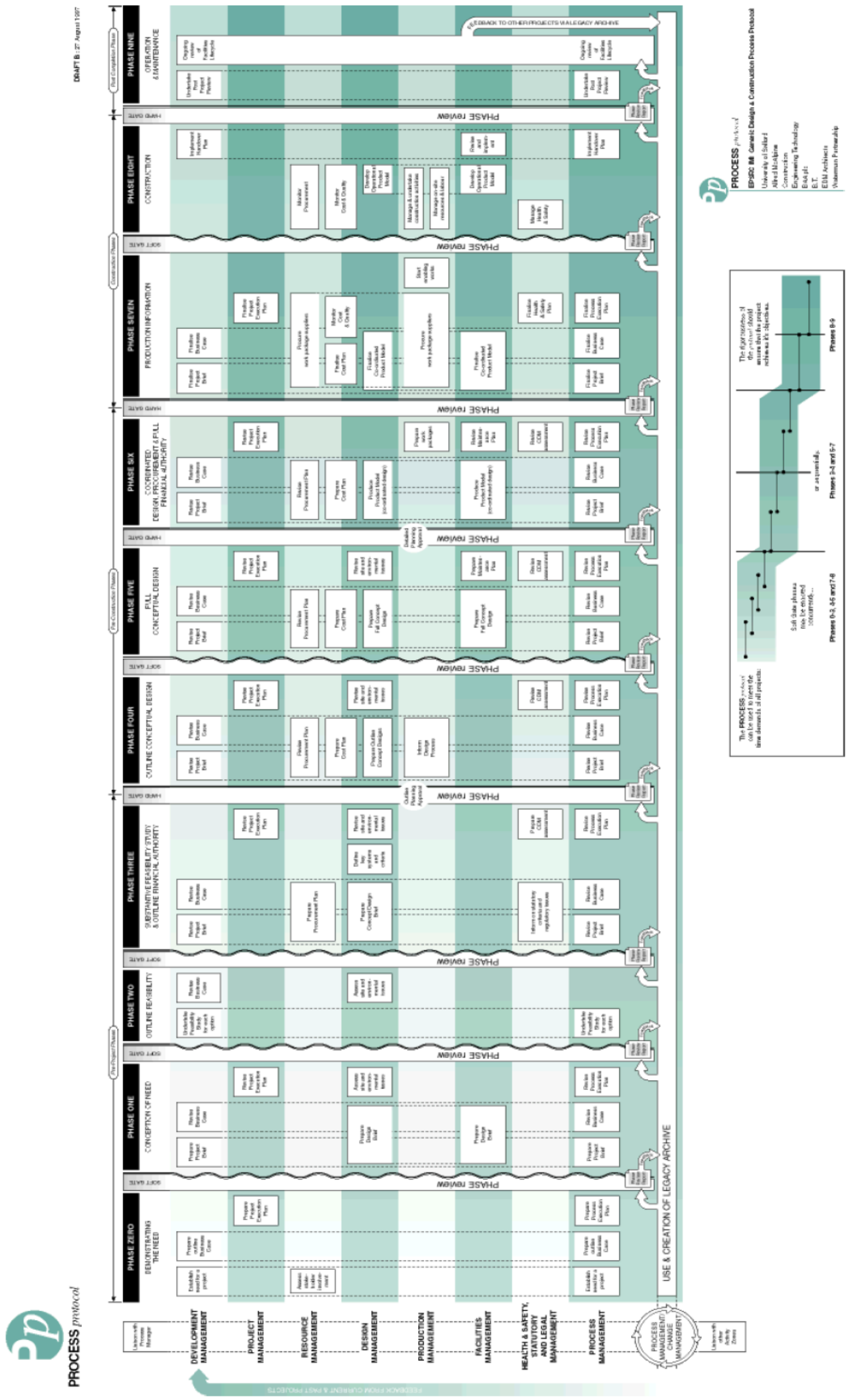


Figure 3.13: Generic Design and Construction Process Protocol (Adopted from Kagioglou *et al.*, 1998)

Furthermore, the construction stage (stage 3) involves implementing the conceived ideas to fulfil the client's needs. The final project or model is produced at this stage and includes production management (phase 7) and construction (phase 8). The post-construction stage (stage 4) focuses on managing the completed project or model, ensuring that the client's needs are continuously met and the project is maintained. It includes the O&M phase. Therefore, the GDCPP's stages and phases can assist project parties and organisations in re-engineering their activities to deliver a model or project that meets client requirements.

4. Comparison of Reviewed Process Mapping

Based on the reviewed process mappings, it can be deduced that the effective use of any or their combinations will support the workflow of organisational activities. In seeking a suitable approach for this study, the process mappings were evaluated against the criteria established in Table 3.5. From the evaluation criteria scores presented in Table 3.6, Nigeria's NBC and GDCPP scored three out of four criteria. For this reason, harmonising both is a suitable fit for this study. Distinctively, they acknowledge certain parties or professionals who play a crucial role from the project's conception through to its usage. Nigeria's NBC emphasises requirements for maintenance activities and the parties responsible for their provision. Both Nigeria's NBC and GDCPP spotlight the various stages involved in executing a building project from conception to usage. The linkages between the stages and processes of the two mappings are presented in Table 3.7.

Table 3.6: Summary of the Reviewed Process Mapping

Criteria	Process layer	Activity zone	Participant responsibility	Maintenance requirements Specification
Nigeria's National Building Code	√	x	√	√
BSI maintenance guideline	√	x	x	√
RIBA Plan of Work	√	√	x	x
Generic Design and Construction Process Protocol	√	√	√	x

Table 3.7: Comparison and Linkages Between the Generic Design and Construction Process Protocol Framework and Nigeria's National Building Code Guide

GDCPP	Sub-Phases	Terms used in the GDCPP	NBC	Terms used in the NBC	NBC requirements at each phase
Pre-Project Phases	0	Demonstrating the need	**Pre-Design**	Environmental and General Building	Perimeter survey and topographical survey of the site
	1	Conception of Need			
	2	Outline Feasibility			
	3	Substantive Feasibility Study & Outline Financial Authority			
Pre-Construction Phases	4	Outline Conceptual Design	**Design**	Architectural Design	Working drawings and specifications

	5	Full Conceptual Design		Civil/Structural/Geotechnical Design	prepared by registered design professionals
	6	Coordinated Design, Procurement & Full Financial Authority		Service Engineering Design	
Construction Phases	7	Production Information	**Construction**	Building Materials and Components	Contract documents
	8	Construction		Building Construction	
Post Completion	9	Operation & Maintenance	**Post-Construction**	Post-Construction	i. Certificate of Fitness for Habitation. ii. As-Built Drawings. iii. Building Maintenance Manual. iv. Building Condition Survey Report.

3.10 Research Framework

Following the review of the literature, it can be deduced that certain maintenance-related issues can be managed using technology. Studies have indicated that DT can address maintenance-related issues that are rich in data (Lu *et al.*, 2020a; Peng *et al.*, 2020; Antonino *et al.*, 2019; Lu *et al.*, 2019; Stojanovic *et al.*, 2018). However, most available studies focus on the technological implementation of DT and overlook the organisational aspect. For organisations to effectively utilise DT in their maintenance activities, it is essential to adjust both the people and process dimensions of the organisational structure to align with it. For this reason, the PPT framework is employed as a research lens to explore how BM organisations can utilise DT for maintenance management. This necessity arises because the staff of BM organisations need to carry out their activities through a well-optimised process supported by DT to enhance efficiency. In fact, for the staff of BM organisations to successfully utilise DT in their activities, an organisational re-engineering of their processes is required to accommodate it. Consequently, several process and mapping models, including Nigeria's NBC, BSI, RIBA Plan of Work, and GDCPP, have been reviewed to facilitate the implementation of DT for maintenance activities. Thus, establishing a clear process that links the people aspect of an organisation with DT can enhance the management of maintenance activities. Integrating DT into the work activities of a BM organisation would create an enabling environment for a more strategic approach to BM management.

Therefore, this study aims to implement DT at the organisational level for BM management by developing a process framework that connects the people dimension of an organisation with DT development, as presented in Figure 3.14. The process framework will identify meeting points where the various BM stakeholders or building professionals and their activities converge to develop a DT model, which comprises five layers (Section 3.8.1). Hence, for DT to be integrated into the work activities of BM organisations, specific milestones need to be identified and achieved regarding personnel involvement, DT, and maintenance requirements across the process layers and activity zones. Subsequently, the framework is developed in Chapter Seven through an empirical investigation.

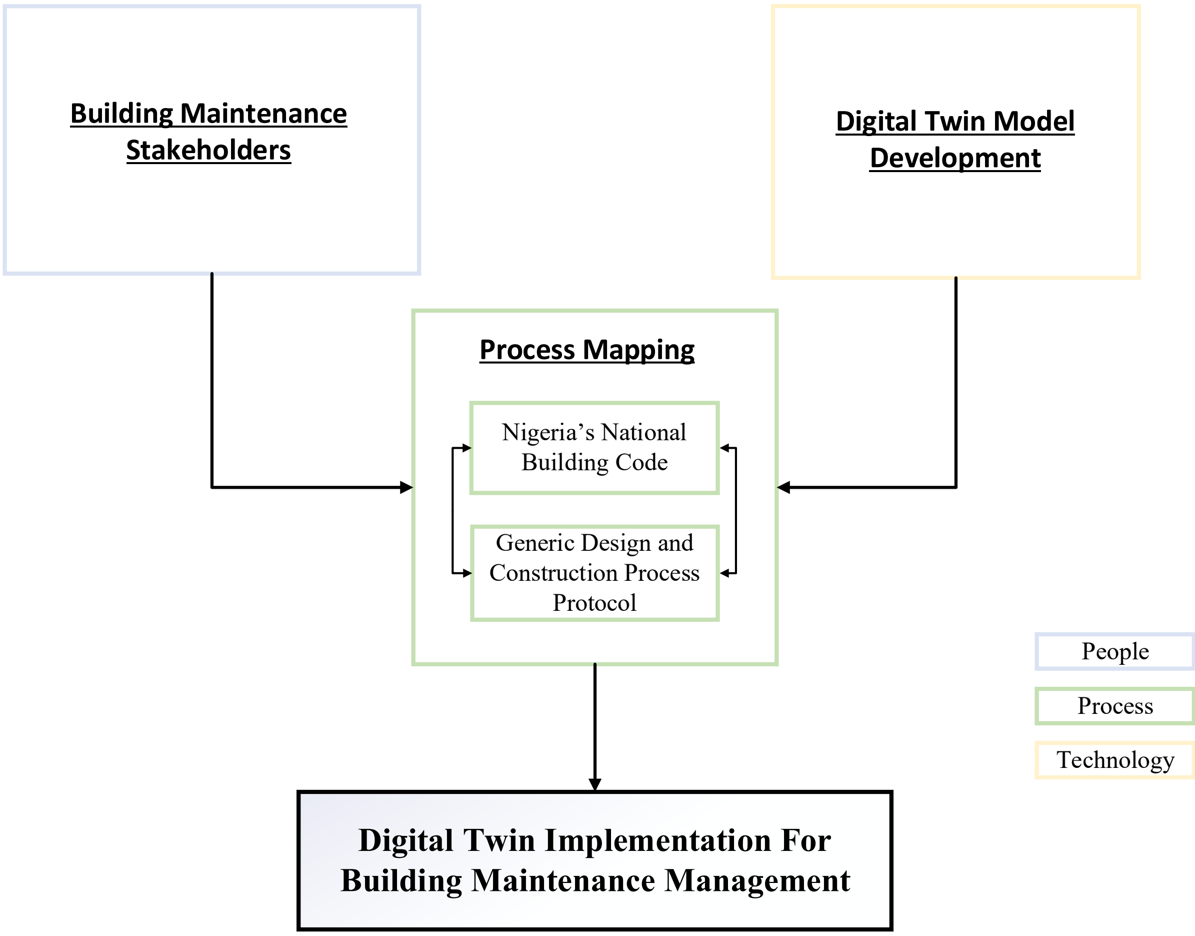


Figure 3.14: Overview of the Research Model

3.11 Summary

This section presents a review of the literature on DT and its related implementation issues, as well as enabling technologies. Following the review of the literature, it can be inferred that DT is still in its early stages within the AEC industry compared to other sectors such as manufacturing and aerospace. Studies on DT for BM management were synthesised, revealing that DT can enhance and better manage maintenance activities due to its capability to monitor buildings and assets in real-time, along with conducting scenario analysis. Considering this capability, BM organisations can adopt a more strategic approach to improve maintenance management.

Meanwhile, most of the available literature focuses on the technical implementation of DT while overlooking its organisational aspects. This situation creates a gap, as organisations, particularly BM organisations, may be unaware of the requirements for effective DT implementation. To address this gap, the PPT framework and process mapping approaches were reviewed as a research lens to guide the study.

Chapter Four - Research Methodology

4.0 Introduction

This chapter presents a roadmap for developing an appropriate methodology to address the research question and achieve the research aim and objectives. It discusses the philosophical underpinnings of the study and subsequently formulates a suitable research plan to realise the study's aim. It elucidates how the research question is addressed and justifies the chosen research method. To facilitate this alignment, Saunders *et al.* (2019) developed a research onion to assist researchers in their pursuit of knowledge discovery, which serves as an appropriate framework for this study. Figure 4.1 illustrates the various choices made based on the research onion to fulfil the study's aim. The research design is utilised to elaborate on the research method for practicality in situating the data collection and analysis choices of the study, which are the research's core elements. Therefore, the research methodology serves as the backbone of any study, as it clarifies the philosophical rationale, research method, and design plan of the investigation (Saunders *et al.*, 2019; Creswell, 2016).

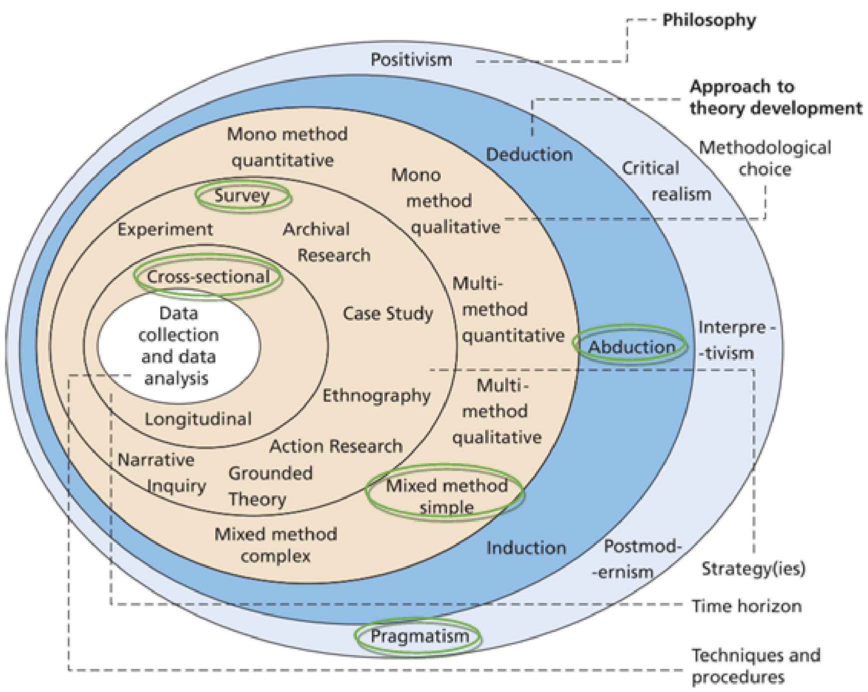


Figure 4.1: Research Onion (Adopted from Saunders *et al.*, 2019)

4.1 Research Philosophy

Research philosophy underpins the pursuit of any research (Kumar, 2011). Saunders *et al.* (2019, p.130) define research philosophy as a "*system of beliefs and assumptions about the development of knowledge*". This includes positivism, interpretivism, critical realism, and pragmatism, among others (Figure 4.1), which serve as the foundations of research. In this study, the pursuit of knowledge revolves around understanding how DT can be implemented to support BM management from an organisational perspective. To arrive at an appropriate research philosophy for this study, a comparison of the various philosophical stances and an examination of their underpinning assumptions are summarised in Table 4.1.

After considering the aim and objectives of the study, a pragmatist research philosophy was identified as the most appropriate approach to address the research question and investigate the problem at hand. It focuses on what works and how things can work. As Creswell (2016) highlighted, pragmatism focuses on practical solutions to research problems. This study addresses maintenance-related issues (the research problem) and explores how DT can assist BM organisations in their management (the workable solution). Saunders *et al.* (2019) indicated that pragmatism is suitable for a study when a researcher aims to develop and enhance organisational practices.

Pragmatic research philosophy is characterised by unique attributes that distinguish it from other philosophies (Kelly and Cordeiro, 2020; Creswell, 2016). One of these attributes is its emphasis on practicality and problem-solving (Rahman and Zakaria, 2008). Pragmatism prioritises addressing real-world issues, such as those identified in this study (maintenance-related issues), by exploring practical approaches. It adopts a pluralistic approach to investigating the research issue (Leavy, 2017; Creswell, 2016). Employing such an approach allows for flexibility in utilising both quantitative and qualitative research methods, thereby achieving a comprehensive understanding of maintenance-related issues. Kelly and Cordeiro (2020) noted that pragmatism places greater emphasis on research participants and stakeholders, who in this context are the BM managers, to understand their approaches to managing maintenance-related issues and to explore further avenues for addressing them. For these reasons, the pragmatist research philosophy is the most suitable for this study as it seeks to collect data from BM and DT experts to fulfil its aim and objectives. While the choice of pragmatism is most appropriate and justified, it is vital to understand the overarching research paradigm to situate this study.

Research philosophies can be described based on ontological, epistemological, and axiological assumptions (Figure 4.2 and Table 4.1) (Saunders *et al.*, 2019; Groat and Wang, 2013). Ontology addresses the question of "what" reality is, focusing on the nature of truth. Epistemology examines the assumptions regarding "how" reality is understood. Axiology considers values and beliefs and their impact on understanding reality. Therefore, understanding these assumptions alongside a chosen research philosophical stance is crucial for the conduct, validity, and generalisation of research and its findings (Akotia *et al.*, 2023).

Conducting research aims to understand and create knowledge, which involves moving from the known to the unknown and articulating reality (Kumar, 2011). Hence, perceptions of reality hinge on ontological and epistemological assumptions, as illustrated in Figure 4.2. These assumptions can be viewed from subjectivist and objectivist research extremes, serving as foundational elements for a better understanding of research philosophies (Saunders *et al.*, 2019; Burrell and Morgan, 1979). For organisational research, Burrell and Morgan (1979) developed a model for organisational analysis that encompasses radical change and regulation. The model is grounded in the interconnection between subjectivist and objectivist extremes and the research paradigms of radical change and regulation (Figure 4.2).

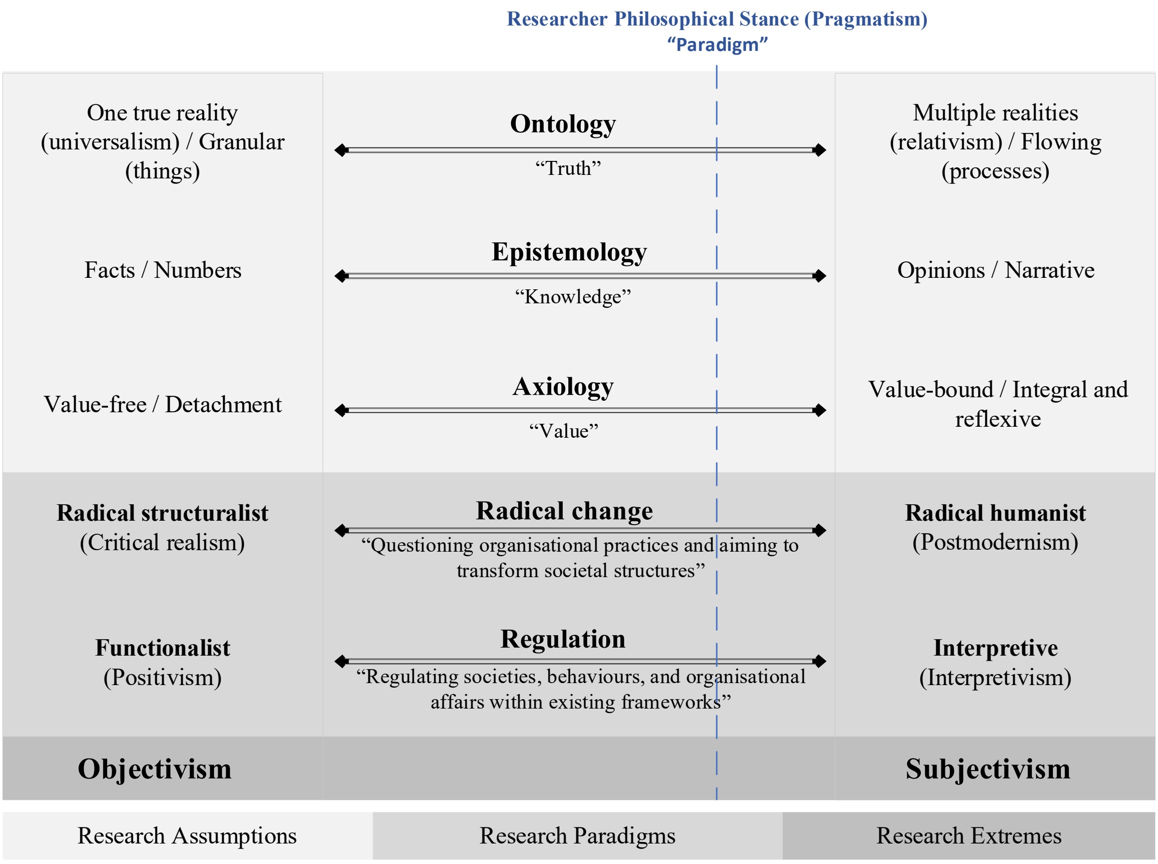


Figure 4.2: Interconnections Among Research Assumptions, Paradigm, and Extremes

(Adapted from Saunders *et al.*, 2019; Burrell and Morgan, 1979)

A subjectivist views the emergence of knowledge as stemming from a shared understanding of a social phenomenon between a researcher and social actors. In contrast, an objectivist sees social phenomena as external to the researcher (Groat and Wang, 2013). Any philosophical stance exists along or between the extremes of the subjectivism and objectivism spectra. This study leans more towards the subjectivism spectrum than objectivism (Figure 4.2). Such a leaning is due to its aim of capturing workable information about reality based on the opinions and expertise of social actors such as BM managers and DT experts. Thus, these research positions are pivotal to how social researchers perceive research philosophically, as reality holds no neutral stance; it is the integration of the ontological and epistemological assumptions of research upon which methodology is based (Al-Ababneh, 2020; Groat and Wang, 2013).

Table 4.1: Comparison of Five Research Philosophical Stances (Saunders *et al.*, 2019; Groat and Wang, 2013; Burrell and Morgan, 1979)

Philosophy	Ontology (Nature of reality)	Epistemology (What constitutes acceptable knowledge)	Axiology (Role of values)	Typical methods
Positivism: This is characterised by the belief that reality is out there and can be understood within some given probability levels	Real, external, independent; one true reality (universalism); granular (things); ordered	A scientific method; observable and measurable facts; law-like generalisations; numbers	Value-free research; researcher is detached; neutral and independent of what is researched; researcher is objective	Typically deductive, highly structured, large samples, measurement, typically quantitative methods of analysis
Critical realism: They believe that truths exist beyond our observations, but sometimes, our observations could expand our comprehension of unobservable constructs that exist as part of the actual reality	Stratified/layered; external, independent; intransient; objective structures; causal mechanisms	Epistemological relativism; knowledge historically situated and transient; historical causal explanation as a contribution	Value-laden research; researcher acknowledges bias by world views, cultural experience and upbringing; researcher is as objective as possible	Retroductive, in-depth historically situated analysis of pre-existing structures and emerging agency; range of methods and data types to fit the subject matter
Interpretivism: This explains that humans generate implications from observations	Complex, rich, socially constructed through culture and language; multiple meanings, interpretations, realities	Theories and concepts too simplistic; focus on narratives, stories, perceptions and interpretations	Value-bound research; researchers are part of what is researched, subjective; researcher interpretations are key to the contribution	Typically inductive, small samples, in-depth investigations, and qualitative methods of analysis.
Postmodernism: It emphasises the role of social norms such as languages and power relations in the quest to seek truthful knowledge	Nominal; complex and rich; socially constructed through power relations; some meanings, interpretations, and realities are dominated and silenced by others	What counts as 'knowledge' is decided by dominant ideologies; focus on absences, silences and oppressed/ repressed meanings; exposure of power relations and challenge of dominant views as the contribution	Value-constituted research; researcher and research embedded in power relations; some research narratives are repressed and silenced at the expense of others	Typically deconstructive, reading texts and realities against themselves; in-depth investigations of anomalies, silences and absences; range of data types, typically qualitative methods of analysis
Pragmatism: It emphasises that humans live in a non-objective environment and that reality is not fixed but can be understood through constant questioning and interpretation	Complex, rich, external; 'reality' is the practical consequence of ideas, flux of processes, experiences and practices	The practical meaning of knowledge in specific contexts; knowledge are those that enable successful action; focus on problems, practices and relevance; problem-solving and informed future practice as a contribution	Value-driven research; research initiated and sustained by the researcher's doubts and beliefs	It follows the research problem and research question; uses range of methods: mixed, qualitative, quantitative, and action research; emphasis on practical solutions and outcomes

4.2 Research Approach

According to Groat and Wang (2013), reasoning is a logical process for synthesising meanings from data, particularly in terms of theory development or confirmation. Based on the research onion (Figure 4.1), the approaches to theory development or confirmation include induction, deduction, and abduction, as illustrated in Figure 4.3. Table 4.2 elucidates these reasoning patterns.

Table 4.2: Comparison of Research Approaches: From Reason to Research (Adapted from Saunders *et al.*, 2019)

	Deduction	Induction	Abduction
Logic	In a deductive inference, when the premises are true, the conclusion must also be true	In an inductive inference, known premises are used to generate untested conclusions	In an abductive inference, known premises are used to generate testable conclusions
Generalisability	Generalising from the general to the specific	Generalising from the general to the specific	Generalising from the interactions between the specific and the general
Use of data	Data collection is used to evaluate propositions or hypotheses related to an existing theory	Data collection is used to explore a phenomenon, identify themes and patterns and create a conceptual framework, Theory generation and building, Generalising	Data collection is used to explore a phenomenon, identify themes and patterns, locate these in a conceptual framework and test this through subsequent data collection and so forth
Theory	Theory falsification or verification	Theory generation and building	Theory generation or modification

Based on inferences drawn from Table 4.2, the abductive reasoning approach is the most suitable for this study, which aims to develop a DT implementation framework for BM management. It utilises the strengths of both deductive and inductive reasoning approaches. In this regard, preliminary exploration was necessary to identify the maintenance-related issues and technologies/systems adopted by BM organisations to manage these issues. The essence of such preliminary exploration through a deductive research approach was to generate knowledge regarding the use of technologies/systems for maintenance activities. Such exploration facilitated the development of a framework through an inductive approach for DT implementation. Thus, the abductive reasoning approach is employed in this study to maximise the benefits of both deductive and inductive research approaches and to establish a framework for DT implementation for BM management.

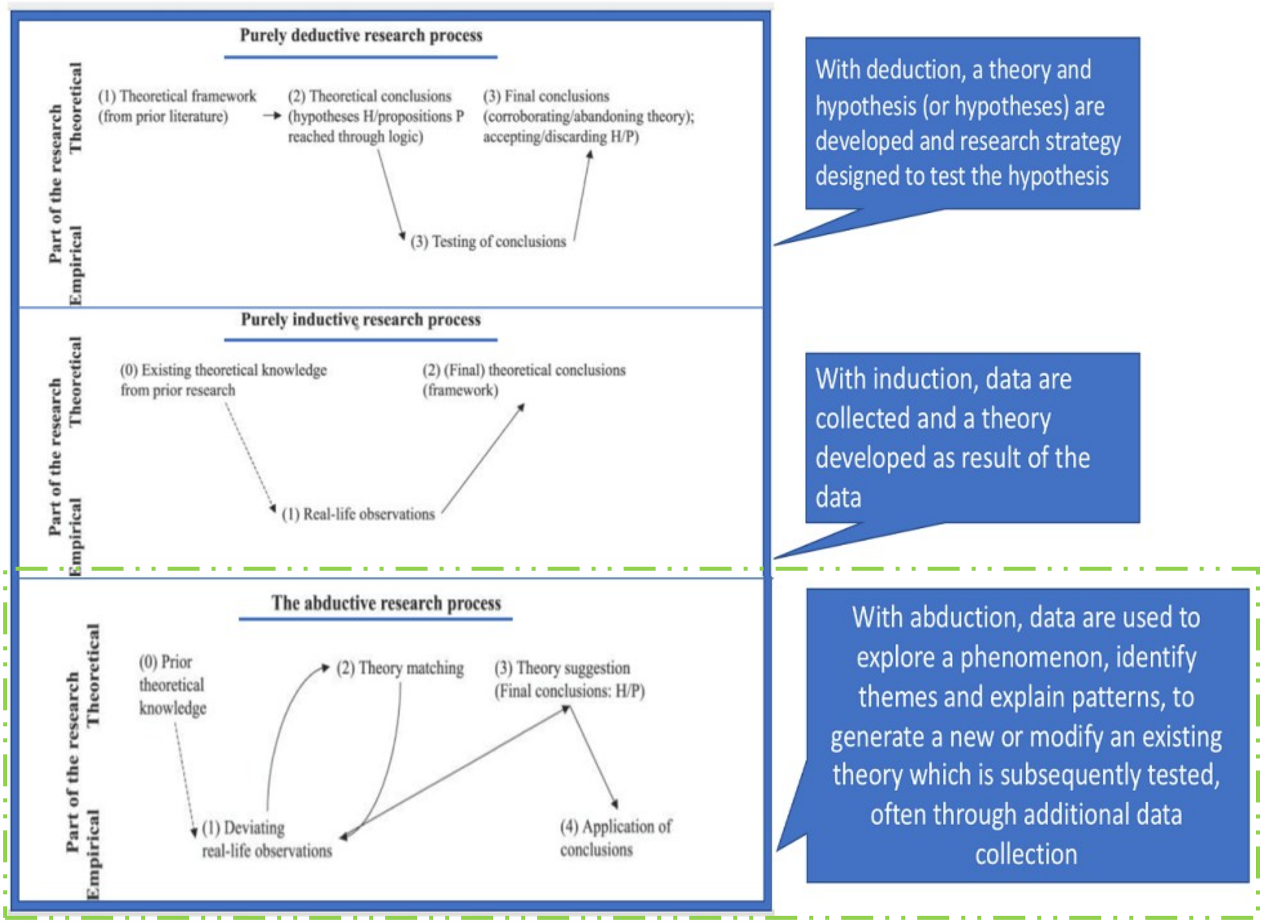


Figure 4.3: The Three Main Reasoning Approaches to Theory Development (Adapted from Mitchell, 2018; Kovács and Spens, 2005)

4.3 Research Design

Research design is pivotal to the reliability of a study's findings (Kothari, 2004). According to Creswell (2016), research design connects a researcher's philosophical worldview, research strategy of inquiry, and data collection and analysis methods to understand or obtain knowledge. Saunders *et al.* (2019) elaborate that research design justifies the selection of a research method for collecting and analysing data to answer a study's research questions. Hence, the choice of an appropriate research method is influenced by the aim and objectives of the research (Lancaster, 2005). As highlighted by studies, there are two types of research methods based on subjective and objective philosophical viewpoints (Groat and Wang, 2013; Creswell, 2009). These are qualitative (subjectivist) and quantitative (objectivist), while the combination of both is termed mixed methods (intersubjective). Thus, choosing the right research method is crucial in the pursuit of knowledge, as this is where the research methodology becomes visible in a study (Saunders *et al.*, 2019; Groat and Wang, 2013).

For this study, mixed-method research was employed, as it facilitated the acquisition of general background knowledge of the BM sector in Nigeria and the possible implementation of DT for maintenance management. The quantitative research method was utilised to identify maintenance-related issues, maintenance strategies, and technologies/systems employed by BM organisations to manage these issues. This research phase opened up areas for the researcher that required further investigation. Following this phase, a qualitative research method was employed to uncover areas needing investigation and the requirements for implementing DT for BM management. These processes are discussed in Section 4.6, which highlights the choice of data collection and analysis instruments in achieving the study's aim and objectives, summarised in Figure 4.7. Thus, using mixed-method research allowed for the elicitation of valuable data to achieve this study's aim.

4.4 Research Strategies

Research strategy serves as a researcher's action plan to address a study's research question (Groat and Wang, 2013). It provides direction for conducting research. According to Saunders *et al.* (2019), research strategy links a researcher's philosophical stance with their choices for data collection and analysis. There are various types of research strategies, including surveys, action research, case studies, ethnography, experiments, and grounded theory (Saunders *et al.*, 2019). Table 4.3 presents a summary of these strategies.

Table 4.3: Research Strategies (Adapted from Saunders *et al.*, 2019)

Research Strategy	Definition
Experiment	This involves the definition of a theoretical hypothesis; the selection of samples of individuals from known populations; the allocation of samples to different experimental conditions; the introduction of planned change on one or more of the variables; and measurement on a small number of variables and control of other variables. See also control group, experimental group.
Survey	It involves the structured collection of data from a sizeable population. Although the term 'survey' is often used to describe the collection of data using questionnaires, it includes other techniques such as structured observation and structured interviews.
Archival Research	This deals with the analysis of administrative records and documents as principal source of data because they are products of day-to-day activities.
Case Study	It involves the empirical investigation of a particular contemporary phenomenon within its real-life context, using multiple sources of evidence.
Ethnography	This focuses upon describing and interpreting the social world through first-hand field study.
Action research	This is concerned with the management of a change and involving close collaboration between practitioners and researchers.
Grounded Theory	It develops a theory from data generated by a series of observations or interviews principally involving an inductive approach.
Narrative Inquiry	This ideals with the collection and analysis of qualitative data that preserves the integrity and narrative value of data collected, thereby avoiding their fragmentation.

For this study, the survey research strategy was employed to achieve the study's aim. As Saunders *et al.* (2019) highlighted, the survey research strategy is a technique used to collect data by questioning a predefined group of participants. It enables the researcher to collect information and understand a research question. According to studies, survey research can be conducted using a questionnaire, observation, or interviews (Adu and Miles, 2024; Saunders *et al.*, 2019; Creswell, 2016). In this study, BM managers were surveyed to collect information on the maintenance strategies used and technologies/systems adopted by their organisations to manage maintenance-related issues in Nigeria quantitatively. The purpose of this survey was to explore the current BM organisational practices and the extent of technological advances employed in maintenance activities. Interviews were subsequently used to qualitatively explore DT's implementation requirements for BM organisations in managing maintenance activities. Thus, the survey research strategy was employed to collect crucial data on current BM organisational practices and how DT could be implemented to support these practices in managing maintenance activities.

4.5 Research Time Horizon

The research time horizon dimension refers to the time frame for conducting a study (Mitchell, 2018). According to Saunders *et al.* (2019), the duration taken to study a phenomenon can be akin to a snapshot at a specific moment in time (cross-sectional) or a sequence of snapshots to represent an event over a period (longitudinal). For this study, the cross-sectional time horizon was deemed most suitable. It was employed owing to time constraints and the challenges of assessing the same participants over time to answer the study's research question. Such a dimension was beneficial as it was quick and cost-effective compared to longitudinal studies, which can be expensive and time-consuming due to repeated data collection and the potential loss of study participants (Babbie, 2007; Marczyk *et al.*, 2005). Hence, this dimension allowed for efficient data collection on BM practices, providing a cost-effective and rapid analysis crucial for promptly advancing to the framework development phase.

Furthermore, the cross-sectional dimension provided a vital baseline for benchmarking current BM organisational practices, generating preliminary insights that highlighted existing conditions and maintenance-related issues without the extended timelines and resource commitments associated with longitudinal studies. Such insights informed the customisation and optimisation of the study's DT framework to support specific organisational needs. Thus, this dimension lays a robust foundation for future longitudinal studies to assess the framework's long-term effectiveness and usefulness.

4.6 Data Collection and Analysis Procedures for a Mixed Research Design

Data collection and analysis are at the core of the research onion (Figure 4.1). They are essential for conducting research and play a key role in empirical investigations of a phenomenon (Babbie, 2007). Hence, they are fundamental to the findings of any study. Consequently, this section is discussed to align with this study's chosen research design, which is the sequential mixed method (Section 4.3), to ensure practicality in selecting the research instruments.

4.6.1 Data Collection

Data collection pertains to the observable aspect of science or a phenomenon (Babbie, 2007). It begins after a study's research question has been established alongside its research design (Kothari, 2004). The research question helps researchers identify important themes and patterns in the collected data (Saunders *et al.*, 2019). Data utilised in a study can be either primary or secondary. Primary data is collected for a specific research project being investigated, whereas secondary data consists of existing datasets from previous studies that are analysed to provide supplementary information for the ongoing study (Saunders *et al.*, 2019). Data may be collected through a literature review, questionnaire, observation, and/or interview. Thus, the data collection method facilitates the systematic selection of the appropriate primary and/or secondary datasets for a given study.

For this study, primary data was collected. The purpose of primary data collection was to address the study's research question, which seeks to explore how DT can be implemented at the organisational level for BM management and to fulfil the study's aim and objectives. Figure 4.4 illustrates this process. Firstly, an exploratory literature review on BM was conducted to pinpoint the challenges encountered by BM organisations in their maintenance activities, particularly in the Nigerian context (research objective (RO) 1). This challenge was narrowed to the technologies/systems utilised in maintenance activities, identifying shortcomings of technologies/systems such as BIM and CMMS, among others, in updating data in real-time to manage the complexities of BM (RO 2).

Further investigation revealed DT as a promising solution for real-time data updates, among other benefits, and its relevance for maintenance activities (RO 3). This inquiry further narrowed the research focus on how DT can be implemented at the organisational level, as previous studies have focused more on its technical aspects. This study explored the organisational determinants for implementing DT, and thus, the PPT framework was employed to identify these determinants (RO 4). Hence, for a BM organisation to adopt the use of DT, a balance among the staff, processes, and the use of DT is necessary. The organisational implementation of DT was achieved through some modelling and process mapping approaches. These process mappings were instrumental in developing the study’s framework after data collection and analysis (RO 5). Thus, the literature review established a foundation for understanding inherent challenges, such as maintenance-related issues and how technologies/systems like DT can be implemented to support BM organisations in maintenance management.

Secondly, primary data was collected through a questionnaire to obtain quantitative data and gain a deeper understanding of maintenance-related issues and BM organisational practices regarding the use of technologies/systems (RO 1 and 2). Thirdly, a semi-structured interview followed the questionnaire collection process to extract qualitative data on DT, its requirements for maintenance activities, and the readiness of BM organisations in Nigeria to implement it (RO 3 and 4). The collected data facilitated the creation of a framework for implementing DT to support BM management (RO 5). Finally, a focus group evaluation session followed the framework development process to obtain qualitative data regarding its applicability for maintenance management (RO 6). Thus, the processes of data collection were vital in achieving the study's objectives; however, the sampling methods used to collect data from a population are fundamental (Saunders *et al.*, 2019; Babbie, 2007).

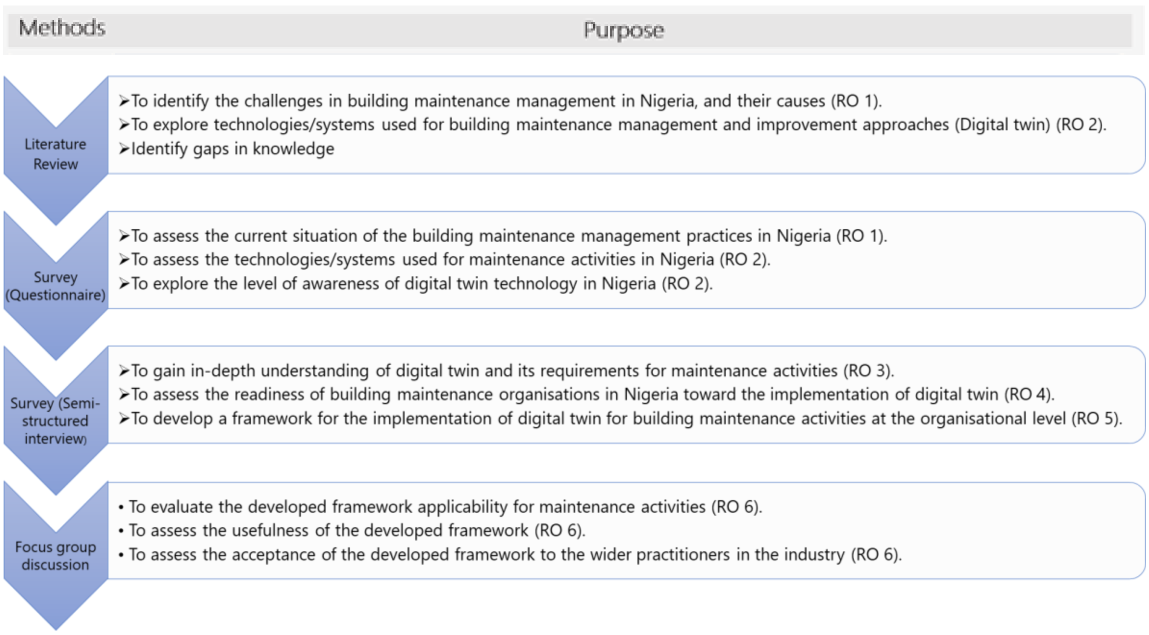


Figure 4.4: Data Collection Methods and its Purpose

4.6.1.1 Sampling Method

Sampling is a statistical technique used to generalise a population from samples (Groat and Wang, 2013). It saves researchers the burden of reaching out to an entire population to collect data. There are two main types of sampling techniques: probability and non-probability (Groat and Wang, 2013; Babbie, 2007). On one hand, probability sampling involves randomly selecting participants to represent a population, with the aim of making strong statistical inferences about the entire known population. On the other hand, non-probability sampling entails selecting participants non-randomly based on specific criteria that facilitate convenient data collection from an unknown population (Saunders *et al.*, 2019).

Based on inferences drawn from Table 4.4 and Figure 4.5, the non-probability sampling technique was employed for this study. This choice was made for some reasons. The first reason was sampling practicality, as the comprehensive list of the study's targeted population was unknown (Saunders *et al.*, 2019; Kothari, 2004). Hence, the selection of available participants was based on subjective criteria such as years of work experience and knowledge of BM management and DT usage, among others. Secondly, non-probability sampling is appropriate for exploratory studies where the study's domain is relatively new, as is the case with DT, and understanding it is vital for its implementation in BM management (Saunders *et al.*, 2019; Babbie, 2010).

For these reasons, purposive and snowball sampling techniques were used to recruit suitable participants based on their uniqueness in achieving the study's aim. The purposive sampling technique aided in selecting participants relevant to the study's research question. This sampling technique is associated with choosing targeted participants who possess knowledge from either a homogeneous or heterogeneous group and who have adequate experience with the phenomenon under investigation, fulfilling specific selection criteria (Saunders *et al.*, 2019; Etikan *et al.*, 2016; Palinkas *et al.*, 2015). The participants were chosen based on their expertise and experiences in BM management and/or the use of DT. Interestingly, studies indicate that the purposive sampling technique allows for flexibility in refining participant selection criteria as the research progresses to address the research question (Saunders *et al.*, 2019; Kumar, 2011).

Conversely, the snowball sampling technique provided access to participants who were initially inaccessible (Saunders *et al.*, 2019). This technique further enabled an in-depth understanding of how DT is used for BM management. Subsequently, each section of the data collection methods elaborates on the participant selection procedures. Thus, these sampling techniques facilitated the selection of appropriate participants to address the study's research question.

Table 4.4: Types of Sampling Techniques (Adapted from Saunders *et al.*, 2019)

Sampling Types	Sampling Techniques	Definition
Probability	**Random**	This method ensures that each case in a study population has an equal chance to be selected in a sample.
	Systematic	This procedure deals with the selection of an initial sampling point at random, and then the selection of other cases at regular intervals.
	Stratified	This method involves the division of a target population into two or more strata, and then a random sampling is carried out from each stratum.
	Cluster	This technique deals with the division of a study population into discrete groups, and then a random sample is drawn from them.
Non-Probability	**Purposive**	This method involves a researcher's judgement on the selection of the cases for a sample, which is based on some criteria (criticality, heterogeneity, homogeneity).
	Convenience	This technique deals with the selection of cases based on the thoughts that the participants are easy to reach.
	Snowball	This involves the selection of participants from information given by an initial participant.
	Quota	This method takes the form of a judgemental process based on the premise that the representation of cases for a sample is targeted at a population.

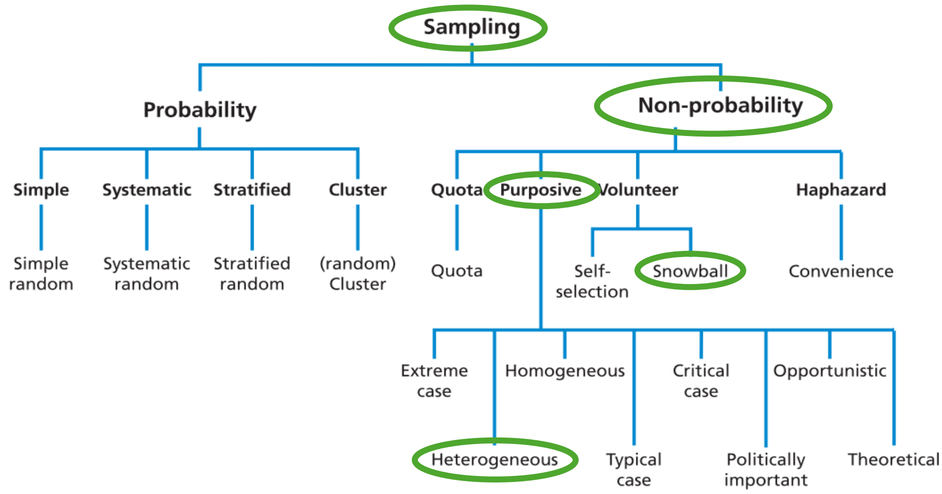


Figure 4.5: Sampling Techniques (Adopted from Saunders *et al.*, 2019)

4.6.2 Data Analysis

Data analysis involves examining observable patterns within a set of collected data (Babbie, 2007). For this study, which adopted a sequential mixed methods approach, the collected quantitative and qualitative data were analysed separately using the most appropriate analytical tools. Creswell and Clark (2017) outlined various procedures for data analysis. These include data preparation, data exploration, data analysis, representation of analysed data, interpretation of analysed data, validation of analysed data, and interpretation of findings. Therefore, the proper analysis of collected data was crucial for the study's final findings.

4.6.3 The First Data Collection and Analysis Procedure Phase (Quantitative)

4.6.3.1 Data Collection through Questionnaire

This study employed a closed-ended questionnaire to collect quantitative data on the inherent issues relating to BM management, along with the technologies/systems adopted by BM organisations for maintenance activities in Nigeria. The questionnaire was aimed to evaluate the present state of BM practices and to explore the utilisation of technologies and systems, particularly DT. Due to the researcher's current residence in the UK and time constraints, the researcher was unable to physically distribute the questionnaire to BM managers within the Nigerian BM sector. Consequently, an online medium was used to distribute the questionnaire, which was facilitated using Jisc online surveys. Jisc online survey was chosen for its automated features that handle data collation, storage, security, and processes, and it is the approved medium of online data collection by Birmingham City University (BCU).

4.6.3.2 Questionnaire Design

The design of the closed-ended questionnaire focused on achieving certain of the study's objectives (RO 1 and 2). It was structured to validate the findings from the literature review and provide critical inputs for developing the study's DT framework for BM management. The questionnaire examined current maintenance activities in the Nigerian BM sector, with questions derived from the literature review (Chapter Two). The questionnaire was organised into four sections (Appendix 1). The first section collected demographic information about the participants and organisational profiles.

The following section focused on maintenance patterns, which helped identify the types of buildings that are most commonly maintained and those that present significant challenges. This information is crucial for developing the DT framework to accurately reflect real-world challenges. Findings would inform the prioritisation of features and functionalities in the framework, such as more detailed simulations for buildings that are difficult to maintain, as user attitudes towards buildings and asset usage are not easily controlled. Furthermore, the literature indicates that BM organisations need to adopt a more proactive approach to maintenance management rather than being reactive. Hence, understanding the maintenance strategies predominantly employed by BM organisations will help identify areas for improvement. Such insights will aid in developing the DT framework to simulate various scenarios and predict their outcomes, thereby facilitating strategic decision-making processes for BM organisations in managing maintenance-related issues.

The third section elicited the technologies/systems used by BM organisations for maintenance activities. Understanding the different technologies and systems currently employed for maintenance management by BM organisations provides insight into the level of their organisational digitalisation. Such information is essential for integrating DT with existing systems or understanding the need for innovative technology implementations. Subsequently, the DT framework can be developed to complement or enhance the functionalities of the existing technologies and systems through capabilities such as real-time data analysis and predictive analytics. All three sections were measured using a nominal scale.

The final section asked questions about the causes of maintenance-related issues that led to BM activities. This section identifies those issues, which is critical as it systematically collects data on organisational, technical, human resources, financial, user-related, and natural causes. Understanding these issues informed the design of the framework's people, processes, and technology-oriented dimensions, ensuring it accommodates and suggests solutions to address organisational inefficiencies in maintenance management. Questions in this section were measured based on a 5-point Likert rating scale of responses ranging from 5 representing “to a very large extent”, 4 “to a large extent”, 3 “to a moderate extent”, 2 “to a minimal extent”, and 1 “not at all”. Thus, the questionnaire was designed to achieve Objectives 1 and 2, focusing on understanding maintenance patterns and the technologies/systems employed by BM organisations for maintenance management, thereby providing better insights for developing the study’s DT framework.

4.6.3.3 Participant Selection

Selecting the right participants for this study was crucial, as the data collected would significantly influence the overall findings. The study population was drawn from professionals involved in BM management to select the participants. Specific criteria were considered for participant selection, including that participants must (1) be over 18 years of age; (2) possess requisite expertise and experience of over five years in the industry; (3) have a solid understanding of BM management; and (4) provide evidence of involvement in the management of a BM project in Nigeria (Adu and Miles, 2024; Ogunbayo *et al.*, 2022; Wang *et al.*, 2020, 2018).

Given the context of Nigeria and the heterogeneous nature of BM managers, the Nigerian Institution of Builders in Maintenance and Facilities Management (NibimFam) was contacted purposefully to obtain a list of prominent professionals engaged in BM management. NibimFam is a specialised division of the Nigerian Institute of Building, affiliated with the Nigerian Academy of Facility Managers. It was established to promote building and facilities maintenance management as a distinct association. Membership necessitates meeting strict criteria, such as academic qualifications and professional experience in building and facilities maintenance management. These criteria have resulted in a limited membership size due to their specialised nature.

NibimFam provided 61 potential participants through stratified sampling by selecting 10 participants from each of the six geopolitical zones of Nigeria and one from the federal capital. Given the targeted focus of this study, a census sampling technique was employed. Census sampling, also known as total enumeration, removes bias from the selection of participants and is frequently applied to small population sizes (Babbie, 2010; Kothari, 2004). 24 participants completed the questionnaire. While this number may appear small, it is significant, representing a 39% response rate from NibimFam's specialised association.

4.6.3.4 Pilot Questionnaire Test

A pilot study was necessary for this research to frame the questions and avoid any ambiguity. According to Kothari (2004), 24 respondents constitute the quorum for conducting a pilot study. However, due to the sample size of this study, such a quorum could not be met. Consequently, the researcher conducted a pilot study with three expert BM managers to frame the questions rather than test the constructs. This study was primarily conducted to examine the language used in framing the questions, enabling participants to comprehend them more easily. The study facilitated the simplification of the questions' wording and the outline of the sections in the questionnaire. One significant change included the initial question, “Do you use any of this software for maintenance activities?", which was refined to “Which of the following software does your organisation utilise the most for maintenance activities?" This initial question was too broad and could result in varied responses that might be difficult to analyse. Another example of a question revision was “How satisfied are you with the current maintenance management practices at your organisation?" This question was vague and did not explicitly measure specific maintenance-related organisational issues. Consequently, it was broken down into measurable variables, as detailed in Appendix 1. Thus, the pilot study was employed to moderate the final questionnaire distributed online to BM managers in Nigeria.

4.6.3.5 Analysis of Quantitative Data

Data collection from a questionnaire is quantitative; hence, the choice of an appropriate instrument for analysis is crucial. As outlined in studies, two types of quantitative data exist: categorical and numerical (Saunders *et al.*, 2019; Kothari, 2004). These types of quantitative data and their corresponding measurement scales are presented in Figure 4.6 and can be analysed using descriptive and inferential statistics (Saunders *et al.*, 2019; Babbie, 2007). Descriptive statistics summarise variables in a sampled population, while inferential statistics compute results and draw inferences that relate them to the larger population (Babbie, 2007).

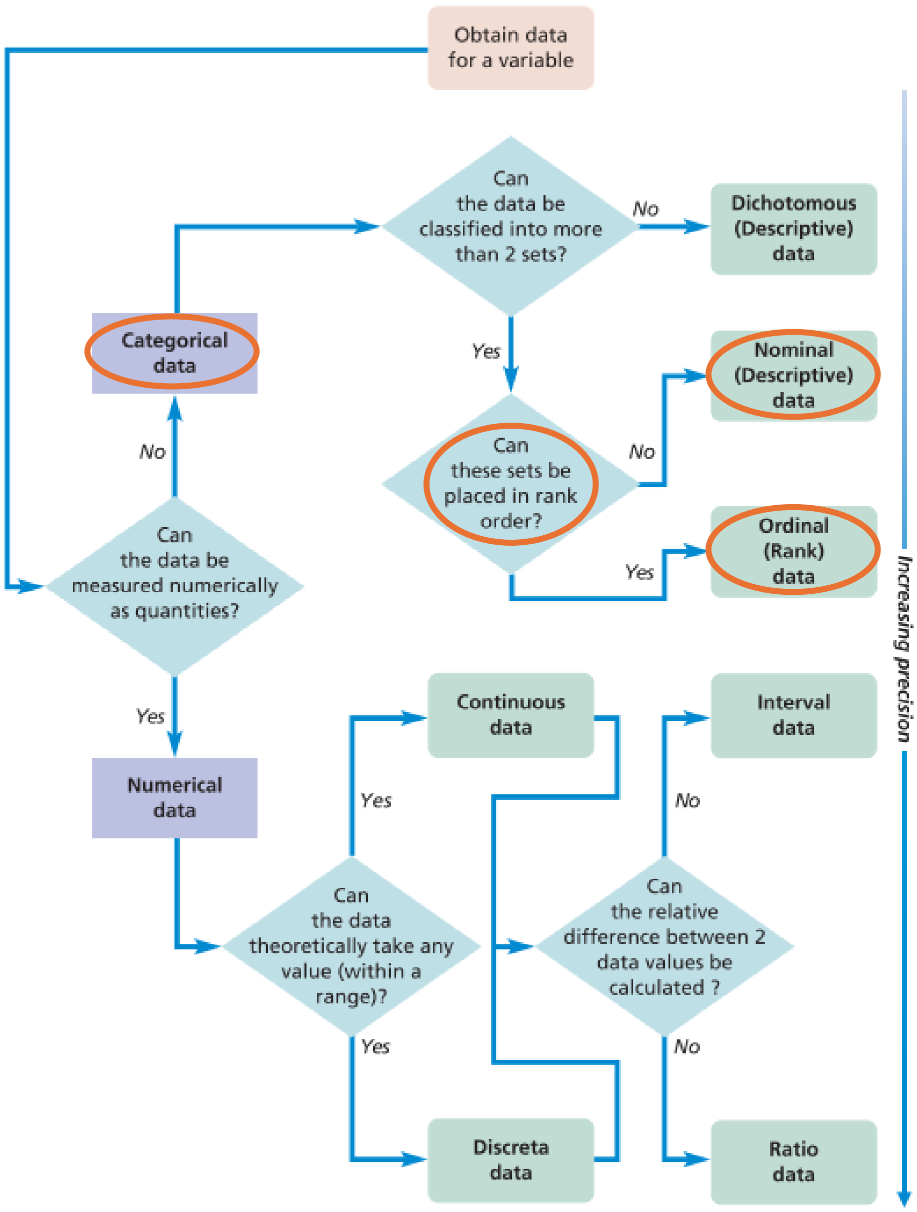


Figure 4.6: Quantitative Data Types (Adopted from Saunders *et al.*, 2019)

Upon careful examination of Figure 4.6 and the targeted nature of this study, descriptive statistics were utilised for data analysis, as it is exploratory and not focused on causal relationships or correlations often associated with inferential statistics. Hence, the collected data were analysed to achieve objectives one and two. These include the BM organisational characteristics (demographic data), maintenance patterns, and technology/system usage. The data collected were nominal as they were not ordered. Furthermore, participants were asked to rate some statements that served as variables contributing to maintenance-related issues leading to BM activities, using a five-point Likert scale ranging from not at all (1) to a very large extent (5). The data collected were ordinal, as they could be ranked for analytical purposes. Consequently, data were collected from BM managers with extensive expertise in maintenance activities.

The collected data were analysed descriptively using the Statistical Package for the Social Sciences (SPSS). SPSS was selected for its extensive data management capacity, data visualisation interface, data security, and data integration with other associated software. Frequency count, percentage, and Relative Importance Index (RII) were employed to analyse the collected data in SPSS. Frequency count and percentage identified the variables preferred by participants, while RII was used for its capability to perform a comparative analysis of the different variables prominent to maintenance-related issues. Previous studies have utilised the RII analysis technique to achieve similar results (Arumsari *et al.*, 2021; Osuagwu *et al.*, 2021b; Nkpite and Wokekoro, 2017). While a measure of central tendency could have served a similar purpose as RII, the data analysis was not aimed at describing the dataset's midpoint. Results from the data analysis were presented using tables (Chapter Five).

4.6.4 The Second Data Collection and Analysis Procedure Phase (Qualitative)

4.6.4.1 Data Collection Through Interviews

An interview data collection method allows a researcher to gain deeper insight into a studied phenomenon (Saunders *et al.*, 2019). This method provides real-life understanding and expert opinions regarding the phenomenon. Data can be collected from participants through personal interactions such as face-to-face, telephone, or online media platforms (Kothari, 2004). Studies highlight three types of interview methods: structured, semi-structured, and unstructured (Babbie, 2007; Kothari, 2004). For this study, a semi-structured interview was employed to collect data. This type of interview permits varying predefined question sets, allowing for additional questions relevant to the study's context and enabling flexibility in the conversation between the researcher and the participant while maintaining the research focus (Saunders *et al.*, 2019). Rowley (2012) elaborates that a semi-structured interview lets a researcher slightly modify the wording of questions to elicit more useful responses from participants. Studies using semi-structured interviews have addressed their research questions with a deeper understanding and achieved their research aim (Elyasi *et al.*, 2023; Fateh and Nikmat, 2023; Wang *et al.*, 2018). Therefore, the semi-structured interview was ideally suited for this study, as it allowed the freedom to explore the research question further while keeping track of its aim.

4.6.4.2 Interview Set-up

Setting up an interview session was essential for collecting accurate qualitative data for this study. According to Saunders *et al.* (2019), interview setups for one-on-one interviews can be face-to-face, telephone, or internet-mediated (online video call). Consequently, this study utilised an internet-mediated interview setup to collect information from participants for several reasons. Firstly, the researcher needed to interview participants from around the world due to the study's focus on implementing DT for maintenance activities, a concept still in its infancy within the AEC industry. Secondly, the researcher was constrained to this method due to residing in the UK and facing time limitations constraints.

To conduct the interview sessions, Rowley (2012) emphasises that video calls are as effective as face-to-face interviews, as the participants' emotions and body language can be observed to assess the authenticity of the information being shared. While this method was convenient for collecting information, it posed challenges related to low internet connectivity. Thus, ensuring a stable and reliable internet connection was crucial on the pre-interview checklist.

This measure facilitated smooth, uninterrupted communication, enabling comprehensive and accurate data collection during each session.

4.6.4.3 Interview Design

The design of the semi-structured interview was focused on eliciting data to achieve objectives 1, 2, 3, and 4 of the study. The interview explored the requirements for implementing DT for BM management. The questions were derived from the literature review (Chapters Two and Three). They were structured into two parts for two different participant groups. The first group consisted of experts in DT, while the second comprised BM managers in Nigeria. The initial question set was designed to collect data on DT and its workings (Appendix 2) and was divided into four sections. The first section sought demographic data from the participants, while the next focused on the fundamental components of DT and its applicability to activities such as maintenance. The third section elicited data on the sequential development of DT, including drivers/enablers, barriers, and organisational requirements. The concluding section collected data on ways to promote DT for organisational use. These questions aimed to provide a grounded understanding of DT, its utilisation, requirements, and development.

The second question set aimed to collect data regarding BM management in Nigeria and the potential for DT implementation in maintenance activities (Appendix 3). This set was divided into six sections. The first section inquired about demographic data, while the next explored how maintenance activities were conducted and whether a formal process or framework existed. This section aimed to establish whether BM organisations have a structured approach to conducting maintenance activities. The third section collected data on the responsibilities of BM stakeholders, including clients and building professionals, as well as maintenance data requirements. The subsequent section explored the technological tools or systems used in BM management, assessing the organisations' awareness of DT. The fifth section inquired about the feasibility of implementing DT for maintenance activities. The final section elicited data on how DT can be promoted for BM management. In summary, these questions were designed to understand how BM organisations conduct their maintenance activities, with a view toward incorporating DT into their management processes.

4.6.4.4 Participant Selection

Selecting the appropriate participants to elicit data for this study was crucial. Individuals engaged with the usage of DT were scarce, as it is still in its infancy within the AEC industry (Arowoiya *et al.*, 2024; Pomè and Signorini, 2023; Delgado and Oyedele, 2021), and Table 5.8 indicates its non-usage in Nigeria. Based on inferences from Table 5.8, continuing a qualitative inquiry into DT's implementation would be inadequate, as the data to be collected would be limited. For this reason, the inquiry was conducted with DT experts located outside Nigeria to gain further insights. As discussed in Section 4.6.1.1, the purposive sampling technique was employed to target the initial group of participants, who were experts in DT and related activities. In this context, 'experts' refer to individuals possessing the requisite knowledge in the DT field and who have been involved in its application for projects (Lu *et al.*, 2022). Specific criteria were considered for participant selection, including that participants must (1) be over 18 years of age; (2) possess requisite expertise and experience of over 5 years in the industry; (3) have a solid understanding of DT for construction and/or maintenance-related management; and (4) demonstrate evidence of being a part of a DT project (Adu and Miles, 2024; Wang *et al.*, 2018, 2020). The participants' details were searched globally through LinkedIn, Google Scholar, and seminar presentations. Subsequently, the snowball sampling technique was employed to recruit additional participants from those obtained through online channels after conducting some interviews.

Furthermore, the second group of participants, who were BM managers in Nigeria, was recruited through snowball sampling. This technique was used due to the low response rate of participants interested in interviews during the questionnaire phase. Only 2 out of the 18 participants responded. Consequently, the contact details of other BM managers willing to participate in the interviews were obtained from them. The selection criteria for the additional participants were in accordance with Section 4.6.3.3.

A total of 20 participants were recruited: 11 for DT and 9 for BM, with their profiles presented in Section 6.3. Overall, the selection of participants for this study was not aimed at reaching a saturation point, a critical feature in qualitative research rigour; instead, it focused on having a solid understanding of the research issue, as the study was exploratory and not centred on causal relationships. Reichwein *et al.* (2015) support the notion that the saturation point does not necessarily need to be reached in qualitative research, but understanding the research domain is essential. Thus, these participants were chosen to obtain in-depth knowledge of DT and its implementation at the organisational level for BM management.

4.6.4.5 Pilot Interview Test

A pilot test was essential for this study to shape the interview questions and avoid any ambiguity. Rowley (2012) emphasises that a pilot interview is necessary for a qualitative study to assess the efficacy of the questions prior to the actual interview sessions. For this reason, the researcher employed the first two participants from each set of interviewees to refine the questions pertinent to their domain. The pilot test focused on the wording used to frame the questions, enabling the participants to comprehend them easily (Akotia *et al.*, 2023). It assisted in simplifying the question phrasing and the outline of the sections. Hence, the pilot test was used to moderate the final sets of interview questions discussed with both categories of participants.

4.6.4.6 Analysis of Qualitative Data

Data collected through interview sessions is qualitative; therefore, selecting the appropriate instrument for analysis was crucial for this study. According to Saunders *et al.* (2019), qualitative data can be analysed using content, narrative, discourse, framework analysis, or grounded theory. These analytical methods are summarised in Table 4.5. After examining these methods, thematic analysis was deemed most appropriate for this study. It allows for data exploration and facilitates a holistic understanding of the participants' narratives. It aids in uncovering complex, interrelated elements within the dataset. It provides a systematic and transparent process to analyse data sequentially, leading to the identification of relevant themes (Braun and Clarke, 2021, 2006). Using such an analysis supported the researcher in discovering themes and patterns across the interview datasets regarding the requirements of DT and its implementation for maintenance management.

The interview datasets were analysed using the six-step procedure proposed by Braun and Clarke (2006). The process commenced with (1) familiarisation with the data, (2) generation of initial codes, (3) theme searching, (4) theme revision, (5) theme definition and naming, and (6) report writing. First, after the interview sessions, the interview transcript was reviewed and refined to understand its contents. Second, descriptive and interpretive categories were developed from the transcript content, and codes were generated. Third, content within categories was revised to observe interconnections during theme searching. Fourth, themes were developed and refined to represent meanings derived from the codes within the transcripts. Fifth, the themes were named in accordance with the study's concepts. Lastly, the findings were documented to address the research question. A detailed explanation of the thematic analysis of the interview datasets is presented in Section 6.1. This analysis contributed to accomplishing the study's objectives 1, 2, 3, and 4, and it enabled the development and modification of the proposed framework.

Table 4.5: Types of Qualitative Data Analysis (adapted from Saunders *et al.*, 2019)

Types of Qualitative Analysis	Definition	Focus
Content analysis	This deals with the categorisation of verbal or behavioural data into classes and summarises to enable their analysis quantitatively.	Classification of verbal data for quantitative analysis
Narrative analysis	This involves the analysis of collected data with the view to preserve its integrity and values.	Preservation of Integrity and values
Discourse analysis	This entails the translation of languages or talks that occur naturally into written text to reveal the changes in the social world.	Translation of languages in the social world
Grounded theory	This ideals the formulation of a theory through the analysis of cases or subjects.	Theory formulation
Thematic analysis	This involves the search for themes or patterns that occur within a data set.	Identification of themes and patterns

For the transcription of the interview datasets, intelligent verbatim transcription was utilised to eliminate distracting fillers, along with non-standard and repeated spoken words. Mcmullin (2021) emphasises that irrelevant sounds, utterances, and grammatical errors must be removed from a transcript to create a reasonable interpretation, unlike full verbatim transcription, where all sounds and errors are included. Subsequently, NVivo software was employed to analyse the dataset, providing a robust coding system. The software facilitated in-depth analysis of transcripts in a hierarchical coding structure. It allowed easy visualisation of data structures as analysis progressed, thereby aiding the coding and analysis of the data.

4.6.5 The Third Data Collection and Analysis Procedure Phase (Focus Group)

Evaluation involves assessing the design, implementation, and outcomes of a programme, which encompasses a framework, to determine its effectiveness and guide future improvements (Adu and Miles, 2024; Patton, 2015). According to studies, six types of evaluation are commonly used to assess a programme or framework in research (Adu and Miles, 2024; Kumar, 2011). These include developmental, formative, implementation, economic, summative, and attribution (impact) evaluation. The developmental type assesses stakeholder needs, expectations, and programme resources before implementation (Adu and Miles, 2024; Patton, 2015). Formative evaluation examines programme activities and resources to ensure they align with expectations during implementation (Patton, 2015; Kumar, 2011). Implementation evaluation assesses programme outcomes to identify success factors and inform future decisions (Adu and Miles, 2024; Patton, 2015). Economic evaluation focuses on cost assessment, analysing programme costs, cost-effectiveness, and cost-benefit ratios (Babbie, 2010; Knight and Ruddock, 2008). Summative evaluation compares programme outcomes against targets, evaluating overall effectiveness post-implementation (Patton, 2015; Kumar, 2011). Attribution evaluation investigates causal relationships between the programme and outcomes, determining the programme's impact and value relative to resources invested (Adu and Miles, 2024). Thus, these various evaluation types provide critical insights for programmes encompassing framework development, improvement, and decision-making across different stages of implementation.

For this study, which developed a framework for implementing DT for BM management, formative evaluation was deemed the most appropriate and was thus utilised. The formative evaluation focuses on assessing the framework’s processes and activities. Its distinctiveness lies in examining how effectively the DT framework supports maintenance activities, identifies implementation challenges, and captures participants' perceptions. Employing this method enhanced the framework's effectiveness, applicability, and relevance by facilitating iterative improvements. It also served as a suitable medium for collecting participants' opinions, which were crucial to the success of the framework evaluation.

4.6.5.1 Data Collection Techniques for Evaluation

The data collection technique used for the evaluation of this study's framework was pivotal to its effectiveness. Studies indicate that data can be collected through interviews, focus group sessions, or open-ended questionnaires (Kumar, 2011; Akotia *et al.*, 2023). Considering the suitability of these methods, a focus group was selected as the best fit for this study's framework evaluation to ascertain its relevance and applicability. Using focus group discussions for formative evaluation provided in-depth qualitative insights, enabling real-time feedback to refine the framework and address barriers during implementation. Such an approach promoted participants' engagement, ensuring the framework aligns with the organisational needs of BM and encourages its successful adoption. Studies have shown that focus groups provide a thorough evaluation of research outputs through informed judgements and assessments from experienced experts with relevant knowledge in the research domain (Domingos *et al.*, 2024; Cotgrave and Wilson, 2020). The experts' feedback serves to reinforce or modify the study's output for improvement and clarity. Therefore, the focus group method is most suitable for this study's framework evaluation.

4.6.5.2 Focus Group Set-up

The configuration of the focus group discussion mirrors that of the interview set-up outlined in Section 4.6.4.2. This arrangement aims to utilise the best available medium, whether an in-person or online session, to elicit the necessary data from participants. The essence of a focus group session was to collect substantial feedback regarding the applicability of the developed framework from an expert opinion perspective. This feedback is intended to help shape the final output of the research. To achieve the focus group session, selected participants were asked to indicate their availability through an online scheduling platform. After the participants' availability was confirmed and the session time was established, they were sent the consent forms, the proposed framework, and evaluation questions.

Given the research's targeted nature, an internet-mediated (online video call) approach was employed to elicit data from participants, as they were located outside the UK. A study by Domingos *et al.* (2024) utilised an online focus group session for their evaluation with successful results. Although this method was convenient for eliciting information, it did present challenges concerning low internet connectivity. Consequently, this was one of the checks conducted prior to the session to ensure smooth and uninterrupted communication.

4.6.5.3 Focus Group Question Design

Studies have established that certain evaluation criteria are used to assess a framework (Adu and Miles, 2024; Patton, 2015). For this study, the evaluation criteria are based on questions related to the PPT framework, which were employed to formulate activities during the development of the study's framework. The design of the questions focused on eliciting participants' opinions about the developed framework regarding its usefulness and applicability from the perspective of the PPT organisational dimensions. The questions were organised into three sections (Appendix 6). The first section addressed the framework's usefulness and applicability within the process structure of the participants' organisations. The subsequent section aimed to determine whether the human resources of the participants' organisations could accommodate the framework, and if other industry practitioners would accept it. The final section elicited participants' opinions on their organisation's technological infrastructure to support the framework. Thus, these questions were discussed, and agreements were reached to improve the study's framework.

4.6.5.4 Participant Selection

Selecting the appropriate expert participants was crucial for evaluating this study's framework. As detailed in Section 4.6.1.1, the purposive sampling technique was utilised to identify expert participants knowledgeable in DT and/or maintenance management. The criteria outlined in Section 4.6.4.4 were also applied in the participant selection process. The organisational profiles of the selected participants are presented in Table 6.1.

4.6.5.5 Analysis of Data from Focus Group

Data collected from a focus group session is qualitative; therefore, choosing the appropriate instrument for analysis is crucial. Hence, the analysis of the collected data was conducted in accordance with Section 4.6.4.6. NVivo software was employed to analyse the dataset, providing a robust coding system. This analysis facilitated the refinement of the developed framework, resulting in its updated version (Figure 7.4).

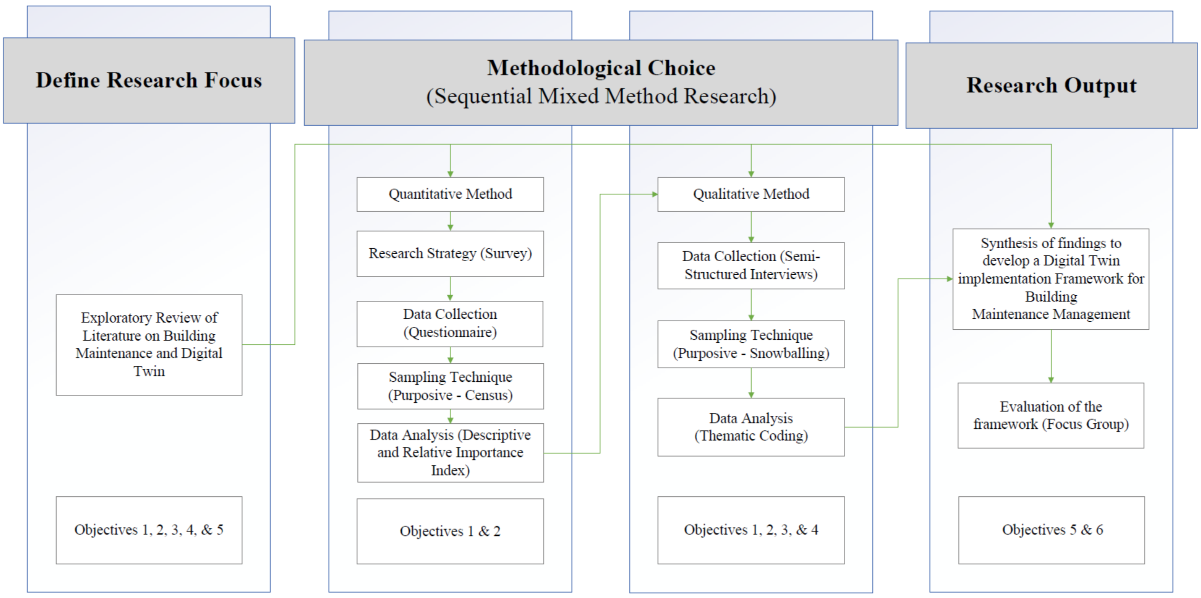


Figure 4.7: Research Design

4.7 Research Quality

Research quality is pivotal to the overall findings of a study. Abowitz *et al.* (2010) argue that empirical research data has often been criticised for its reliability. In this light, Creswell and Clark (2017) emphasise that a research design must meet high standards and be followed precisely throughout a study to achieve quality. According to studies, good research quality is assessed using indicators such as reliability and validity (Saunders *et al.*, 2019; Babbie, 2007). On one hand, reliability measures the consistency and repeatability of research. On the other hand, validity addresses the appropriateness and accuracy of data collection and analysis instruments to yield generalisable findings (Babbie, 2007). However, studies indicate that reliability and validity cannot adequately assess the quality of a qualitative research design because it is socially constructed and typically involves a limited sample size (Saunders *et al.*, 2019; Yilmaz, 2013). These studies recommend employing dependability (reliability), credibility (internal validity), transferability (external validity), and authenticity criteria (promoting fairness) as alternatives.

Furthermore, according to Saldana (2013), there are challenges in the repeatability of the semi-structured interview approach, which may be attributed to its inherent flexibility. As such, a researcher's skillset plays a crucial role in overcoming this challenge. To address such challenges in this study, the researcher made a concerted effort to vary the questions posed while remaining within the semi-structured interview framework during the data collection process. This effort ensured consistency in data collection, which was video-recorded alongside the transcription (using an intelligent verbatim approach).

Quantitatively, the reliability of a questionnaire measures the consistency with which a set of questions can elicit the same information from participants each time they are asked. Groat and Wang (2013) highlight that research reliability pertains to the consistency of measurements across participants and their responses on a given scale. Saunders *et al.* (2007) elaborate that reliability refers to the degree of consistency in findings derived from a data collection and analysis method. In this context, consistency encompasses measurement over time, across variables, and among several researchers. Moreover, the reliability of a questionnaire can be assessed through various methods, such as Cronbach's alpha, the split-half method, repeatability or test-retest, and the Kuder test, among others (Akotia *et al.*, 2023; Ahmed *et al.*, 2022; Saunders *et al.*, 2019; Babbie, 2010; Knight and Ruddock, 2008).

Specifically, Cronbach's alpha is valuable for evaluating the internal consistency of multiple items within a scale measurement. The split-half method divides a test into two segments to assess its consistency. The repeatability or test-retest method evaluates the stability of measured items over time. The Kuder test is specifically designed to assess dichotomous responses from survey respondents. Based on these assessment methods, this study utilised Cronbach's alpha to measure the internal consistency among variables on a specified scale. The results from the Cronbach alpha reliability tests for the study's questionnaire are presented in Section 5.1.1. Additionally, validity is employed to substantiate the outcomes of a reliability test (Saunders *et al.*, 2019; Abowitz and Toole, 2010; Kvale, 2007).

This study's validity and transferability were achieved through a thorough literature review and the use of the most appropriate instruments for data collection and analysis, resulting in findings that are applicable in similar contexts. The pilot tests for both the questionnaire and the interviews ensured the validity of the study questions. Participants' responses during the evaluation session indicated that the study's findings were credible, thus supporting its credibility. Furthermore, research rigour underpins the research process. According to Yilmaz (2013), research rigour is a key measure of authenticity criteria, as it promotes fairness, transparency, repeatability, and a comprehensive analysis of the research process. In this study, research rigour was maintained throughout the development of the research methodology, allowing replication by other researchers conducting similar studies. It was diligently observed throughout the research process, from the literature review to the design of research questions, data collection, and analysis of the collected data. Moreover, the selection of mixed-method research facilitated a deeper understanding of the research question while employing the most suitable approach for addressing it, leading to the development of the study's framework. This method aligns with previous research methodologies, thereby ensuring the study's validity.

Regarding transparency, Leavy (2017) indicates that research methodology can highlight a study's strengths and limitations. Saunders *et al.* (2019) emphasise that research paradigms, methods, data collection techniques, and analysis procedures are integral to demonstrating research quality. In this study, the choice of methodology was transparent, leading to the development of the study's framework, which was presented to the industry for evaluation through focus group discussions (Section 7.2). Thus, the findings of this study are deemed reliable and valid due to the use of appropriate methodology.

4.8 Ethical Considerations

Ethics is a crucial aspect of research as it ensures that participants are safe and protected from any potential harm associated with their involvement in a study. Accordingly, this study was conducted in line with the ethical guidelines and regulations set forth by BCU research standards. The study mainly relied on primary data collected through questionnaires and interviews. Moreover, literature, encompassing journal articles, textbooks, codes, guidelines, and frameworks, was reviewed. Adequate resources, citations, and credits to the authors were duly acknowledged in this study. This study adhered to BCU research ethical practices, along with approvals from the supervisory team.

Before data collection methods commenced, all participants were provided with a research information sheet and a consent form. The information sheet outlined the research objectives, the contributions of participants through data collection, and how the collected data would be utilised. The consent form emphasised issues of confidentiality and anonymity. All participants signed this form, confirming their understanding of the research context, potential risks, and their right to withdraw from the research at any time. Furthermore, this study posed no significant risks to participants beyond those encountered in daily life. Participants' involvement in this study was voluntary, and their anonymity was maintained in the results report sections. Consequently, numbers were utilised to code the participants' responses, facilitating the inclusion of quotations during the discussion of results.

In terms of data security, the researcher ensured that all information from this research strictly complied with the Data Protection Act (Data Protection Act, 1998). The data collected in this study fell under the responsibility of the lead researcher and the supervisors, who adhered to BCU research ethics rules and regulations. This data was stored electronically on the University's secure 'One Drive' and/or locked away in a secure cupboard until the study's completion. Thus, adherence to BCU ethical rules and regulations was consistent throughout this study.

4.9 Summary

This chapter explains the methodology adopted for this study. The research onion serves as a systematic route to gain an in-depth understanding to address the research question. A pragmatic research philosophy is adopted, employing the abductive research approach. A sequential mixed-method research design is used to address the research question and achieve the study's aim and objectives, beginning with quantitative research followed by qualitative research. Given the targeted nature of the study, a survey research strategy is employed. For the quantitative research method, an online questionnaire is utilised to collect primary data from prominent BM managers in Nigeria. The questionnaire explores the current state of maintenance activities in the Nigerian BM sector concerning maintenance-related issues, strategies adopted, and technologies/systems utilised. A census sampling technique surveys sixty-one participants provided by NibimFam. The collected data is analysed descriptively using frequency count, percentage, and RII with SPSS software. This phase of the research process assists the researcher in exploring the level of technologies/systems usage and strategies adopted for maintenance activities, aiding the design of the interview questions to achieve the study's aim.

The qualitative research method is then employed to understand the requirements for implementing DT in maintenance activities. Semi-structured interviews are conducted with two sets of participants. The first set comprises experts in DT and other construction-related activities, while the second set consists of BM managers in Nigeria. The first set of participants is purposively selected from around the globe, as DT is still in its infancy, particularly in the AEC industry. Consequently, online searches on LinkedIn and Google Scholar are utilised to recruit participants, along with seminars and workshops. A total of eleven participants were recruited. The second set of participants is recruited through the snowball sampling technique, yielding a total of nine BM participants. The data collected from both sets of participants is transcribed using intelligent verbatim transcription techniques and subsequently analysed thematically. NVivo software is employed to analyse the qualitative dataset. This research phase is aimed at developing the study's proposed framework.

Furthermore, a focus group discussion session is employed to evaluate and refine the developed framework. The session involves expert participants knowledgeable about DT and/or maintenance management, with a total of six experts recruited. The collected data is transcribed using intelligent verbatim transcription techniques and analysed thematically. The analysed results are used to refine the final version of the study's framework.

Chapter Five - Quantitative Data Analysis and Discussions

5.0 Introduction

This chapter presents an analysis of the completed questionnaire survey returned by the sampled participants involved in BM management and the findings. The survey aims to assess the current state of BM management in Nigeria, which includes the utilisation of technologies and systems, maintenance strategies, and the challenges contributing to maintenance-related issues. Out of the study's sample, 24 completed questionnaires, representing 39.3%, were correctly returned from the 61 copies distributed. The collected questionnaires are analysed using descriptive statistics. All tables in this chapter are extracts from the researcher's field survey conducted between May 2022 and July 2022. The collected questionnaires will enable the researcher to evaluate the current situation of the BM sector in Nigeria, particularly for NibimFam, and explore how technological advances, such as DT, can be implemented to support BM management.

5.1 Descriptive Analysis

This section summarises the results of the questionnaire, which is divided into four parts, each containing questions relevant to the study. These sections cover the participants' details, maintenance patterns, technologies and systems used, and the causes of maintenance-related issues. Meanwhile, reliability was assessed for the section using the Likert scale for measurement.

5.1.1 Questionnaire Reliability

Cronbach's alpha ascertained the reliability of the questionnaire, and the rationale for its use is discussed in Section 4.7. As Saunders *et al.* (2019) pointed out, Cronbach's alpha assesses reliability on a scale from 0 to 1. A higher value indicates greater consistency in responses to a specific question, which implies greater reliability. Hinton *et al.* (2014) further categorise Cronbach's alpha values as 0.90 and above (excellent), 0.70 to 0.90 (high), 0.50 to 0.70 (moderate), and below 0.50 (low reliability). A benchmark of 0.7 is regarded as the minimum acceptable score for a study (Saunders *et al.*, 2019). Consequently, SPSS was employed to compute Cronbach's alpha values for participants' responses regarding the causes of maintenance-related issues. The results are presented in Table 5.1. It is vital to note that while most variables revealed high consistency, financial-related causes had a moderate Cronbach's alpha value. Some studies suggest that a Cronbach's alpha slightly above 0.5 is moderate but acceptable when the number of measured items is small, which is applicable to this study's items (Hinton *et al.*, 2014; Dall'Oglio *et al.*, 2010). Based on these studies, the financial-related cause value of 0.581 was retained for this preliminary study, as its analysis aims to explore the prominent causes of maintenance-related issues rather than establish a causal relationship or effect correlation consistent with inferential statistics.

Table 5.1: Reliability Statistics Test for Causes of Maintenance-Related Issues

Statement	**No. of Items**	**Cronbach's Alpha**
Organisational-related causes	9	0.883
Technical-related causes	8	0.758
Human resources-related causes	5	0.809
Financial-related causes	4	0.581
Building user-related causes	5	0.781
Natural-related causes	4	0.794

5.2 Participants Profile

The participants' demographics were analysed based on their job titles and years of experience in the BM sector. The results show that most participants were building managers (58.3%) and building executives/supervisors (29.2%), while 8.30% were facility managers and 4.2% were project managers, as shown in Table 5.2. In terms of years of experience in the BM sector, 37.5% of participants had 6-10 years, 33.3% had more than 15 years, and 29.2% had 11-15 years (Table 5.3). These results indicate that the majority of participants were building managers and executives/supervisors. Notably, over half of them have more than ten years of experience in the BM sector. Such experience implies that the participants possess a well-informed knowledge of BM management, and the data they provided is adequate for this preliminary investigation, thus reinforcing the study’s data reliability.

Table 5.2: Participants’ Job Title

Job Title	Frequency	Percentage
Building manager	14	58.3%
Building executive/supervisor	7	29.2%
Facility manager	2	8.30%
Project manager	1	4.20%

Table 5.3: Years of Experience in the Building Maintenance Sector

Years of Experience	Frequency	Percentage
Less than 5 years	0	00.0%
6 – 10 years	9	37.5%
11 – 15 years	7	29.17%
More than 15 years	8	33.3%

5.3 Building Maintenance Patterns: Types and Strategies

This section seeks to understand the predominant types of buildings maintained by the participants and the strategies they adopted for their maintenance. Most participants maintained private residential buildings (33.3%) and public office buildings (29.2%). Conversely, 12.5% maintained private offices, while 8.3% maintained public residential buildings (Table 5.4). Moreover, regarding the buildings that were problematic to maintain, 41.7% of participants indicated public residential buildings, and 33.3% cited public office buildings, as shown in Table 5.5.

Based on these results, BM managers actively maintain private residential and public office buildings. In contrast, public residential and office buildings present significant maintenance challenges. These difficulties may be attributed to the behaviour of the users. This finding is supported by Table 5.14, which shows that users' misuse of building facilities was one of the most notable causes of maintenance-related issues. This finding highlights the need for BM managers to develop more strategic approaches to mitigate potential misuse of these buildings, thereby promoting their longevity and functionality.

Regarding the maintenance strategies adopted (Table 5.7), 41.7% of participants noted that they employ preventive maintenance techniques, 33.3% indicated corrective maintenance, and 4.2% highlighted their strategies as predictive. Moreover, 62.5% reported that it takes less than a week to respond to a maintenance request, 20.8% within two weeks, and 4.2% within three to six months, respectively (Table 5.6). Although this finding slightly corroborates those of Aghimien *et al.* (2019), Ndulue and Ifeanyiemoh (2021), and Osuagwu *et al.* (2021b), which found that most maintenance professionals utilised reactive/corrective strategies, it suggests that BM managers are increasingly adopting proactive preventive maintenance strategies. This indicates a transition from unplanned maintenance to a more structured approach, as the response times to maintenance requests align with their techniques. Thus, this trend serves as a prompt for BM managers to explore more strategic approaches to minimise the potential misuse of buildings, ensuring their preservation and longevity.

Table 5.4: Types of Building Participants Maintain the Most

Building types	**Frequency**	**Percentage**
Private residential buildings	8	33.3%
Public office buildings	7	29.2%
Tertiary institution	4	16.7%
Private office buildings	3	12.5%
Public residential buildings	2	8.30%
Hospitals	0	0.00%
Hotels	0	0.00%
Monuments	0	0.00%
Religious buildings	0	0.00%

Table 5.5: Building Types Most Problematic to Maintain

Building types	**Frequency**	**Percentage**
Public residential buildings	10	41.7%
Public office buildings	8	33.3%
Hotels	2	8.30%
Private residential buildings	2	8.30%
Hospitals	1	4.20%
Tertiary institution	1	4.20%

Table 5.6: Response Time to Maintenance Request

Response time to maintenance	**Frequency**	**Percentage**
Within a week	15	62.5%
Within two weeks	5	20.8%
Within a month	2	8.30%
Within three months	1	4.20%
Within six months	1	4.20%

Table 5.7: Types of Maintenance Strategy Adopted for Maintenance Activities

Maintenance strategy	**Frequency**	**Percentage**
Preventive maintenance	10	41.7%
Corrective maintenance	8	33.3%
Condition-based maintenance	3	12.5%
Emergency maintenance	2	8.30%
Predictive maintenance	1	4.20%

5.4 Technologies and Systems for Building Maintenance Management

This section investigates the technologies and systems employed by participants for maintenance activities. Over a quarter (33.3%) of the participants reported using CMMS for maintenance tasks, 20.8% indicated the use of BIM and no software, and 12.5% reported using CAFM. Meanwhile, 4.20% stated they employed BAS and Microsoft programmes. In contrast, none of the participants made use of DT for their maintenance activities (Table 5.8). While some BM managers do not utilise technologies or systems for their maintenance activities, the proportion of those who do is significant. This finding suggests a widespread acceptance of technological advancements in maintenance activities, indicating that BM managers are becoming more proactive rather than reactive (Section 2).

Table 5.8: Platforms or Software Utilised for Maintenance Activities

Maintenance software	**Frequency**	**Percentage**
Computerised maintenance management systems	8	33.3%
Building information modelling	5	20.8%
No Software	5	20.8%
Computer-aided facility management	3	12.5%
Integrated workplace management systems	1	4.20%
Building automation systems	1	4.20%
Microsoft programs	1	4.20%
Digital twin	0	0.00%

This trend aligns with the findings of Eti *et al.* (2006), underscoring that if the Nigerian maintenance sector aspires to attain best-in-class status, it must be 80% more proactive in its maintenance activities and 20% reactive. However, the underutilisation of DT points to a knowledge gap or a potential lack of awareness regarding its advantages. This inquiry raises a crucial question: Although benefits have been derived from CMMS and BIM, are these sufficient to address the complex challenges of contemporary BM management? The integration of more advanced technologies could be the key driver propelling the sector towards predictive strategies that can optimise maintenance activities and enhance building longevity.

Furthermore, Table 5.4 previously indicated that BM organisations have focused on maintaining private residential buildings (33.3%) and public office buildings (29.2%); however, they are deficient in the upkeep of hospitals, hotels, monuments, and religious buildings. This deficiency may arise from their inability to adopt proactive maintenance techniques for management, as discussed in Section 3.6 regarding DT. For instance, in hospital structures, Ebiloma *et al.* (2023) substantiated that knowledge of DT will assist BM organisations in managing these facilities. By employing DT, BM organisations can access more comprehensive data through continuous monitoring and real-time updates of these buildings, facilitating improved planning for their maintenance. For this reason, it is essential to explore how DT can be utilised in BM management.

5.5 Causes of Maintenance-related Issues

This section examines the major causes of maintenance-related issues that lead to the reoccurrence of BM activities. These causes may be natural or human-induced. The human-induced causes encompass organisational, technical, human resources, financial, and building user-related causes (Ebekozien, 2021). The participants rated several statements, as discussed in Section 4.6.3.5. The results were analysed using the RII. The RII score was calculated based on the criteria highlighted by various studies conducted in the built environment (Olanrewaju *et al.*, 2018; Kothari, 2004; Osuagwu *et al.*, 2021b; Waziri and Vanduhe, 2013). Some studies also presented a guide that categorises the RII scores according to their level of significance (Waziri and Vanduhe, 2013; Olanrewaju *et al.*, 2018). The higher the index score, the higher the significance level and ranking. Table 5.9 presents a template for determining the level of significance, and the RII score can be expressed mathematically as:

$$RII = \frac{5n5 + 4n4 + 3n3 + 2n2 + n1}{(5N)} \tag{1}$$

Where: N = Total number of participants, n5 = Number of participants for “to a very large extent”, n4 = Number of participants for “to a large extent”, n3 = Number of participants for “to a moderate extent”, n2 = Number of participants for “to a minimal extent”, and n1 = Number of participants for “not at all”.

Table 5.9: Level of Significance in Relation to Relative Importance Index Scores

Level of Significance (LOS)	**Rating**
Very significant (VS)	0.76 – above
Significant (S)	0.67 – 0.75
Fairly significant (FS)	0.45 – 0.66
Not significant (NS)	0.44 – below

The results in Table 5.10 reveal the organisational causes linked to maintenance issues. Notably, seven of the nine variables were highly significant in contributing to maintenance reoccurrences. The most prominent issues included the selection of unqualified maintenance contractors, the lack of planned maintenance and regular inspections, and challenges with maintenance policy implementation, all with RII values of 0.79. Conversely, incomplete strategic management plans, unclear organisational structure, and ambiguous job descriptions ranked lowest, with RII values of 0.73 and 0.65, respectively. These findings support those of Faremi *et al.* (2019) regarding unqualified maintenance contractors, Onyili *et al.* (2020) on the management approval for building inspections, and Osuagwu *et al.* (2021a), which identified communication among staff and maintenance policies as factors contributing to maintenance reoccurrences. Such reoccurring issues may be attributed to a lack of operational coordination within BM organisations, indicating an urgent need for operational re-engineering.

In contrast, the unclear organisational structure and job descriptions were less impactful causes. This finding suggests that the efficiency and productivity of an organisation's operational practices outweigh its structure. Therefore, BM organisations need to focus more on their workflow processes to enhance maintenance activities and prolong the longevity of buildings and assets.

Table 5.10: Ranking of Organisational-related Causes of Building Maintenance

Causes	Frequency of Response					RII	Rank	LOS
	5	4	3	2	1			
Choosing an unsuitable maintenance contractor	11	6	3	3	1	0.79	1	VS
Lack of planned maintenance and regular inspection	7	11	5	0	1	0.79	1	VS
Issue of maintenance policy implementation	6	13	3	2	0	0.79	1	VS
Low-quality maintenance works	9	8	4	2	1	0.78	4	VS
Lack of collaboration between stakeholders	7	10	5	2	0	0.78	4	VS
Improper planning and scheduling	6	10	5	3	0	0.76	6	VS
Lack of timely response to maintenance requests	6	11	5	0	2	0.76	6	VS
Incomplete strategic management plan	7	6	7	3	1	0.73	8	S
Unclear organisational structure and job descriptions	3	6	11	2	2	0.65	9	FS

Concerning the technical causes of maintenance issues, Table 5.11 presents the RII scores along with their corresponding ranks. Faulty construction (RII=0.82), a lack of maintenance consideration during the building design stage (RII=0.81), along with the use of substandard building materials (RII=0.81), ranked as the top issues. The adoption of ICT and maintenance software tools, as well as the remoteness of the building, had RII scores of 0.62 and 0.54, respectively, representing the least significant causes. These findings corroborate those of Ibitayo *et al.* (2019) on faulty construction, Waziri and Vanduhe (2013), Ajetomobi and Olanrewaju (2015) on building design, and Ibitayo *et al.* (2019), Lekan *et al.* (2021), and Osuagwu *et al.* (2021a) on substandard building materials, all of which were factors contributing to maintenance-related issues. This evidence highlights the significant noninvolvement of BM managers at the beginning of a building project's design and construction phases. Interestingly, the remoteness of buildings contributed less to maintenance-related issues. This finding suggests that a building's geographical location, in terms of an individual's choice of residence, has a lesser impact on maintenance-related issues.

Table 5.11: Ranking of Technical-related Causes of Building Maintenance

Causes	Frequency of Response					RII	Rank	LOS
	5	4	3	2	1			
Faulty construction	9	10	3	2	0	0.82	1	VS
Neglecting maintenance considerations in the building design stage	10	8	4	1	1	0.81	2	VS
Substandard building materials	9	8	6	1	0	0.81	2	VS
Faulty design inaccessibility to building maintenance works	6	8	8	2	0	0.75	4	S
Lack of advanced techniques and tools to detect building defects	6	6	7	4	1	0.70	5	S
Non-availability of maintenance materials	3	10	7	3	1	0.69	6	S
Lack of ICT adoption and maintenance software tools	4	4	8	6	2	0.62	7	FS
The remoteness of the building	1	3	9	10	1	0.54	8	FS

The results of human resources-related causes of maintenance issues are presented in Table 5.12. Lack of work experience (RII=0.73) and inadequate training to conduct job tasks (RII=0.73) ranked highest. This aligns with the findings of Aghimien *et al.* (2019) and Emoh and Ndulue (2021), which identified inexperienced staff as a cause of BM issues. This finding suggests that continuous employee training is crucial for effective maintenance activities. Conversely, an insufficient number of staff and specialists (RII=0.64) ranked lowest among the causes. This finding may be due to the fact that while having specialists and a larger workforce could facilitate maintenance activities, the operational readiness of these individuals to undertake the correct job tasks is more crucial in mitigating maintenance issues.

Table 5.12: Ranking of Human resources-related Causes of Building Maintenance

Causes	Frequency of Response					RII	Rank	LOS
	5	4	3	2	1			
Lack of work experience	5	9	7	2	1	0.73	1	S
Training is not adequate to conduct work tasks effectively	4	11	6	2	1	0.73	1	S
Recruitment of employees without training	3	12	5	2	2	0.70	3	S
Lack of courses and workshops to improve staff skills	3	6	9	6	0	0.65	4	FS
Lack of adequate staff, engineers, and specialist	3	6	9	5	1	0.64	5	FS

The results in Table 5.13 show the financial-related causes of maintenance issues. Systemic corruption (RII=0.83) and poor economy (RII=0.81) were ranked first and second, respectively, and were significantly related to BM issues. However, the lack of a standard to define the exact cost (RII=0.71) was the least ranked cause. This finding supports the conclusions of Emoh and Ndulue (2021), who revealed that funding was responsible for poor maintenance management. This finding implies that maintenance activities depend on finances, and insufficient financial allocation would adversely affect maintenance activities, leading to a deviation from best practices. In contrast, the lack of standardised costs had a lesser impact on the causes of maintenance-related issues. This finding highlights that the assessment of maintenance costs should correspond with the actual maintenance activities.

Table 5.13: Ranking of Financial-related Causes of Building Maintenance

Causes	Frequency of Response					RII	Rank	LOS
	5	4	3	2	1			
Insufficient budget to maintain the buildings	11	10	3	0	0	0.87	1	VS
Systemic corruption	9	12	1	2	0	0.83	2	VS
Poor economy	6	14	3	1	0	0.81	3	VS
Lack of a standard to define the exact cost	3	12	5	3	1	0.71	4	S

The building user is one of the BM stakeholders, and their activities within a building are crucial to its maintenance. Table 5.14 displays the RII scores and their corresponding ranks. The misuse of building facilities (RII=0.87) and the lack of a maintenance culture (RII=0.84) were ranked as the first and second related causes, both of which are significant to BM issues. These findings reinforce those of Emoh and Ndulue (2021) and Osuagwu *et al.* (2021b), which indicate that building users and a poor maintenance culture are major factors contributing to maintenance reoccurrence. This finding can be attributed to their attitudes toward using buildings and their assets/facilities. Conversely, the absence of signs to guide users in utilising the facilities (RII=0.70) and the delayed reporting of building defects (RII=0.69) were ranked fourth and fifth, respectively. This finding suggests an improvement in the functions of BM personnel regarding maintenance activities, likely due to their transition from unplanned maintenance practices to planned ones (Table 5.7).

Table 5.14: Ranking of Building User-related Causes of Building Maintenance

Causes	Frequency of Response					RII	Rank	LOS
	5	**4**	**3**	**2**	**1**			
Misuse of building facilities	11	10	3	0	0	0.87	1	VS
Lack of maintenance culture	13	6	3	1	1	0.84	2	VS
Lack of awareness among the building users	6	8	6	4	0	0.73	3	S
Absence of signs to guide users to use the facilities	3	12	4	4	1	0.70	4	S
Delayed report of building defects	1	14	4	5	0	0.69	5	S

The results concerning natural-related causes of maintenance issues are presented in Table 5.15. The age of the building (RII=0.73) and usual wear and tear due to constant use (RII=0.70) were ranked first and second, respectively. This finding supports the study by Ndulue and Ifeanyiemoh (2021), which concluded that normal wear and tear are among the primary causes of maintenance-related issues. This finding suggests that increased maintenance activities are necessary to restore or preserve a building as it ages, keeping it close to its original state and ensuring it remains functional. In contrast, the death of a building's owner and natural factors arising from unforeseen circumstances had the same RII score of 0.64, ranking as the least related causes, and were fairly significant to BM issues. These findings indicate that while events such as a building owner's death or unpredictable natural disasters play a lesser role in BM reoccurrences, they highlight that the continuous use of buildings and their ageing significantly contribute to maintenance activities.

Table 5.15: Ranking of Natural-related Causes of Building Maintenance

Causes	Frequency of Response					RII	Rank	LOS
	5	4	3	2	1			
Age of building	6	10	3	4	1	0.73	1	S
Normal wear and tear due to the constant usage	4	10	5	4	1	0.70	2	S
Death of the owner of a building	2	11	3	6	2	0.64	3	FS
Natural factors arising from unforeseen circumstances	3	7	8	4	2	0.64	3	FS

5.6 Summary

This questionnaire survey explored insights into the practices of BM managers, particularly those of NibimFam, along with the technologies and systems used for maintenance management and the causes of maintenance-related issues that led to the reoccurrence of BM in Nigeria. Analysis of the questionnaire revealed that most participants were building managers, executives, or supervisors, with over half having more than 10 years of experience in the BM sector. Such experience reinforced the reliability of the collected data.

Emerging findings from data analysis revealed hurdles challenging Nigeria's BM sector. Some insights on maintenance strategies, technologies, and systems used by BM organisations, as well as the causes of maintenance-related issues, supported those identified in the literature with minimal contrast. Data analysis indicated that organisational dynamics emerged as the primary cause of maintenance-related issues, with seven of its nine variables significantly intertwined with BM reoccurrences. These findings spotlight an urgent need for BM organisations to restructure their operations, enabling them to better manage other maintenance-related issues and complexities. By doing so, BM organisations can enhance their maintenance strategies and effectively manage potential or unforeseen maintenance-related issues.

Meanwhile, the findings showed a transition in maintenance strategy from reactive to preventive maintenance, as BM organisations increasingly adopt proactive approaches towards condition-based and predictive maintenance strategies in their activities. In fact, if these proactive maintenance strategies are effectively employed, particularly the currently underutilised predictive strategy, BM organisations will be more strategic in their maintenance activities. Moreover, the findings indicated that the proper utilisation of technologies and systems is crucial for BM organisations to be proactive in their maintenance activities. The technologies and systems presently used by BM organisations include CMMS, BIM, CAFM, IWMS, BAS, and Microsoft programs. While these technologies and systems have supported BM organisations in their maintenance activities, it is noteworthy that DT has yet to find a place in Nigeria's BM sector; despite its potential for providing real-time data updates and scenario analysis crucial to BM. Thus, if BM organisations can harness the potential of DT, they will unlock their underutilised predictive capabilities and enhance their strategic approach to overcoming unforeseen maintenance complexities.

To explore the potential of DT for BM organisations, the researcher investigated whether DT could assist these organisations in maintenance management in Chapter 3. Based on literature reviews, BM organisations can leverage DT to become more strategic and proactive in managing maintenance issues that are data-intensive, which is vital for predictive analysis. Section 3.7.1 highlights how DT can be leveraged to manage organisational, technical, financial, and user-related issues. Moreover, issues stemming from faulty design and construction, along with substandard materials, cannot be rectified during a building's use;

however, they can be effectively managed through diligent monitoring, enabling timely maintenance activities (Sections 3.7.1 and 3.8.1).

Based on the analysis derived from the quantitative data, which spotlights the usefulness of DT and its lack of use by BM managers in Nigeria, it suggests that proceeding solely with this group of participants for qualitative inquiry would be limited in understanding how DT can be implemented to support BM organisations. Therefore, the inquiry was conducted with DT experts outside Nigeria to gain further insights, which will be discussed in the next chapter.

Chapter Six - Qualitative Data Analysis and Discussions

6.0 Introduction

This chapter presents the analysis of findings from the transcripts of the sampled participants involved in both BM and DT activities. Excerpts are drawn from the transcripts to clarify the findings from the questionnaire regarding the probable causes of maintenance-related issues and the technologies/systems used for BM management (objectives 1 and 2). Additionally, these excerpts are utilised to explore the applicability of DT and ascertain the requirements for its implementation in BM management (objectives 3 and 4). Meanwhile, the methods used for designing the interview questions, setting up the interviews, and recruiting participants are discussed previously in Chapter 4. Thus, this chapter provides an overview of the qualitative findings and subsequent discussions to fulfil the research objectives.

6.1 Data Analysis Process

The empirical qualitative data were elicited from 20 participants and analysed using thematic analysis. The interview transcripts were analysed following the six-phase procedure proposed by Braun and Clarke (2006). The analysis began with (1) data familiarisation, (2) generation of initial codes, (3) theme searching, (4) theme revision, (5) theme definition and naming, and (6) report writing. After transcribing the interviews and familiarising with the data sets on BM and DT, NVivo software was employed to analyse the transcripts for coding and theme identification. The transcripts were thoroughly read, and codes were generated to derive meanings. The coding facilitated the labelling of vital data items and points, minimising repetitions and allowing for effective theme searching (Braun and Clarke, 2021, 2006).

An initial list of open codes was generated from the 20 interview transcripts. These codes were utilised to extract all vital data related to BM and DT from the transcripts. The list was refined by eliminating irrelevant codes that did not align with the study's objectives. The codes were drawn from the transcripts to gain an understanding of the various components surrounding BM activities, the development of DT, and its application. Theme searching was conducted using a deductive approach, as it captures the essential aspects of a data extract in relation to the research question and adds meaning to the data set (Braun and Clarke, 2021, 2006). Braun and Clarke (2006) highlight that the deductive approach in thematic analysis provides a more detailed data analysis.

Moreover, themes were identified at the semantic level rather than at the latent level, as the study does not aim to investigate the reasons behind the participants' responses. This study focuses on exploring what works (DT) and how it can work (DT implementation) to manage an issue (maintenance-related issues). For this reason, semantic theme identification was conducted to explore various avenues for BM organisations to implement DT in managing maintenance activities. Braun and Clarke (2006) note that theme identification at the semantic or explicit level deals with the surface meaning of data. In contrast, the latent level examines the theoretical assumptions and ideologies inherent in the data. The themes were subsequently reviewed to ensure alignment with the extracted codes and the data set, facilitated by the generation of a thematic map. The themes were then defined and named to achieve specificity by aligning certain themes with the analytical focus. Braun and Clarke (2006) mention that defining and naming themes assist in identifying the essence of the captured themes. Consequently, the analysis concluded with the interpretation and writing of the report.

6.2 Focus of Interview Questions

The interview questions were designed to collect data from experienced participants in BM and/or DT. Although two sets of questions were tailored for the respective categories of participants, the design structure is the same. The questions were organised into sections. The questions in the first section sought to ascertain the participant's knowledge of the research topic and assess the potential value of the provided data for the study. The subsequent sections collected data on the core subjects of the research, namely BM and DT, as outlined in Section 4.6.4.3 and Appendices 2 and 3. These questions assisted the researcher in correlating the participants' perceptions and responses with the literature review (Chapters 2 and 3) to gain a more in-depth and comprehensive understanding of the research topic.

6.3 Profile of the Interviewees

The demographics of the two participant groups were analysed based on their job details and years of experience within their respective industries. The results indicated that nine participants were BM experts, while eleven were DT experts engaged in various construction-related activities. It was observed that, although participants described themselves as digitally proficient, this self-identification may not necessarily align with actual expertise or experience, especially given that DT is still evolving (Section 3.1). Therefore, the term "expert" has been suitably replaced with "enthusiast" to reflect their competencies more accurately. This information is summarised in Table 6.1. In terms of years of experience, all BM participants had over 10 years in the industry. For DT, 8 participants also possessed more than 10 years of experience, while the remaining 5 had less than 10 years. Regarding the participants' job roles, 6 were fully immersed in the BM industry, and 3 held positions as full-time academics, engaging in part-time industry work. For DT, 7 participants were fully involved in the industry, and 4 were full-time academics with part-time industry roles. Given the targeted nature of this study, which aims to explore the implementation of DT for BM management at the organisational level, the analysis of data was not focused on comparing participants' responses but rather on understanding what approaches may be effective based on their insights and how the recommended solutions could function, thus justifying the purposeful recruitment of participants (Section 4.6.4.4). These results indicate that the participants possess a robust understanding of BM management and the application of DT, making the data acquired from them adequate.

Table 6.1: Profile of Participants

Respondent	Respondent Categories	Job Details and Background	Years of Experience
R1	BM Enthusiast	Industry (Building Management)	20
R2	BM Enthusiast	Academics/Industry (Building Management)	30
R3	BM Enthusiast	Industry (Facility Management)	10
R4	DT Enthusiast	Industry (Construction Management)	10
R5	BM Enthusiast	Academics/Industry (Building Management)	11
R6	DT Enthusiast	Industry (Construction Management)	14
R7	DT Enthusiast	Industry (Facility Management)	9
R8	DT Enthusiast	Industry (Facility Management)	11
R9	DT Enthusiast	Academics/Industry (Construction Management)	10
R10	BM Enthusiast	Industry (Building Management)	13
R11	BM Enthusiast	Industry (Facility Management)	10
R12	DT Enthusiast	Industry (Construction Management)	10
R13	DT Enthusiast	Academics/Industry (Construction Management)	16
R14	BM Enthusiast	Industry (Building Management)	30
R15	BM Enthusiast	Academics/Industry (Building Management)	27
R16	DT Enthusiast	Industry (Facility Management)	6
R17	DT Enthusiast	Industry (Asset Management)	5
R18	DT Enthusiast	Academics/(Construction Management)	11
R19	BM Enthusiast	Industry (Facility Management)	16
R20	DT Enthusiast	Academics/Industry (Facility Management)	10

6.4 Thematic analysis results

Four main themes emerged from the thematic analysis of the data. These themes included BM and its requirements, DT development and its requirements, DT utilisation for BM, and the potential organisational requirements for implementing DT in BM management, as illustrated in Figure 6.1. Insights into the themes, sub-themes, and codes in relation to the objectives of this research are detailed in the following sections. The responses of the interview participants, which serve as evidence, are labelled with R, followed by their reference number. Consequently, the results of the thematic analysis are discussed in relation to the study's objectives.

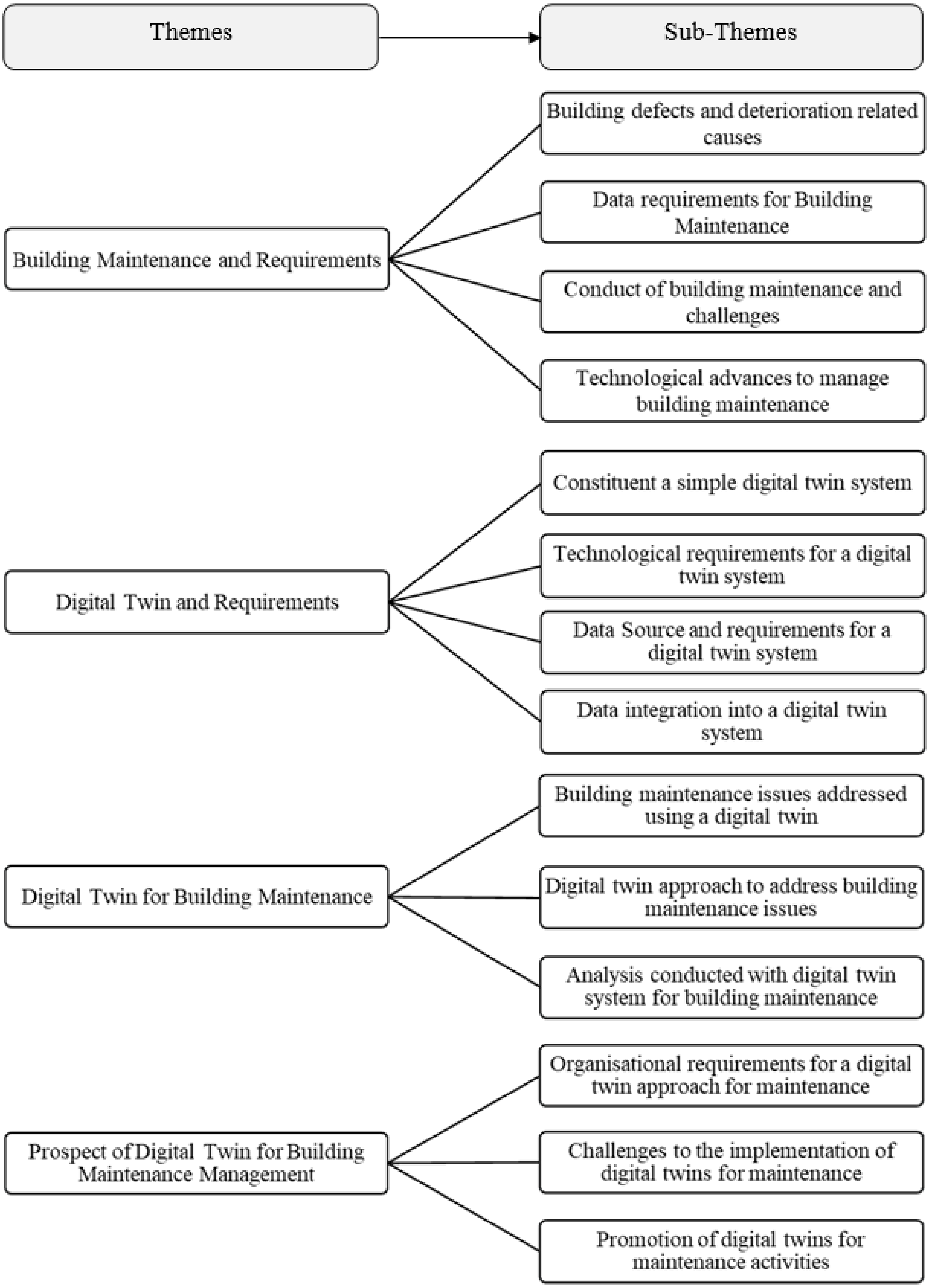


Figure 6.1: Themes and Sub-themes from Interviews

6.4.1 Theme One: BM and Its Requirement

This section provides an overview of BM and its requirements for conducting maintenance activities. It includes sub-themes such as the causes of maintenance-related issues in buildings, the implementation of BM and its challenges, the data requirements for maintenance activities, and advances in technologies/systems for managing maintenance. These sub-themes highlight the empirical results from the participants' responses regarding BM management.

Sub-theme I: Causes of Maintenance-Related Issues

This sub-theme examines the causes of maintenance-related issues in buildings, elaborating on findings from the quantitative data analysis that clarify areas needing further exploration. Following the data analysis, nine respondents identified human-related causes as contributors to maintenance issues, while seven attributed them to natural-related factors. The human-related causes include user-related issues, financial considerations, organisational factors, technical challenges, and policy deficiencies. Given the quantitative data analysis that underscores organisational-related factors as the primary contributors to maintenance issues, it is crucial to understand the organisational dynamics that lead to poor maintenance management.

Responses regarding the organisational-related causes of maintenance issues came from eight out of the nine respondents. Their feedback generated sub-codes such as the attitudes of stakeholders, inadequate documentation, lack of technology/system usage, and ineffective maintenance strategies. The specifics of these codes underscore the necessity for BM managers and organisations to be diligent in their maintenance activities. For instance, the indifferent attitudes of BM stakeholders often give rise to maintenance challenges. While the blame for poor maintenance typically rests with BM managers, other stakeholders also play a role in this issue (Kangwa and Olubodun, 2004). One respondent corroborated that:

"The attitude of stakeholders does not just stop at the professionals alone; it involves even the administrators, the management staff, and the users. So, they could have their piece in it and how they are not handling the cases of the facilities they use or manage" – R5

This issue sometimes reflects maintenance activities that are not accurately documented by the administrators or management staff (Ismail *et al.*, 2020). An example of this concern was highlighted by one of the respondents:

"…You would expect that institutions would have a works department, but you will find out that there is really no documentation to fast-track the maintenance of buildings" – R3

Furthermore, the issue of inadequate documentation processes could be attributed to the underutilisation of technologies and systems (Osuji *et al.*, 2020; Ofide *et al.*, 2015). One respondent emphasised that:

"The major challenge we have in maintenance in Nigeria is that most of the failures are supposed to have been recorded on a computer so that you can have a history of the maintenance activities……The records are not actually there, and it is a problem"– R15

In addition to the underutilisation of technologies and systems, four respondents pointed out that ineffective maintenance strategies have contributed to the reoccurrence of BM issues. A statement supporting this point was:

"When you do not have predictive maintenance but have time-based maintenance, that is the reason you face troubles when your components are not being investigated routinely" – R8

From these responses, it can be inferred that BM managers and their organisations contribute to the causes of maintenance-related issues through their actions. This finding supports the results of the quantitative data analysis and the existing literature (Sections 5.5 and 2.6.1). To mitigate this issue, BM organisations need to improve the coordination of their maintenance activities by utilising technological advancements (Ndulue and Ifeanyiemoh, 2021; Osuagwu *et al.*, 2021b; Aghimien *et al.*, 2019). Such advancements would assist them in accurately documenting maintenance activities and enable a more proactive approach.

Moreover, financial resources are critical for maintenance activities. BM organisations require them, as maintenance activities account for nearly 50% of a building's running costs (Mourtzis *et al.*, 2017; Abdul Lateef *et al.*, 2011). In this context, buildings become susceptible to problems when financial constraints hinder maintenance efforts. Two respondents highlighted the lack of funding and its detrimental effect on maintenance activities. A statement to support this point was:

"There is virtually no budget allocated to building maintenance. So, it only comes up as lumpsum when those building fabrics have become an eyesore" – R3

Based on this response, some finance-related causes contributing to maintenance issues in BM organisations can be linked to building owners. Adeniyi *et al.* (2020) have stressed that inadequate funding is a key factor in poor BM management. This finding indicates that building owners' financial responsibilities regarding maintenance activities are insufficient. To address this issue, BM organisations need financial autonomy from building owners to carry out maintenance tasks independently. Such autonomy would empower BM organisations to proactively resolve maintenance issues without relying on the building owners. At the same time, inadequate funding may stem from the absence of BM management policies, as building owners are not obliged to maintain their properties

(Adeniyi *et al.*, 2020). One respondent connected the causes of maintenance-related issues to a lack of policies:

"In Nigeria, there is no law that says you should carry out maintenance in a building, just like in the UK, they may say after three or four years, you must repaint your building" – R19

This response highlights the crucial role of policies in maintenance activities, as they would encourage building owners to conduct these tasks regularly. By doing so, BM organisations are consulted for maintenance activities, which significantly enhance the longevity of buildings and assets. The urgency and necessity for building owners to adhere to policies are evident, as they serve as essential tools for preventing maintenance issues and ensuring the sustainability of buildings.

It is evident from these findings that the causes of organisational-related issues lie within its dynamics. These include staff work attitudes, insufficient documentation, underutilisation of technologies and systems, and ineffective maintenance strategies. These factors contribute to the reoccurrence of BM activities, and deliberate efforts are needed from organisations to mitigate them. If these issues are not addressed, they will continue to hinder BM organisations from conducting maintenance operations effectively. Thus, BM organisations must adopt a more strategic approach to enhance their dynamics for maintenance management. One way to achieve this is through technological advancements such as DT (Jiao *et al.*, 2023; Pomè and Signorini, 2023; Eromonsele, 2021). Such an approach will improve BM organisations' utilisation of technologies and systems for better documentation of maintenance activities, allowing them to maximise their predictive capabilities through scenario analysis. Consequently, BM organisations will be more strategic in their operations, and units within the organisation will be held more accountable for their responsibilities.

Furthermore, the causes of maintenance-related issues identified in the literature and quantitative data analysis, such as faulty design, poor construction materials, and users' misuse of building assets, can be managed if BM organisations take a strategic approach. Although DT presents a promising solution for managing issues arising from these causes, not all problems can be addressed without data availability. Literature suggests that data is central to employing DT for scenario analysis, which is crucial for BM (Sections 3.6.1 and 3.6.2). Therefore, BM organisations require an appropriate data set to manage maintenance activities using DT.

Sub-theme II: Data Requirements for Building Maintenance

This sub-theme outlines the data requirements necessary for conducting maintenance activities. The generated codes include organisational procedures, the client's responsibilities, considerations for conducting maintenance surveys, and the essential documents and records required for maintenance tasks. For BM organisations to effectively carry out their maintenance activities, a structured procedure is essential (Kobbacy and Murthy, 2008; Kagioglou *et al.*, 2000). Five respondents noted that they had a structured procedure for their maintenance activities, while two indicated they did not. Regarding the structured procedure, one statement reinforced their claims:

"Definitely, there are manuals, guides, and steps to be followed to carry out maintenance activities" – R2

One respondent distinguished between the practice styles of BM managers in academia and those in full practice:

"It depends on the office policy. Those in practice do not have a framework. It is those in academia who will begin to talk about the framework" – R15

Two respondents substantiated this opinion with practical examples. A statement supporting this point was:

"Here, there is really nothing like procedure or framework" – R5

Based on these responses, it can be inferred that having a framework or procedure is vital for conducting BM activities. Vom Brocke and Rosemann (2014) support that a framework, process model, or procedure aims to capture business activities at a suitable level of detail for an organisation's operations. Creating such a structured procedure promotes a more sustainable work plan, enabling BM organisations to maintain standardised sets of BM data documents and records for their maintenance activities. Moreover, seven respondents elaborated on the necessary documents for the effective conduct of maintenance activities. A consensus of their responses is encapsulated in the following statement regarding the importance of these documents:

"If we have a maintenance contract for a building, we try as much as possible to acquire enough data about the building. Why, how, and what component was used, and gathering this data assists us during maintenance work. It is very important" – R14

These documents are essential for conducting maintenance activities. As highlighted by NBC (2006), these documents include conditions of contracts, as-built drawings, maintenance manuals, and building condition assessment records. Six respondents confirmed the necessity of these documents for the proper execution of any maintenance task. Regarding as-built drawings, two respondents emphasised that these are design and construction drawings provided by the building professionals used for the construction project, and their point is supported by the following statement:

"All drawings for a building project are regarded as as-built drawings" – R15

These as-built drawings are crucial for maintaining the building and its assets, as they provide BM managers with the necessary data for effective maintenance (NBC, 2006). Furthermore, five respondents pointed out that the as-built drawings were part of the maintenance manual and were often given to BM managers after project completion. The following statements support their claim:

"Once the building has been constructed, and everybody involved has done their bits, the maintenance manual and drawings used in construction are usually handed over to the clients at the handover period. These documents are needed for the maintenance activity to be seamless" – R11

"All components installed in the building have specifications and accompanying manuals incorporated into the maintenance manual. The as-built drawings are included in it" – R14

One respondent emphasised the significance of proper documentation in the maintenance manual to facilitate maintenance activities:

"The maintenance manual is supposed to state the lifespan of each building component you have used in the construction. In most cases, when the contractor finishes his work and is okay, what would be the lifespan of this building? They do not know" – R15

It is evident from these responses that the maintenance manual is crucial for maintenance activities. However, questions arise regarding how such a document should be updated. Some respondents indicated that the maintenance manual was updated by a consortium of professionals or an establishment's in-house maintenance team. Four respondents unanimously stated that the consortium of professionals is responsible for updating the maintenance manual, as demonstrated by the following statement:

"The National building code approved by the Federal Executive Council 2006 put it as a consortium of professionals: Builders, Architects, Quantity surveyors and engineers, are responsible for producing and updating the maintenance manual" – R15

Additionally, the building condition assessment record constitutes another essential document required for maintenance activities (NBC, 2006). It pertains to evaluating the current state of the building. One respondent elaborated that building condition assessment involves observing a building and developing defect schedules with the following statement:

"For maintenance tasks, all the documents, such as a list of different kinds of defects observed and a record of all the building elements, including floors and paints, among others, are required. They have a life span. You have to get a record of them" – R2

Another respondent pointed out that if the building condition assessment report was unavailable, someone needed to produce it:

"The assessments and maintenance survey include the schedule of defects and dilapidations. In some cases, the contractor will be the one to carry out the assessment" – R15

These responses highlight the critical importance of the building condition assessment prior to executing any maintenance activity. Two respondents further reinforced this stance with the statements:

"Before you carry out maintenance, there must be an inspection of the building" – R14

In summary, the success of maintenance activities for BM organisations is significantly influenced by the availability of data. According to the respondents, data is central to maintenance activities and is generally drawn from documents and records such as contract conditions, as-built drawings, maintenance manuals, and building condition assessment records, which are summarised in Figure 6.2. Therefore, it is essential for clients and building professionals to provide BM organisations with adequate documentation to ensure the seamless execution of maintenance activities. Furthermore, the manner in which maintenance activities are conducted is another crucial factor for their success. Thus, the next sub-theme concentrates on the procedures for carrying out maintenance activities.

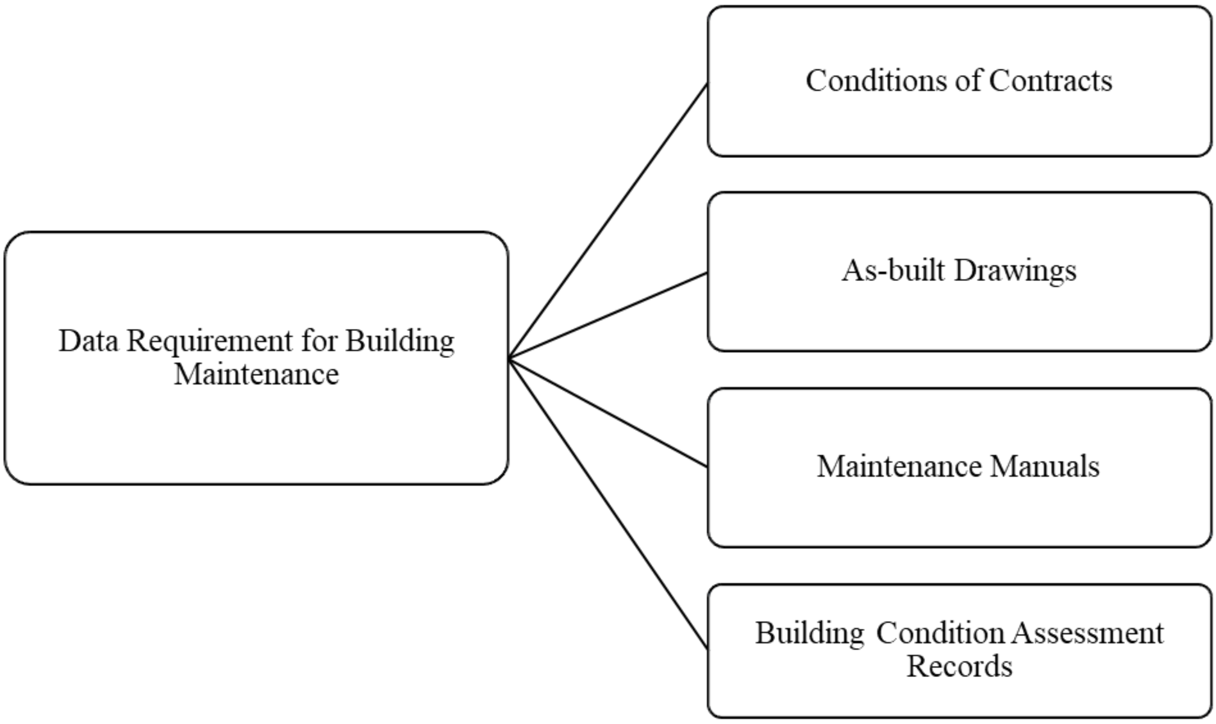


Figure 6.2: Data Requirements for Building Maintenance

Sub-theme III: Conduct of Building Maintenance and Challenges

This sub-theme examines the conduct of BM activities and possible challenges. The generated codes encompass the client's maintenance responsibilities, factors to consider in maintenance surveys, and the execution of maintenance tasks. They also cover financial aspects, collaboration with other building professionals to enhance maintenance activities, and challenges encountered during these tasks. The client's responsibilities arise because someone needs to oversee the maintenance activities (Ali *et al.*, 2002). Six respondents indicated that the clients were responsible for selecting maintenance personnel, providing documents and finances, making decisions about materials, and supervising the quality of work. Choosing the right maintenance team is pivotal to the success of any maintenance activity (Osuagwu *et al.*, 2021a). One respondent emphasised that the client has the authority to choose the maintenance personnel for such activities:

"Client is responsible for deciding whether maintenance will be in-house or outsource"– R14

Two respondents further stated that clients were required to provide documents to the maintenance personnel for the execution of tasks:

"The clients are responsible for providing every piece of information. They hand every drawing and information they have on the building, for us to carry out these activities" – R11

The clients' provision of necessary documents enables BM organisations to perform maintenance activities effectively. Moreover, these activities can only be seamless if the clients provide adequate funds in a timely manner. As highlighted by Adeniyi *et al.* (2020), funds are central to the success of any maintenance task. In this regard, six respondents pointed out that clients were responsible for providing the necessary funds. This statement supports the assertion:

"Building owners make funds available because they are solely responsible for the work to be executed" – R2

The proper provision of funds by clients leads to high-quality maintenance activities, often reflected in the durability of materials used. Additionally, clients must provide the necessary approvals and commissioning to actualise this fit (Onyili *et al.*, 2020). Four respondents corroborated that clients determine the work scope and specifications. A statement that supports this is:

"The client is to provide specifications and guidelines. This is in terms of the work standard and quality of material to be used to carry out the maintenance" – R15

It is clear from these responses that clients need to provide adequate funds and make necessary approvals to ensure the smooth execution of any maintenance activity. In fact, if clients cede autonomy, such as financial approvals, to the BM organisations, maintenance activities will be seamless. Such autonomy would allow BM organisations to conduct their tasks and respond appropriately to any maintenance issues (Kobbacy and Murthy, 2008; Kagioglou *et al.*, 2000). However, several criteria must be considered for the smooth execution of maintenance activities. Six respondents mentioned that these criteria include the procurement route, maintenance survey, and deploying competent, skilled personnel for the tasks. The correct procurement route is crucial to the success of any maintenance activity (NBC, 2006). Four respondents elaborated on the procurement route concerning maintenance jobs. This statement illustrates their point:

"Maintenance is treated as like a lump sum where you go in. It is like a contract package, the same way you go in when trying to construct a building" – R3

Furthermore, the competence of skilled personnel facilitates the execution of maintenance activities (Emoh and Ndulue, 2021). Two respondents corroborated this point with the following statement:

"We consider the personnel more around the technical staff if they are available; their level of understanding or expertise on that particular area that requires maintenance" – R5

From these findings, it can be inferred that selecting the right skilled personnel and contract terms significantly influences the success of maintenance activities. A study by Emoh and Ndulue (2021) found that incompetent maintenance personnel were among the factors contributing to poor maintenance management. Thus, deploying competent and skilled personnel ensures that maintenance activities run smoothly. However, the success of a maintenance task relies heavily on the execution procedures. Seven respondents provided insights into these procedures. According to their responses, the maintenance activity begins with a reconnaissance survey and concludes with developing a work plan. One of them summarised the conduct of the maintenance activity:

"First, you have to go for a reconnaissance survey. Then, physical measurements are carried out to produce a schedule of defects. A schedule of dilapidation is then prepared, which contains the cost for maintenance activities" R15

Six respondents indicated that the reconnaissance survey assists in the preliminary investigation of a maintenance issue. The following statement supports their claims:

"When we go on-site for recognisance, we inspect the building to see the extent of what needs to be done....... Then, go back to the drawing board to plan, before execution" R11

Two respondents pointed out that schedules must be developed following the reconnaissance survey and elaborated with this statement:

"You need to know the level of defects, and that is where you need to do a lot of work establishing the state of those defects and their causes" – R2

Another respondent emphasised the need to prepare a dilapidation schedule after identifying defects:

"... prepare a schedule of dilapidation once you are done with the schedule of defects" – R15

The schedule of dilapidation includes elements of cost evaluation to develop the work plan for the identified defects that require maintenance (Musa, 2018). Four respondents highlighted that developing the work plan aids in executing maintenance activities. A statement in support of this is:

"You have to develop a maintenance program of activities. You must take into consideration a schedule of work that will not affect occupants' comfort, but give you room to work" – R14

It is evident from these responses that maintenance activities follow specific routes. These routes facilitate the collection of adequate field data, known as building condition assessment (NBC, 2006), and the development of a work plan for the seamless execution of maintenance activities. However, certain challenges exist in achieving this fit. Nine respondents provided insights into these challenges, which included inappropriate tools and technology, delays in information dissemination, funding, inadequate documentation, and insufficient skilled human resources. One respondent noted that the use of inappropriate tools and technology posed a challenge to the conduct of maintenance activities:

"If you want to seal a crack in a building, people will still use cement and mortar. However, several chemicals can be used in an advanced environment, such as propylene foams. This technology is not so common in Nigeria" – R14

The issue of information dissemination presents another challenge encountered during maintenance activities (Ofor-Douglas, 2022). Two respondents highlighted this challenge with the following statement:

"Getting data is a problem in our country Nigeria, where they always hide data" – R2

Funding is a critical factor to consider in the execution of any project or activity (Emoh and Ndulue, 2021; Osuagwu *et al.*, 2021a). BM management is no exception. Four respondents agreed that adequate funding is essential for executing maintenance activities. A statement that underscores their point is:

"The problem of maintenance persists if people or organisations do not naturally allocate sufficient funds for maintenance as they allocate for new buildings" – R14

Another respondent pinpointed the lack of funds from the clients and emphasised that:

"Sometimes, we advise the client that for their building to maintain a particular standard, we need to set aside funds for maintenance and periodic checks. However, they don't" – R19

This issue underscores the importance of financial autonomy in carrying out maintenance activities. Four respondents emphasised the necessity of financial autonomy, supported by the following statement:

"It depends on the terms of the contract…If the maintenance contract is a cost-reimbursement contract, that is where financial autonomy varies" – R15

Another respondent elaborated on the need for financial autonomy with a specific example:

"Yes, while managing xxxxx properties' maintenance, we had a running contract….. Major contracts are incidental and not part of our maintenance contract……they happen and must be done within a time frame…any incidental contract that happens must be completed within three days. We provide funds and get reimbursed immediately after work certification" – R14

From these responses, it is clear that funding is central to the conduct of maintenance activities. This finding reinforces the earlier observations regarding the need for financial autonomy in maintenance activities for BM organisations (Section 6.4.1; Sub-theme I). Accordingly, BM organisations need to be granted financial autonomy by the building owners to conduct their maintenance activities. Furthermore, documents and records are vital for executing any activity, and maintenance is no exception (NBC, 2006). Three respondents agreed that the provision of insufficient documentation hinders the conduct of their maintenance activities. A statement elaborating on this point is:

"The major problem we always have is the non-availability of working drawings. A building is supposed to have a maintenance manual, but most clients do not even keep them…." – R1

The issue of inadequate documentation could be traced back to the maintenance organisation itself (Au-Yong *et al.*, 2017). One respondent elaborated that staff changes due to retirements or recruitment lead to documentation issues:

"Let us even talk of the drawings that should have been available at the unit because the staff have been changed and some retired. So, those staff newly employed might not have the knowledge required to access the buildings and to know the spots where the issues are" – R5

Moreover, skilled workers or professionals are essential for the smooth execution of maintenance activities (Emoh and Ndulue, 2021). The absence of these personnel leads to challenges during maintenance activities. Two respondents agreed that this was a significant challenge:

"To get the experts to be involved in an issue is difficult because it is not something that could be done by a single person – R2

The challenge concerning skilled workers could be addressed or improved through adequate collaboration with other building professionals (Au-Yong *et al.*, 2017; Kobbacy and Murthy, 2008). Six respondents believed collaboration would improve the shortfall of skilled personnel in maintenance activities. A statement substantiating their claims is:

"..aspects of the work cannot be done by the crew alone, and that requires specialists" – R14

One respondent emphasised that collaborations between building professionals and building management managers should be initiated even at the construction stage to prevent issues that may arise during the O&M stage:

"Over the years, we have been clamouring that at the construction stage, we have all the professionals involved, including the building maintenance manager, from the construction stage to the post-construction stage…, to factor in its maintainability"– R11

In summary, conducting maintenance activities presents challenges such as inadequate tools and technology, lack of information dissemination, funding, and insufficient documentation and skilled personnel, as presented in Figure 6.3. These challenges could be mitigated by providing necessary documents and granting financial autonomy to BM managers from clients or building owners. Additionally, collaboration with other building professionals and the exploration of technological advancements by BM managers and organisations can significantly enhance maintenance management. Implementing these measures will ensure seamless maintenance activities and prolong the longevity of the buildings.

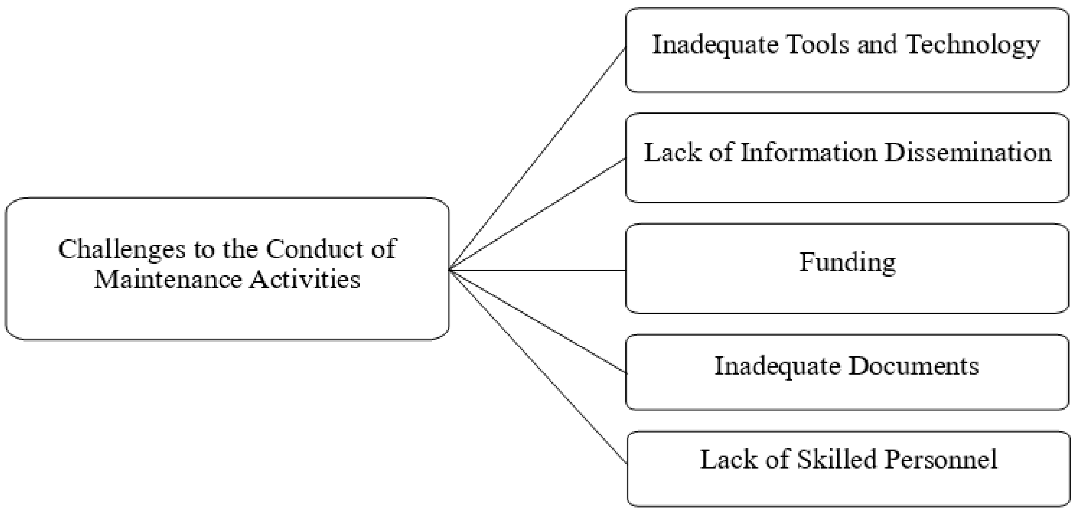


Figure 6.3: Challenges to the Conduct of Maintenance Activities

Sub-theme IV: Technological Advances in Building Maintenance Management

This sub-theme explores technological advances in the management of maintenance activities in Nigeria. The codes generated pertain to software/platforms and digital technological tools/systems used for BM, awareness of digital technology platforms such as DT, perception of DT, and actual usage of DT. Regarding the software utilised for BM management, nine respondents indicated that they use it, five of whom employ CMMS, four use BIM, two use facility management software, one uses the Microsoft package, and three utilise a combination of two software. Based on the responses, CMMS was the most widely used, supported by the following statement:

"We use CWorks and PRO works, which are computerised maintenance management systems" – R15

BIM was another technology utilised by most respondents for their BM activities, as illustrated in this statement:

"We use Revit CAD, especially when working for clients who do not have access to the drawings. We need to redesign the building by going on-site to make actual measurements and take specifications for the components, and then also update them as well" – R11

Additionally, one respondent mentioned their use of sensors in conjunction with certain software platforms to perform maintenance activities:

"…… sensors, and material for conducting tests. Through these infrastructures, we were able to use CMMS and BIM to get the state of our building projects and maintain them" – R2

Another respondent emphasised the use of visualisation and capturing devices such as VR and drones for maintenance activities:

"We use virtual technology like virtual reality. We use drones. Sometimes, there are places where you want to capture shots of assets" – R19

Furthermore, two respondents noted the use of facility management software, while one respondent utilised the Microsoft package:

"We use facility management software such as computer-aided facility management" – R19

"We use Microsoft Word/Excel spreadsheets, and perhaps, Microsoft project at times" – R5

From these responses, it can be deduced that the respondents employ technologies/systems to manage their maintenance activities. These technologies/systems include CMMS, BIM, facility management software, and the Microsoft package, supported by sensors, VR, and drones. These findings validate the quantitative data analysis, which revealed that BM organisations utilised CMMS, BIM, CAFM, and Microsoft packages, respectively. Interestingly, both sets of findings indicate a lack of DT usage by BM organisations for their maintenance activities. This finding again suggests a call for BM organisations to fully explore technological advances such as DT to manage their maintenance activities more strategically and proactively. Thus, for BM organisations to manage the complexities of maintenance posed by issues such as faulty design, poor construction materials, and users' misuse of building assets, they need to unlock their predictive capabilities through scenario analysis, among other methods, supported by DT (Section 3.7.1).

Moreover, for BM organisations to maximise the potential of technological advances, it is imperative to assess their knowledge of these technologies. Six respondents provided insights into their exposure and knowledge of global technological advances, acknowledging the use of BIM, CMMS, and CAFM for maintenance activities. The following statements support their claims:

"There are a lot, but the ones that presently I know are CMMS and BIM" – R2

"They use systems like CMMS. There are even other ones called CAFM computer-aided facility management" – R19

These responses indicate that respondents in Nigeria are aware of technological advances in maintenance activities. Furthermore, regarding awareness of DT, eight respondents stated they were aware of it. A supporting statement is:

"I know about the digital twin. It is presently not being used in Nigeria" – R10

Six of them further shared their perceptions of DT and its usage. A supporting statement is:

"I believe digital twin would improve maintenance activities. This is in terms of maintenance planning" – R10

Two respondents viewed DT from the perspective of its proactive features that would benefit BM management, explaining that:

"Well, a digital twin is more proactive and dynamic. It will give better information and then make things faster in the area of planning than the use of conventional methods" – R2

Another two respondents linked DT to BIM, describing it as an enhancement of BIM with the added feature of real-time updates:

"Digital twin is a comprehensive package that you can apply on buildings from inception or even use it for only post-construction, depending on the level you want to go. When you talk of digital twin, it has taken BIM to a higher level and covers real-time data updates…. " – R1

Regarding the actual usage of DT for BM management, all respondents agreed that DT is not currently in use. This finding substantiates that of Bello *et al.* (2024) and Eromonsele (2021), who discovered that awareness of DT was low in Nigeria. One respondent corroborated this:

"No, we have not gotten to that stage of using digital twin for any public building in Nigeria. We are still at the theoretical stage……, with emphasis on its adoption in the industry" – R5

In summary, these findings, along with those from the quantitative data analysis, indicate that several causes contribute to maintenance-related issues. These issues are multifaceted and can be categorised into human-related and natural-related causes. Based on the findings, human-related causes are predominant and include organisational, technical, human resources, financial, and building user-related factors. The most prominent of these is organisational-related issues. Notably, the causes of organisational-related problems are internal, including inadequate documentation, non-usage of technologies/systems, and poor maintenance strategies. Hence, BM organisations need to proactively address these issues to avoid the continuous hindrance of other issues management.

Meanwhile, BM organisations have employed technologies and systems to address these organisational and maintenance-related issues. Such technologies include CMMS, BIM, and CAFM for overseeing maintenance activities. Despite the benefits offered by these systems, maintenance-related issues remain persistent. Therefore, BM organisations need to adopt a more strategic approach to enhance their maintenance management dynamics. One effective approach for achieving this alignment is through technological advancements such as DT (Jiao *et al.*, 2023; Pomè and Signorini, 2023; Eromonsele, 2021). Implementing such an approach will enhance BM organisations' use of technologies for improved data management, budget optimisation, and attitudes towards maintenance activities (Section 3.7.1). Additionally, it allows them to leverage their predictive capabilities through scenario analysis, which is vital for BM (Sections 3.6.1 and 3.6.2). Consequently, BM organisations will be more strategic in their operations, and individuals involved in maintenance activities will demonstrate greater accountability in their roles. Therefore, for BM organisations to effectively utilise DT in their maintenance processes, they first need to thoroughly understand its architecture, functionalities, and the requirements necessary for its implementation.

6.4.2 Theme Two: Digital Twin and its Requirements

This section provides an overview of DT and its prerequisites for executing maintenance activities. It encompasses sub-themes such as the components of DT, technological requirements, data requirements, and the integration of data from other software applications into DT. These sub-themes are presented to underscore the empirical results derived from participants' feedback regarding DT for BM activities.

Sub-theme I: Component of a Simple Digital Twin

This sub-theme examines the components that make up DT. Such an examination aims to clearly delineate the actual components of DT, as it remains relatively nascent in the AEC industry (Section 3.1). Numerous definitions and interpretations exist regarding the components of DT (Sections 3.2 and 3.3). To develop a framework for effective DT implementation, it is crucial to ascertain its actual components. Ten respondents shared their insights regarding the components of a simple DT. Three described DT as a digital representation of a physical asset. The following statements support their viewpoints:

"A realistic representation of a physical asset. It is accurate to some level of detail to what is physically existing. So, it is a digital representation of something that exists physically" – R4

Two respondents conceptualised DT from the perspective of data transmission, acknowledging its bi-directional nature:

"It depends on the complexity of the physical assets, such as what system or physical asset you want to replicate. Then, based on that, we can build up the complexity of the system, but the main thing is having this connection between the physical and the digital assets" – R12

Another two respondents viewed DT through the lens of data integration, considering the gradual flow of data from the physical asset to the digital model:

"I look at the digital twin on a spectrum. It starts from a digital model, and you fill in the information into the digital model. You start to make it more accurate, and as the spectrum moves, you are getting closer to what you describe as a digital twin" – R16

Another two respondents elaborated on the various components of DT. They argued that it is not merely a digital solution but rather something that should have specific goals from its inception:

"You need a physical facility, you need a virtual representation of that facility, and you need sensors and information to flow from the real to the virtual, and the fourth thing,... you need actuators in the real world, which implement the decisions made by the digital twin" – R13

These responses clearly indicate that DT consists of diverse components. Notably, the implicit notion is that it serves as a digital representation of a physical asset, involving a degree of data communication between the two. Furthermore, for a digital representation to exist, certain information technological tools need to be established. The following section will outline the technological requirements for setting up a DT system.

Sub-theme II: Technological Requirements for a Digital Twin

This sub-theme establishes the technological requirements that constitute DT. As Sharma *et al.* (2022) highlighted, DT incorporates different technologies in its operations. Therefore, understanding these technologies is essential for identifying DT's technological requirements. Meanwhile, according to the literature review (Section 3.8), there are no standard requirements specifically for DT development, only policy documents regarding digital technology usage. Reinforcing this point, one respondent emphasised that there are essentially no standard requirements for DT, although there are case studies available:

"I have no idea about the digital twin requirement because it is still new. The National Digital Twin Program is trying to come up with some requirements. They established this national program in 2018 and have not come up with any requirements" – R12

Based on this response, which substantiates the absence of policy documents on DT requirements, this study frames its technological requirements based on literature extracts (Hosamo *et al.*, 2022a; Lu *et al.*, 2022; Madubuike *et al.*, 2022; Rasheed *et al.*, 2020). These include technologies for data capturing devices from physical assets, data transmission devices, model development, data integration devices, data analysis tools, and implementation devices. Data capturing devices are essential for acquiring both static and dynamic data from physical assets (Opoku *et al.*, 2021; Lu *et al.*, 2020a). Two respondents noted that static data can be captured through certain mediums:

"If you are talking about static data of an existing building, then we need to do some sort of surveying using advanced surveying, point cloud, laser scanning or thermal cameras" – R12

Six respondents underscored that dynamic data can be captured through IoT devices. The following statement elaborates on their claims:

"You need technologies that can capture data points such as track heat, air quality, and the amount of air that is being cycled through a building as well maybe the operation of the HVAC, putting sensors throughout the system to understand and track different metrics"– R4

From these responses, it can be deduced that static data can be captured using RFID, laser scanning, thermal cameras, drones, and advanced surveying tools. Conversely, dynamic data is captured using sensors. These findings confirm those observed in earlier studies on data-capturing mediums for DT development (Pomè and Signorini, 2023; Hosamo *et al.*, 2022c; Madubuike and Anumba, 2021; Lu *et al.*, 2020c). This finding indicates that both static and dynamic data are vital for DT development, and such data must be captured appropriately using suitable mediums. Furthermore, the captured data must be transmitted to be usable (Lu *et al.*, 2022). Three respondents provided potential mediums for transmitting data to the digital layer:

"You can go for fibre optics. You can go with the optical transmission, you have Bluetooth, Wi-Fi, and you have the Internet wherein you have various communication protocols" – R7

"You would need some sort of way to connect to the building data loggers. This could be through rest API, FTP, email, or MQTT" – R16

These responses indicate that captured data can be transmitted through Wi-Fi, fibre optics, Bluetooth, REST API, FTP (File Transfer Protocol), email, or MQTT. Some of these findings align with those mentioned in previous studies, such as Wi-Fi, fibre optics, and Bluetooth, regarding the transmission of captured data (Omrany *et al.*, 2023; Fang *et al.*, 2022; Lu *et al.*, 2019). This finding suggests that data transmission mediums are central to the transfer of captured data. Moreover, the transmitted data from the sensors and the physical asset's static data (historical data) need to be stored for seamless integration with the digital model (Lu *et al.*, 2022). Two respondents confirmed that the data for DT needs to be stored in high-capacity mediums:

"You need a sort of database, actually, to store the data that describes the digital twin" – R6

Another respondent provided further insights into various options for data storage:

"We need to look at a storage solution or cloud-based storage solution. Microsoft Azure could be one of them. Google Cloud also has some sort of platform. We also have, for example, Amazon Web Services (AWS)…… Google Firebase is a database system where you can store data, and this could be connected to your IoT sensors" – R12

This finding reveals that both transmitted data and other data sources can be stored in a database such as Microsoft SQL, among others, for a DT system. Furthermore, the digital layer or model is central to establishing a DT system (Lu *et al.*, 2022; Camposano *et al.*, 2021). This layer is where the model of the physical asset is developed for analysis. The model can be created as a 3D or analytical model (Brunone *et al.*, 2021; Angjeliu *et al.*, 2020; Lu *et al.*, 2020b). Six respondents indicated the use of BIM and other similar software to create the 3D digital model. A statement in support of their claims is:

"Obviously,….. to create a digital twin, you need to build it from a digital model of the facility, and if you have that in a BIM model, you can create a lot of things" – R6

One respondent highlighted the use of CAD for developing the 3D digital model:

"You need a modelling interface. A 3D computer-aided design model can be used to give information to digital twins…. We create reduced-order models so you can read them" – R7

However, one respondent argued that CAD models were unsuitable for a DT system, as they lack the capacity for semantic data enrichment:

"Regarding a digital twin for construction, there must be a BIM model, and that is not AutoCAD. AutoCAD is not smart and does not use semantically enriched data" – R6

Furthermore, two respondents emphasised the use of numerical simulation to develop a digital model. The following statements reinforce their claim:

"There is Ansys, Comsol Multiphysics, and computer-aided machines with 3D models for numerical simulation. These are models for physical modelling, numerical simulations" – R7.

"We also modelled the building in a discrete event simulation" – R8

These findings suggest that digital models are developed as 3D or numerical simulation models. Depending on their usage, 3D models are developed using software like BIM and CAD, as well as numerical simulation models such as Ansys, Comsol Multiphysics, and discrete event simulation. Conversely, analytic models are developed using technologies such as AI (Brunone *et al.*, 2021). Three respondents confirmed the use of AI applications or similar tools for developing the analytic model, as evidenced by this statement:

"Typically, nowadays people use Java, so you can use Java or R or something like that to create your machine learning models" – R17

One respondent elaborated on the use of programming languages for the analytics model:

"To create an analytics model, you need a programming interface. You have to use Python to develop your machine-learning model..... You have Julia,... 'R',... 'Ruby on Rails'" – R7

It can be inferred from these responses that the analytics model, which could be a machine learning model, is developed using programming languages such as Python, Java, R, Julia, and Ruby on Rails, among others. Based on these findings, accurate modelling of the physical asset, either through a 3D or an analytical model, is essential for its usage in the digital layer. Furthermore, integrating captured data into the digital or virtual model is crucial for successfully utilising DT (Lu *et al.*, 2022; Li *et al.*, 2020). Both sensors and the historical data of the physical asset need to be integrated with the digital model (Li *et al.*, 2020). Two respondents highlighted the necessity for consolidating data into a cohesive system:

"You would need to have or be able to pull data from sensors into a system so that all of these data points can be accessed in one centralised kind of ecosystem" – R4

Three respondents further elaborated that an application interface is required for the seamless integration of captured data into the digital model:

"When trying to map the physical asset into a digital model, you can utilise software like Ansys, and then you have Matlab. API is an interface which actually communicates both with the physical layer and the digital layer of your digital twin" – R7

From these responses, it can be deduced that effectively integrating static and dynamic data into the digital or virtual model is critical for the use of DT systems. Such integration can be realised through an API. Additionally, analysing the integrated data with the digital model is vital for DT utilisation (Fang *et al.*, 2022). The analysis layer serves as the core or engine room of a DT system (Lu *et al.*, 2022). This layer is where analysis and simulation activities take place, as discussed in Sections 3.6.1 and 3.6.2. One respondent noted the importance of mediums for converting acquired data into usable commands:

"You need to convert information from the sensors into commands for the actuators" – R13

Three respondents also identified tools for analysing data into actionable commands:

"A digital twin is mainly machine learning and AI. These two are the main important technologies that should exist if we want to move forward to the digital twin. I mean, even if you have a BIM and you do not have an AI, you do not have a digital twin" – R8

Moreover, the analysed data needs to be converted into actions for effective utilisation (Lu *et al.*, 2022). This conversion can be formatted in a readable file type or dispatched to the actuators for implementation. Two respondents highlighted pathways for the action or utilisation of analysed data:

"These models need to have an output…… and that would be a CSV file" – R17

"Actuators action the decision made with digital twin so that everything is autonomous"– R6

It is evident from these findings that several technical requirements exist for developing a DT system. These requirements include data capture devices, transmission devices, model development platforms, data integration mediums, data analysis tools, and implementation devices. These technologies facilitate seamless communication of data and actions between the physical asset and its digital or virtual model. Additionally, the communicated data consists of various types. The following section will outline the components of this data.

Sub-theme III: Data Requirements for a Digital Twin System

This section presents the respondents' findings regarding some of the data requirements of a DT system. It includes codes related to geometric models and data on the asset. Angjeliu *et al.* (2020) underscore that accurate geometrical information of a digital model is a key component of a DT. Seven respondents noted that a DT system requires a model to represent the physical asset. The following statement supports their claims:

"You need an information model of the systems that make up the actual facility" – R13

Three respondents indicated that the model can be a BIM file model:

"One of the data sources should be the model data. So, how you can have the architecture model, the mechanical model, the plumbing model, and the structural model integrated into one Federated database or Federated environment, which can be in BIM software" – R18

The geometric model can accommodate static data, dynamic data, and data from generative modelling (Jiao *et al.*, 2023; Lu *et al.*, 2022; Angjeliu *et al.*, 2020). Three respondents emphasised that the geometric model needs to include more details beyond the static data of the asset when using DT. The following statements substantiate their claims:

"I would say that if we think about a typical BIM model, it has document components and spaces. However, that is probably not the main information you need for digital twin system... as they often do not represent the systems, zones, and characteristics of the facility" – R13

Based on these responses, it can be deduced that a DT requires a comprehensive dataset of an existing building and its assets for maintenance, and the static data should encompass more than just the component information. Furthermore, the static data can take the form of historical data for the asset (Wang *et al.*, 2022). Five respondents corroborated that historical data is vital for understanding the physical asset or system. The following statement supports this point:

"We look at the kind of BMS system. Some historical data that are recorded over time" – R12

However, one respondent argued that detailed information on every building component is not necessarily required, but rather an abstract representation:

"You do not necessarily have to have information about every window, door, or floor. What you need is an abstract; it can be a fairly abstract representation" – R13

These responses highlight the importance of a comprehensive static dataset when using DT. Moreover, in bolstering the static dataset to encompass more than just component information, one respondent emphasised the necessity of understanding the usage patterns of building components through some data for better comprehension:

"You would then need detailed information on the type of building, how it is being used, and as much occupancy/operational information as possible. Detailed information on the building fabric and glazing ratio" – R16

This finding emphasises the role of static data in developing a DT system as it provides historical information about the asset. It underscores the need to efficiently gather static data on buildings and assets to ensure adequate information is available for analysis. However, static data alone cannot convey the actual status of buildings and assets; hence, there is a need for dynamic data (Jiao *et al.*, 2023; Lu *et al.*, 2019). Dynamic data, captured through IoT devices, offers real-time insights into the condition of buildings and assets. Four respondents confirmed that dynamic data is collected in real-time to monitor the status of buildings and assets. A statement supporting this point is:

"We also need dynamic data, which we collect from the environment. Let us say the data comes from the HVAC system. So, we continuously collect data through time from it" – R12

Moreover, dynamic data reveals the actual status of the asset and its environment. Six respondents highlighted that dynamic data comprises various components necessary for a comprehensive diagnosis of the asset. The following statement buttresses their claims:

"We also need dynamic data, which we collect from the environment. These data could be on temperature, humidity, air velocity, and radiant temperature" – R12

Seven respondents indicated they used IoT devices, such as sensors, to capture dynamic data. A statement supporting this claim is:

"You need an array of sensors, which continuously capture data from your physical asset and communicate this data to the digital space" – R7

Another respondent also highlighted the usefulness of dynamic sensor data for maintenance activities:

"……..you can put a temperature sensor on a really big heat pump. So, if there is anything wrong or some nominee data you find from the operating status of that heat pump, you can do some predictive maintenance to avoid some of the damage or even disaster" – R18

It is evident from these responses that dynamic data, captured using IoT devices such as sensors, is useful for gaining a better understanding of an asset and its environment for effective maintenance activities. Dynamic data offers more robust information to complement static data in understanding the asset better. However, both static and dynamic data alone are insufficient for a DT system to function effectively. Hence, there is a need to examine data generated during asset usage, which can be referred to as system data (Lu *et al.*, 2022; Barni *et al.*, 2018). Such data is crucial for understanding the asset's actual status. Five respondents corroborated the need for such data. The following statement supports their claims:

"There is data that an asset generates for changing its status or some of its properties" – R6

Two respondents further elaborated on the necessity of system data using some scenarios:

"You look at the data from the system itself. So, the time and hours of the operation of that system, the thermostat: what is the set point of the thermostat, and then we will look and compare these data through some certain time spam" – R12

Based on these findings, it is clear that the development of a DT system is intricately tied to various types of data, such as static, dynamic, and system data related to the physical asset. These findings support earlier studies that highlight the central role of data in the operations of a DT system (Lu *et al.*, 2022; Wang *et al.*, 2022; Angjeliu *et al.*, 2020; Lu *et al.*, 2019; Barni *et al.*, 2018). Such a finding underscores the importance of data in DT development, with continuous data availability being crucial for the seamless functioning of a DT system. Meanwhile, the acquired data needs to be transmitted and integrated with the digital or virtual model for analysis. Thus, the next section will explore avenues for integrating various data sets into a DT system.

Sub-theme IV: Avenues of Data Integration into a Digital Twin Model

This sub-theme identifies various avenues for integrating data, including static data from numerous sources, dynamic data, and system data into a DT system. These avenues include using an analytical model, API, COBie, IFC, and ontology, among others (Hosamo *et al.*, 2022c; Mokhtari *et al.*, 2022; Lu *et al.*, 2020a). Hosamo *et al.* (2022c) highlighted that ontology integrates data from domains with similar data structures or formats. Two respondents corroborated the use of ontology for integrating the static data of a building asset with the digital model:

"The ontology is probably going to connect properties of building elements, as they are being made up of zones and systems and maybe other things" – R13

Moreover, IFCOWL represents building data using state-of-the-art web technologies (semantic web and linked data technologies) (Boje *et al.*, 2020). IFC data could be available in directed labelled graphs such as Resource Description Framework. Studies indicate that such graph models and the underlying web technology stack facilitate the linking of building data to material data, product manufacturer data, sensor data, classification schemas, and social data, among others (Boje *et al.*, 2020; Lu *et al.*, 2019). One respondent further pointed out that schemas are used to represent ontologies due to their abstractions:

"Ontologies are an abstraction of the schemas; the schemas are just one way to represent the ontologies. So, an ontology defines the domain knowledge and its technology-agnostic" – R6

Schemas could include IFC and Brick (Hosamo *et al.*, 2022c; Mokhtari *et al.*, 2022). Six respondents unanimously indicated that they use IFC as a schema for ontology representation. The following statement emphasises their point:

"I think IFC is one that comes to my mind as being kind of open-sourced and allows you to integrate at least geometry and other kinds of metadata" – R4

IFC is useful for data integration, and its files can be presented through various avenues, such as spreadsheets (Lu *et al.*, 2020b). Spreadsheets offer easier data presentation, ultimately enhancing the readability of the information contained within the IFC files. Two respondents further elaborated on this, highlighting the usefulness of spreadsheets:

"You need a presentation because you may not want to read the raw data from the IFC files. You may want to have a viewer or a business dashboard or something like spreadsheets" R13

Conversely, Brick is a schema used for the representation of ontology. It serves as an open-source platform to standardise semantic descriptions of the physical, logical, and virtual assets in buildings and the relationships between them (Hosamo *et al.*, 2022c). Two respondents confirmed the use of Brick as a schema for ontology representation:

"You can represent ontologies in bricks for the building management system" – R13

Furthermore, COBie schema integrates building information into BIM as a computerised data set (Hosamo *et al.*, 2022c). Two respondents supported the use of COBie for data integration:

"…COBie is a very specific subset of the information that could be in a digital twin with only one purpose,.. to communicate to the owners the operations and maintenance system" – R13

Based on these responses, it is evident that ontology plays a crucial role in integrating diverse data with a standardised structure within a particular domain or domains using IFC, Bricks, or COBie schemas. This integration fosters the seamless integration of building data, such as static, dynamic, and system data, into a centralised data pool. These findings substantiate earlier studies that explored the effectiveness of ontological mediums, including IFC, Bricks, and COBie schemas, in data integration (Hosamo *et al.*, 2022c; Moretti *et al.*, 2020). Although the correct utilisation of ontology is vital for successfully integrating data into a pool, other avenues for integration exist. One such avenue is the analytic model (Lu *et al.*, 2020b). Three respondents highlighted the use of analytic models for integrating data, such as geometric data (historical data) and sensory data (dynamic data). This statement supports their claim:

"I guess geometric data can be combined with sensory data through the use of Analytical models or simulation models" – R9

Another respondent emphasised the necessity of using APIs to integrate sensory data with the analytic model:

"Once we get that file, we bring it into the analytic platform. We look at this model data set and try to connect the historical and live data to the data analytic platform. We connect like a live data stream through Rest API to the data analytic platform" – R16

Three respondents further corroborated that the use of APIs by software or platform providers has simplified the seamless integration of static data, such as the BIM geometric data model, with dynamic data into DT without schemas (IFC). This statement elaborates on their claim:

"For example, Revit data, maybe Autodesk can give you an API; therefore, you do not need to use an IFC model" – R6

One respondent pointed out the utilisation of web services to integrate data into the digital layer:

"Autodesk Forge is a web-based viewer for Autodesk, and it is a development platform. So, if that is the case, you do not need IFC; you can just use a direct Revit file" – R12

It is evident from these findings that static, dynamic, and system data play a crucial role in establishing a digital twin system. Despite originating from diverse sources, such data can be seamlessly integrated into a cohesive structure through avenues such as ontology, analytical models, and APIs with the digital model. The integration process involves screening and filtering to eliminate unwanted and erroneous data, which can act as impurities that negatively impact data analysis (Jiao *et al.*, 2023). Therefore, such screening facilitates the effective analysis of integrated data for various activities.

In summary, this theme has provided requisite insights into DT and its components. It has unravelled information on the components of a simple DT system, technological requirements, data requirements, and data integration from other software applications into DT. While understanding such information is crucial for demystifying the complexity of a DT system, it is essential to explore its applicability for activities such as BM management. The subsequent section will delve into the specific usage of DT for maintenance activities.

6.4.3 Theme Three: Digital Twin for Building Maintenance

This section presents the respondents' insights on using DT to manage maintenance activities. It includes sub-themes such as maintenance activities that can be managed with DT, approaches to managing maintenance-related issues through DT, and enablers utilising DT for maintenance activities.

Sub-theme I: Building Maintenance Activities Managed Using Digital Twin

This sub-theme explores the potential maintenance activities that can be managed using DT. It includes building operations, decision-making processes, operating costs, and fault prediction (Lu *et al.*, 2022). One respondent elaborated on the possibilities of utilising DT for maintenance activities:

"The role of a digital twin in maintenance would be to have sensors on equipment, receive those readings, and optimise them when you call out the maintenance team to do a repair. So, the actuator part is not sent directly to the facility but to the maintenance department" – R13

Moreover, building operations could be effectively managed using DT to reduce or mitigate maintenance activities (Zhao *et al.*, 2022). Four respondents substantiated the utilisation of a DT to manage building operations. The following statement highlights this point:

"A digital twin can be used to enhance or improve our current BMS system because you are collecting more data…… We can also look at how to minimise energy usage because we are not only collecting the system data but also the data from the occupants themselves" – R12

The effective coordination of building operations using DT would result in improved decision-making at the appropriate time, thereby enhancing the comfort of building users

(Hosamo *et al.*, 2023b). Two respondents indicated that DT could improve the comfort level of a building for its users:

"Occupants always want a cosy environment to reside…. using sensors to automatically tune the temperature and the operation of systems, it can provide comforts for occupants" – R18

In addition, effective management of building operations would lead to more data being available for the BM organisations to make better and more strategic decisions regarding their maintenance activities. Five respondents highlighted that DT would improve the maintenance decision-making process. A statement supporting their claim is:

"A digital twin is basically a concept for a decision support system. You want intelligent decisions….. wherein you try to understand issues and make decisions using data" – R7

One respondent further elaborated on the utilisation of DT to improve decision-making in managing maintenance activities:

"It could look into upgrading/replacing HVAC equipment or building fabric to improve overall performance and reduce the need for maintenance activities" – R16

These responses reveal that using DT for building operations will foster benefits such as improved decision-making and strategic planning of maintenance activities. Such benefits will, in turn, reduce the operational cost of a building and its maintenance (Zhao *et al.*, 2022). In this context, three respondents elaborated that using DT effectively will reduce operational and maintenance costs for buildings and assets. This statement highlights their point:

"Using digital twin.., I think this is probably the most important consideration by facility manager owners around the world. So, the ultimate goal either from an academic or business point of view is to reduce operating costs or the life cycle cost for running facilities" – R18

One respondent further emphasised that the feasibility of DT in cost reduction for building operations and management is more theoretical than practical, likely because it is still in its infancy:

"Digital twin can effectively reduce maintenance costs……. In theory, yes. We should be able to reduce the cost of maintenance, but in practicality, most industries are not ready" – R17

These responses indicate that using DT could lower operational costs for building and maintenance activities. Such cost reductions could be achieved through accurate fault predictions, which in turn contribute to optimising building assets and prolonging their usefulness (Mihai *et al.*, 2021). Moreover, four respondents emphasised the importance of fault predictions in buildings and the use of DT to achieve this purpose. This statement supports their point:

"…. focusing on digital twin for predictive maintenance is to understand how faults develop. If a fault is developed, which kind of fault….? How could the prognostic parts help us save on O&M costs…..? So here, maintenance is done to avoid faults develop" – R7

This response reinforces the significance of DT for optimising building assets/systems discussed in Section 3.6.2. Meanwhile, for the RUL of an asset to be effectively determined, it requires optimisation through fault diagnostics (Davies *et al.*, 2022; Agostinelli, 2021). Four respondents corroborated that fault diagnostics aid in identifying faulty parts of an asset. The following statement supports their claim:

"….Once the faults develop, you have to diagnose those faults and suggest a kind of decision which could be used to emulate a situation to prolong the life of the equipment" – R7

This response indicates that DT can efficiently manage certain maintenance issues related to physical asset data. Due to its analytical potential, BM organisations can easily gain insights into an asset's current status, optimise its performance, and predict its future. The responses underscore the role of DT in diagnosing building assets/systems, as discussed in Section 3.6.1. This finding highlights that BM organisations can leverage DT for necessary strategic planning regarding asset preservation and longevity. While DT is undoubtedly useful, it is crucial to understand its application, particularly concerning maintenance activities, which will be the focus of the next discussion section.

Sub-theme II: Building Maintenance Management Using Digital Twin

This sub-theme explores how DT can be used for BM management. It includes codes regarding the steps to utilise DT and potential analyses conducted using DT for maintenance activities. Certain procedures exist for employing DT to manage maintenance activities (Zhao *et al.*, 2022). Four respondents outlined the steps involved in utilising DT for maintenance activities. The following statement highlights these steps:

"We have to collect the data and determine how this data can be integrated into a digital system because we need to build that connection between the digital and the physical. The next stage is to look at the data analysis and what kind of knowledge we can produce" – R12

One respondent further emphasised that understanding the issue to be managed using DT is crucial for its utilisation:

"The first part would be to understand the business problem. If the business problem requires a digital twin-based solution, only then should we proceed. Otherwise, there is no point"– R7

These responses indicate that specific milestones need to be achieved when employing DT for maintenance activities. Based on the responses, the initial step in utilising DT is to understand the maintenance issue or problem, which is vital, as not all issues can be managed by it. Furthermore, supporting this point, one respondent underscored that the maintenance-related issue to be addressed was central to the utilisation of DT for management purposes:

"The first and foremost is trying to get information on the states of the HVAC systems… and try to keep sensors in place, which would give a good approximation of those states" – R17

This finding highlights that understanding the maintenance-related issue to be managed is fundamental when considering the use of DT for maintenance activities. It suggests that if the maintenance issue is not suitable for management with DT, then its utilisation would be unnecessary. Furthermore, after identifying the maintenance issue to be managed, the subsequent step is data acquisition from the asset, which is essential for DT development, as discussed in Section 3.8.1.1 (Lu *et al.*, 2022; Opoku *et al.*, 2021; Lu *et al.*, 2020a). One respondent reinforced that data acquisition is paramount to establishing a DT system:

"..Until the data ingestion aspect is extremely clear and accurate, there is no point in going forward to create a digital twin. So, the major hurdle for a digital twin is not the requirement of more technical expertise to execute a project; instead, it's the data acquisition stage"–R17

As elaborated in Section 6.4.2; Sub-theme II, data can be acquired or captured using various technological devices, such as IoT devices, random collection tools, cameras, and scanners, among others. Therefore, utilising the appropriate devices for data acquisition is essential for maintenance activities. Three respondents corroborated the use of sensors to capture live data for a DT system. The following statements support their point:

"So, what sensor does is to detect data from this facility and give exact feedback into your virtual model or virtual environment" – R18

The acquired or captured data necessitates transmission to the digital or virtual layer (Lu *et al.*, 2020a, 2019). Such transmission is crucial for its usage in the digital layer for analysis. Section 6.4.2; Sub-theme II highlighted various methods for transmitting acquired data, such as Wi-Fi and fibre optics. Four respondents substantiated the necessity to transmit or communicate maintenance data effectively to the digital layer. A statement in support of their point is:

"When you have the virtual model ready, you have to connect the virtual model with the data communication protocols" – R18

As discussed in Sections 3.8.1.3 and the technological requirements detailed in 6.4.2; Sub-theme II, the transmitted maintenance data requires a digital model within the digital layer platform for its utilisation. The digital model comprises the asset's 3D geometric details. Four respondents elaborated on the necessity of developing the 3D model for DT usage to support maintenance activities. The following statement substantiates their assertion:

"You need to model your asset and then try to understand the key variables which govern the operation of that asset. Physical modelling or physics-based modelling is required" – R7

The 3D model and the transmitted maintenance data require integration within the digital or virtual layer (Sections 3.8.1.4 and 6.4.2; Sub-theme IV). Such integration is vital for their use in analysis and simulation purposes. One capability of DT is its potential to optimise building assets and systems through scenario analysis (Sections 3.6.1 and 3.6.2). Accurately integrating the 3D model and transmitted maintenance data would facilitate such analysis.

Four respondents confirmed the necessity for integrating acquired or captured data, including historical and dynamic data, with the 3D model. Statements supporting this point include:

"If you have data coming from the sensors, it can be integrated……. If you are going to use the BIM, you can integrate it into it using some complicated coding systems" – R8

One respondent elaborated that the method for data integration depends on the complexity of the maintenance data:

"For most practical cases,… if the size of the data set is not that huge, it can be simply ingested… The complexities will come into play when you are handling the latency, but when the size of your datasets is huge, there is an industry-agnostic way of handling things" – R17

Based on these responses, it is evident that DT operations revolve around data (Section 6.4.2; Sub-theme III). The proper acquisition, transmission, and integration of data with the digital model are imperative for its effectiveness in scenario analysis and, ultimately, optimising buildings and assets for increased longevity. Although data is vital for DT operations, not all data may be relevant for analysis or useful (Fang *et al.*, 2022; Hosamo *et al.*, 2022c). Hence, the integrated data requires some screening and filtering to remove any unwanted or duplicated information, ensuring accurate and precise results post-analysis (Hosamo *et al.*, 2023a; Omrany *et al.*, 2023; Hosamo *et al.*, 2022a). Three respondents underscored that data screening and filtering/cleaning are necessary for the data to be usable for analysis in DT:

"The structure of your data will not be workable for direct consumption to your machine learning model. Then, you would want to convert it into some structure that can be directly consumed. What that means is to clean the datasets" – R17

After the maintenance data has been formatted, screened, and cleaned, it requires analysis to be useful for maintenance activities (Lu *et al.*, 2020b). Five respondents were unanimous in their support for utilising AI for data analysis. The following statement elaborates on their claim:

"The digital space computes the entire thing, and various numerical simulations are done within it. This space means your AI, ML, DL models, which continuously take data from physical space and try to generate insights which could be used again" – R7

Another respondent emphasised the necessity for continuous updates of the digital layer, as AI functions best when supplied with up-to-date data:

"AI analyses the collected data and always be up to date with the digital twinning. So, if you do not update your digital atmosphere continuously, it is not anymore a digital twin" – R8

These responses reveal that the analysis of integrated data is central to the usability of a DT system. Such analysis constitutes the processing core of a DT system, facilitated by AI technology, which aids in identifying patterns and anomalies related to maintenance issues (Section 3.6.1). This finding substantiates the highlighted use of AI for data analysis in a DT system, as indicated in earlier studies (Pomè and Signorini, 2023; Lu *et al.*, 2020b). Based on this finding, BM organisations can leverage the analytic capabilities of DT to optimise building assets and strategically plan their maintenance activities for enhanced functionality and increased longevity. Moreover, such analytic capabilities of DT can be executed through a variety of analyses, including performance, diagnostic, optimisation, and prognostic analysis, among others (Pomè and Signorini, 2023; Villa *et al.*, 2021; Lu *et al.*, 2020b). One respondent confirmed that DT can be employed for making comparisons through performance analysis:

"…would that degree of automation improve the usefulness of the building or reduce its running costs by only doing maintenance when it is time? So, you would want to have some years of data before you introduced a digital twin and for some years afterwards to compare whether it was actually saving money or making a more comfortable building" – R13

Performance analysis is supported by other analyses, such as predictive analysis (Lin and Low, 2019). As Delgado and Oyedele (2021) highlighted, effective monitoring of buildings and assets is crucial in predicting their performance. Four respondents substantiated the importance of effective predictive analysis in averting unforeseen issues. The following statement underscores their point:

"DT can certainly be used to monitor the efficiency of the asset and can be used for predictive maintenance rather than waiting until things fail" – R20

Moreover, predictive analysis encompasses several subsets, including diagnostic, prognostic, and optimisation analysis (Delgado and Oyedele, 2021; Aivaliotis *et al.*, 2019). Asset diagnoses are crucial through effective monitoring to identify faults and their likely causes. One respondent confirmed that:

"Another aspect is to diagnose faults through condition monitoring because the world faces a situation where much money is spent on maintenance activities. So, a digital twin will…"– R7

Effective diagnoses of an asset would help predict when it will need servicing or replacement (Delgado and Oyedele, 2021). This finding indicates that the initial step in employing DT for predictive analysis is a thorough diagnosis of an asset to understand or trace the origin of the fault. Regarding asset services, using DT to forecast an asset's RUL will enable BM organisations to carry out necessary activities (Davies *et al.*, 2022; Mihai *et al.*, 2021). One respondent confirmed that one application of DT in maintenance management was to estimate the RUL of an asset:

"One part is to predict the asset remaining useful life" – R7

Predicting an asset's RUL may facilitate its optimisation by BM organisations if the DT results are favourable (Davies *et al.*, 2022). Such optimisation supports asset preservation and enhances its operational capacity. One respondent elaborated on how an asset can be optimised using DT:

"So, you can try to optimise your asset's operation by reassessing your asset over a period of time and see if you have enhanced its working efficiency……." – R7

These responses evident the potential and application of DT for predictive maintenance, reinforcing its relevance for predictive activities highlighted by earlier studies discussed in Sections 3.6.1 and 3.6.2. This finding suggests that the diligent application of DT will aid BM organisations in becoming more proactive and strategic in their maintenance activities. While the predictive capabilities of DT are clearly beneficial, the analysed data needs to be acted upon to be useful for its users, such as BM organisations (Madubuike and Anumba, 2021; Lu *et al.*, 2020b). Three respondents emphasised that the results from data analysis can be acted upon by actuators, robots, or human intervention. A statement in support of their point is:

"It depends on what you use for action. If you have robots on site, you can push the data to the robots and update the set of actions. Suppose it is more like a manual kind of activity; then, in that case, you can communicate with workers and send them an update" – R6

Another respondent highlighted that actions taken through human intervention can be supported by technologies such as AR and VR, enabling the maintenance team to visualise the data in relation to the physical asset.

"VR and AR could be like an advanced way for data visualisation of the connection between the digital and the physical structure" – R12

The respondent further explained how AR and VR can assist the maintenance team in acting on results from DT. Previously underscored by Hodavand *et al.* (2023), AR and VR offer improved opportunities for the visualisation and execution of maintenance activities. Based on this finding, AR can assist maintenance personnel in mapping and visualising data from a DT throughout the building being maintained. VR would help the maintenance personnel acclimatise to the building and its environment, leading to a better understanding of how to act on the analysed results. The following statements elaborate on this point:

"So, with AR, you can map the entire building over the existing one, and can see some digital components in the building that give you more information about its maintenance" – R12

"So, VR could be your solution for the maintenance issue and fix some of the problems. So, you can wear your headset, navigate through the building, and see where the problem is because you have the entire building, the digital one" – R12

It is evident from these findings and literature that certain steps or procedures are involved in utilising DT for maintenance activities. These procedures begin with identifying the maintenance issue and then progress to the actual application of DT to manage it. These findings highlight the crucial steps that BM organisations need to follow when employing DT. Based on these findings, if BM organisations fully utilise DT for maintenance activities, they will become more effective and strategic in their management. However, despite the potential of DT, some barriers hinder its utilisation for maintenance activities. The following section will identify some of these barriers.

Sub-theme III: Barriers to the Utilisation of Digital Twin for Building Maintenance

This sub-theme identifies certain barriers to using DT for BM management. It includes codes such as the initial cost of establishing a DT system, organisational structure, adequate skill sets, human resistance to technology, lack of asset instrumentation, data quality, and data acquisition. These codes are derived from the respondents' responses. As underscored in Section 3.6.3.2, the cost of setting up a DT system poses a significant barrier, given the high expenses associated with its infrastructure and equipment. Two respondents confirmed that cost is a major consideration in establishing DT. A statement in support of this point is:

"Most of the infrastructure costs a lot for digital twin deployment" – R18

This response indicates that cost is central to DT implementation. It suggests that BM organisations should allocate funds for its implementation during their budgetary planning. To achieve this, clients should grant BM organisations financial autonomy in managing maintenance activities, as discussed in Section 6.4.1; Sub-theme III. Moreover, studies have emphasised that clients' and other stakeholders' understanding of implementing a DT system is crucial to its development (Elyasi *et al.*, 2023; Pomè and Signorini, 2023). Besides cost, there are other factors influencing DT implementation. Perno *et al.* (2022) noted that an organisation's structure could hinder the use of a DT system, particularly in terms of the managerial structure and the willingness to innovate in maintenance management. One respondent stressed that the initiative for DT should begin with top management:

"If you do not have a good CEO, it is difficult to implement a digital twin. It is more efficient when we have the top-down approach for promoting new technologies and policies" – R18

The respondent further elaborated that while the initiative should begin at the managerial level, decisions regarding DT usage should span all levels of the organisational hierarchy, as it is the personnel at the bottom down who actually implement the outcomes derived from DT's data analysis:

"So, you have to make sure all of the people have horizontal decision-making rather than hierarchical one because you have different levels at the organisation, and you need the decision from your operating staff, rather than the decision from the CEO level" – R18

This finding reveals that maintenance personnel in the field should be well-informed about the usefulness of DT in easing their work activities. To address this issue, Perno *et al.* (2022) recommend that DT users, primarily the BM personnel in this study, acquire the requisite knowledge and skills for its application. One respondent corroborated that specific skill sets were essential for the effective use of DT:

"The required skills are a factor. I believe that the industry is moving in a direction where you cannot be any construction-related engineer if you do not know computer science. There is big gap between the AEC and the world of computers, and it is hard for us to merge" – R8

This finding suggests that possessing the right skill set is vital for utilising DT. It highlights the need for BM personnel to be adaptable in acquiring knowledge, particularly in IT. However, the innovation brought about by DT in organisational processes for managing maintenance activities may lead to resistance from some personnel, who may feel threatened by potential job loss due to technological innovations (Perno *et al.*, 2022; Shahzad *et al.*, 2022). Two respondents affirmed that technological resistance was a factor affecting the usage of DT:

"Often people are reluctant to adopt new technology for their assets" – R9

Another respondent further emphasised that resistance to technological innovations by personnel could interfere with the operations of DT:

"….Will the people in the organisation be prepared to let a digital twin do its job, or whether they would be constantly interfering and overruling it" – R13

These responses underline that the issue of technological resistance among BM personnel necessitates serious attention if DT and its capabilities are to be fully harnessed for maintenance activities. This finding suggests that BM organisations must make concerted efforts to educate their staff on the benefits of using a DT system to enhance their work processes. Essentially, a DT system complements rather than replaces personnel in executing maintenance tasks. Furthermore, DT is not a standalone technology; it collaborates with various Industry 4.0 technologies. The lack of these technologies and the insufficient knowledge about them within BM organisations is a significant barrier to DT utilisation (Hosamo *et al.*, 2022a; Madubuike and Anumba, 2021). These technologies include big data, IoT, and AI, as highlighted in Section 3.8. Four respondents indicated that for any meaningful digital transformation of an asset using DT, the right technologies are required to be in place. The following statement supports their point:

"The industry is still trying to work on digital transformation and how to digitalise existing buildings. We have many existing buildings, and we do not have a digital asset for them" R12

Another respondent further emphasised the necessity of having the right technology in place, as DT involves the bi-directional connection of a physical asset and its virtual counterpart:

"The technological aspect may include factors like how you can really ensure data transmission and data integration. Also, how you can really improve the accuracy of your virtual model to represent the real world of the physical objects realistically" – R18

Based on this response, one crucial factor could be the collection and transmission of quality data, including BMS, AMS, SMS, and sensor data, among others, from the physical asset using the right technology (Hosamo *et al.*, 2022c; Lu *et al.*, 2020a, 2019). Three respondents corroborated that quality data is central to DT, and its collection must be conducted properly. Statement to support their point is:

"The barrier would be data collection and data accumulation of required data" – R7

Another respondent further emphasised that integrating collected data creates a barrier to DT usage, as the data originates from diverse sources:

"Data formatting is a major issue when integrating data from different sources" – R16

These responses reinforce the centrality of data in the functioning of a DT system and highlight the necessity for it to be of high quality. Such data includes sensor and historical information such as BMS, AMS, and SMS. However, several barriers hinder the collection and integration of such data due to their varied sources and formats. These barriers lead to issues with data standardisation, which, in turn, inhibit the effective utilisation of a DT system (Section 3.6.3.1). To address this challenge, BM organisations can explore the use of ontology, analytical models, and APIs for integrating, structuring, and cleansing data (Theme Two: Sub-theme VI). If this issue remains unresolved, a DT system will be unable to accurately interpret and analyse the data necessary to conduct maintenance activities.

In summary, leveraging DT for BM management will support organisations in being strategic and effectively planning their maintenance activities. The effective utilisation of DT necessitates a series of steps spanning from data acquisition to its utilisation. Moreover, before deploying DT for BM management, it is crucial first to identify the maintenance issue and assess whether DT can be employed to manage it. However, utilising DT entails certain barriers, such as data quality and technological infrastructure. To overcome challenges related to data quality, it is essential to collect and screen data using appropriate technologies to eliminate uncertainties. Besides, blockchain technology can be employed to ensure data security (Delgado and Oyedele, 2021). Such technology will facilitate secure data sharing (Omrany *et al.*, 2023). This theme has underscored the usefulness of DT for maintenance activities; thus, it is important to explore how it can be implemented for BM organisational use, which is the focus of the subsequent section.

6.4.4 Theme Four: Prospects for Organisational Requirements in Implementing Digital Twin for Building Maintenance Management

This section presents the respondents' responses on the possible prospects of using DT technology to manage maintenance activities. It includes sub-themes regarding the organisational requirements of DT for maintenance, possible technological infrastructures to support a DT system, challenges and feasibility of implementing DT for BM management, and the promotion of DT for maintenance activities. These sub-themes aim to highlight the empirical results based on respondents' responses concerning DT implementation.

Sub-theme I: Organisational Requirements for Digital Twin Implementation

This sub-theme examines the organisational requirements for implementing DT for BM management, with a focus on understanding the basic organisational needs. However, as discussed in Section 6.4.2, Sub-theme II, there are no official documents outlining the requirements for DT. Although this finding reinforces the absence of official documentation regarding DT requirements, particularly at the organisational level, the PPT framework discussed in Section 3.9.1 serves as a research lens to extract common patterns from the thematic analysis on how BM organisations can implement a DT system.

Regarding the people dimension, the respondents highlighted the necessity for BM organisations to focus on their human resources in relation to DT implementation. This focus is crucial, as competent human resources are fundamental to the operations of any organisation, with employees acting as the primary drivers of work activities. For efficiency and optimisation, they may utilise additional resources, such as technological tools, to execute their work activities (Tripathi *et al.*, 2023a; Parida *et al.*, 2011). Seven respondents unanimously emphasised the necessity of skilful human resources to oversee the operations of a DT system. The following statement elaborates on their point:

"Employees with appropriate experience in modelling and also a technical background in the building services industry would also be essential" – R16

Additionally, three respondents underscored the necessity for experts to manage the virtual layer of a DT system, as it functions as the processing unit. A statement supporting their point is:

"You need to have a machine learning team in place. Some experts from the industry, which would help identify what metrics that need to be looked as key performance indicators"– R17

These responses indicate that recruiting the right human resources is imperative for BM organisations to utilise DT effectively in their maintenance activities. This finding corroborates those from the literature review, indicating that human resources such as data analysts, document controllers, and personnel for monitoring and controlling automation are crucial for employing Construction 4.0 technology during the O&M phase (Karmakar and Delhi, 2021). This suggests that BM organisations should prioritise recruiting staff, particularly technical experts, to carry out maintenance activities, as the AEC industry is gradually transitioning towards the utilisation of digital technological tools. While the recruitment of technical experts is fundamental for DT usage, the involvement of BM stakeholders, including the maintenance team and client input, remains vital for the success of BM management (Sections 2.5 and 6.4.1; Sub-theme II). Such success relies on documentation provided by building professionals (Section 6.4.1; Sub-theme II). It can, therefore, be inferred that the actions of these stakeholders are pivotal for utilising DT for maintenance management.

Moreover, for BM organisations to effectively recruit the right human resources, especially technical staff, there is a need for organisational re-engineering to integrate the operations of a DT system with personnel who manage its technical aspects (Shahzad *et al.*, 2022; Colquhoun *et al.*, 1996). Such activities pertain to the process dimension of an organisation (Kumar *et al.*, 2022; Love *et al.*, 1996). In this context, two respondents pointed out the necessity for organisations to re-engineer their operations in order to integrate a DT system into their activities. Statement in support of this point is:

"You will have to integrate the existing workflow with a digital twin" – R7

These responses reveal that organisational re-engineering is imperative if BM organisations are to proceed with implementing a DT system. The respondents underscored the importance of workflow integration and data management, along with the need for interconnection between both the people and technology dimensions of organisations. Based on these findings, BM organisations need to integrate DT with their existing workflows through an appropriate and sustainable approach that considers the findings related to DT model development discussed in Section 6.4.3; Sub-theme I. Meanwhile, Section 3.9.1.2 of the literature review established that effective data management is critical for maintenance management, which involves data governance, integration, and analysis. This section revealed that data governance is paramount when using digital technologies such as DT, emphasising that individuals' rights should be respected during data acquisition to avoid infringements. Hence, BM organisations need to consider the rights of building occupants during data acquisition processes to prevent or avoid any infringement.

Furthermore, Section 6.4.2; Sub-theme VI, discusses various avenues, such as ontology, analytical models, and APIs, through which BM organisations can integrate data into a DT model. These avenues provide BM organisations with the necessary models and formats to align their existing processes with the DT system. While integrating existing data processes is crucial, Section 6.4.3; Sub-theme I revealed that analyses such as performance, diagnostic, optimisation, and prognostic of this data equip BM organisations with the essential information to plan their maintenance activities strategically. By doing so, issues arising from poor data management, such as data silos, are mitigated through the decentralisation of decision-making and the central integration of data within the organisation, enabling the effective management of complex maintenance-related issues.

These findings corroborate the literature suggesting that organisations implementing any innovation should focus on workflow integration (both vertical and horizontal) and data management (Section 3.9.1.2). Figure 6.4 summarises the organisational components of the process dimension for DT implementation. The implications of these findings call for a complete overhaul of organisational processes in cases where BM organisations do not utilise any technological tools and devices, as well as a partial or re-engineering overhaul for those already employing technological advancements.

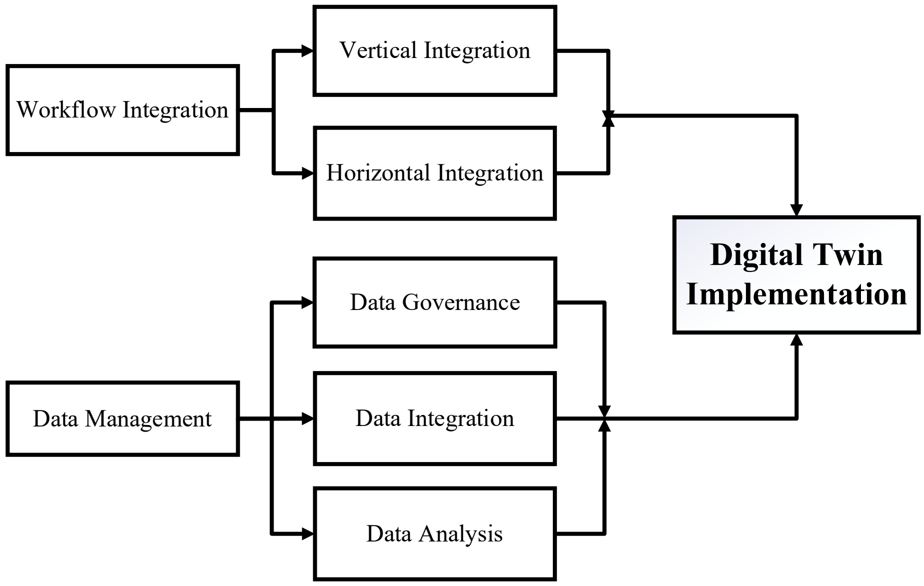


Figure 6.4: The Components of Process Dimension for Organisational Digital Twin Implementation

On the technology dimension, findings from Section 6.4.2; Sub-theme II revealed several technological resources central to the operations of DT, including data capturing devices, transmission devices, model development platforms, data integration mediums, data analysis tools, and implementation devices. Meanwhile, Section 3.9.1.3 of the literature review established that for organisations to implement any innovation, clarity is essential in the digitalisation of their workflow, focusing on data quality and security, connectivity, integration capability, and scalability. Hence, for BM organisations to digitalise their workflow, it is imperative to assess the scalability of their organisational infrastructures before proceeding with the implementation of a DT system. The literature emphasised the importance of such evaluation, as the people and process dimensions of organisations have to align with DT technology for it to be effective in enhancing organisational operations (Han *et al.*, 2023; Hamou-Lhadj and Hamou-Lhadj, 2008).

Based on this finding, BM organisations seeking to implement DT could utilise the stepwise flow of the DT development model discussed in Section 6.4.2; Sub-theme II as a checklist to gradually digitalise their workflow. Additionally, when acquiring data through capturing devices, BM organisations should ensure the quality of the data (R7) and take preventive measures to protect the rights of individuals from being infringed upon.

"You need an up-to-date instrumentation system that can collect data and sample data at a desired frequency, as well as the data from the physical assets…. So, technologically speaking, you need a sophisticated array of sensors" – R7

The successful transmission of acquired data through transmission devices and communication protocols to the virtual layer of the DT system will facilitate the connection of various data sources into a cohesive unit for storage. After the virtual models of the physical structure are developed using 3D models or analytical model avenues, as outlined in Section 6.4.2; Sub-theme II, they need to be integrated with the transmitted data. Integrating this data with existing organisational technologies and systems, such as CMMS, BIM, and CAFM, is crucial for DT implementation. Section 6.4.2; Sub-theme VI identified different avenues for data integration, including ontology (COBie, Bricks, and IFC), analytical models, and APIs. These findings will enable BM organisations to explore various pathways for integrating their existing data, organisational technologies, and systems into the DT model. The integrated data model can subsequently be analysed, with the outcomes communicated back to the maintenance issues requiring management. Figure 6.5 summarises the connection between organisational digitisation and DT model development.

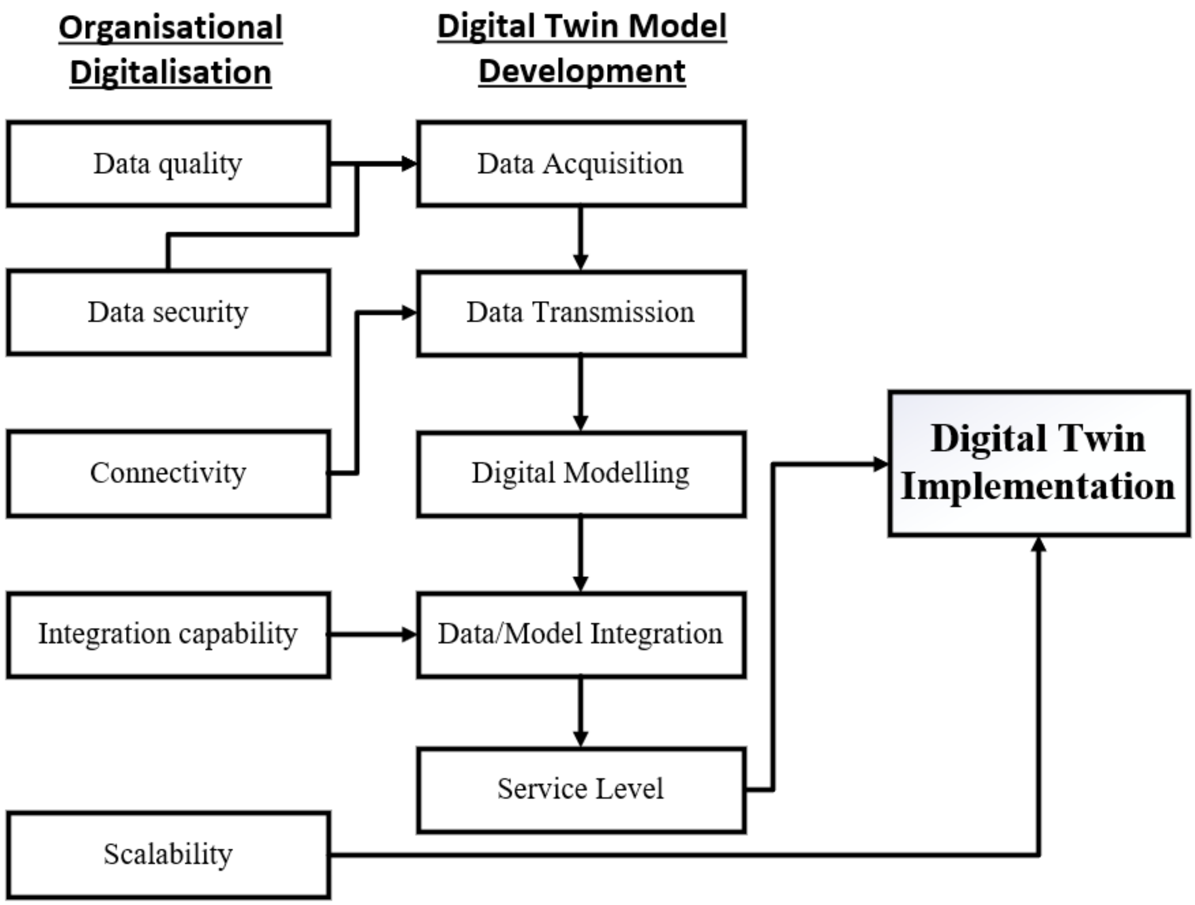


Figure 6.5: Linkage between Organisational Digitisation and Digital Twin Model Development

It can be deduced from these findings that each of the PPT dimensions of BM organisations plays a crucial role in the organisational implementation of DT for maintenance management. Hence, BM organisations should prioritise each dimension to achieve a balance among them for successful DT implementation. Meanwhile, for BM organisations in Nigeria intending to implement a DT system, evaluating their existing organisational structure and infrastructure is necessary to ascertain which aspects will require changes or upgrades.

Sub-theme II: Existing Organisational Structure and Infrastructure for Implementing a Digital Twin System in Nigerian Building Maintenance Organisations

This sub-theme explores the organisational structure and infrastructure within BM organisations in Nigeria to accommodate a DT system. It aims to gain insight into the existing organisational structures used for maintenance activities that align with the PPT dimensions suitable for a DT system. Regarding the people dimension, although no questions were asked during the interview sessions about the human resources of BM organisations, Nigeria's NBC (2006) specified that building owners/clients were responsible for the maintenance of their buildings. This service is contracted to BM organisations for execution. Meanwhile, Section 6.4.1; Sub-theme I revealed that building owners/clients, maintenance staff work attitudes, and poor documentation of BM activities by the administrators or management contribute to maintenance-related issues. These findings suggest that BM organisations' human resources in Nigeria are comprised of maintenance staff, maintenance managers, and administrative units, among others, who are tasked with conducting maintenance activities.

On the process dimension, Section 6.4.1; Sub-theme II revealed that some BM organisations in Nigeria follow a structured procedure in conducting their maintenance activities. While employing structured procedures is good practice for some BM organisations and facilitates the easy implementation of DT, those not using any procedure should leverage its advantages. Moreover, a structured procedure creates a more sustainable work plan, enabling BM organisations to adopt a standardised workflow and a better data management approach for maintenance activities. Bello *et al.* (2024) substantiated that if the construction industry in Nigeria, including the maintenance sector, can address issues relating to standardised tools and inconsistencies in data management, the DT implementation process will be feasible.

Furthermore, the technological tools used for maintenance activities and those suitable for DT technology were explored. In this context, seven respondents unanimously acknowledged the availability of IT infrastructure, such as computers and the Internet, in their organisations. The following statements elaborate on their point:

"The office has an IT infrastructure set up, computers and technologically inclined people. That would be a good way to start" – R11

One respondent indicated their use of sensors in conjunction with certain software platforms to conduct maintenance activities:

"We have our system, such as laptops, sensors, and other material for conducting tests. With these infrastructures, we were able to use CMMS and BIM for maintenance activities" – R2

Another respondent emphasised their use of visualising and capturing devices for maintenance activities:

"We use technology like virtual reality. We use drones to capture shots of assets" – R19

Based on these findings, it can be inferred that BM organisations in Nigeria are equipped with certain indicators of the PPT dimensions to accommodate a DT system. Moreover, they will require upgrades to meet the organisational requirements highlighted in Section 6.4.4; Sub-theme I. Such upgrades will enable BM organisations to harness the full potential of a DT system for maintenance management, making them more strategic and better able to plan their activities. However, BM organisations may encounter challenges in implementing DT, which are explored in the next section.

Sub-theme III: Challenges in Implementing a Digital Twin System for Organisational Management of Building Maintenance in Nigeria

This sub-theme examines the likely challenges of implementing a DT system for BM organisational management in Nigeria. The codes generated for these challenges specifically stem from BM managers' responses in Nigeria, particularly in the areas of finance, inadequate infrastructure, technological pushback from BM personnel, compatibility, and building type. Finance is a crucial requirement for the establishment of a DT system, as infrastructure, equipment, and gadgets are needed (Bello *et al.*, 2024; Madubuike *et al.*, 2022; Opoku *et al.*, 2021). Thus, this poses a challenge for BM organisations willing to implement DT. Four respondents highlighted that finance would be a major challenge in implementing a DT system for their maintenance activities. A statement in support of their claim is:

"Finance is the most challenging. If there is money, you achieve what you want" – R1

These responses substantiate that finance is a fundamental factor in implementing any technological and innovative solutions to improve organisational work performance (Section 6.4.3; Sub-theme III). Bello *et al.* (2024) corroborated that finance was crucial for DT's implementation in Nigeria. This finding implies that BM organisations in Nigeria should consider allocating sufficient funds if they wish to implement a DT system for their maintenance activities. However, while finance poses a major challenge, other issues exist, such as the lack of infrastructure, including consistent electricity and internet access. One respondent indicated that robust internet connectivity and consistent electricity are essential for DT usage, and without such infrastructure, a DT system cannot function:

"If the digital twin components like IoT operate based on the availability of the Internet. Then, you require a constant electricity infrastructure supply, which is not regular" – R14

Findings by Bello *et al.* (2024) corroborated that poor and unstable internet connectivity is a barrier to the implementation of DT in Nigeria. These responses and findings reveal that certain national infrastructure needs to be in place to enable the optimal functioning of a DT system. For DT to function effectively, consistent electricity is required to power the IoT devices for the collection of real-time data from the building and its assets and the subsequent transmission of collected data to the DT digital layer. Moreover, the transmission of collected data relies on strong internet connectivity, and without this, a DT system will not function in real-time but offline. Such an offline mode negates one of the vital characteristics of DT established in Sections 3.3.2 and 3.4, distinguishing it from other digital technologies, such as BIM. These challenges indicate that the Nigerian Government needs to provide consistent electricity and strong internet connectivity for DT to function, so that those provided by BM organisations will serve as alternatives or backups.

Furthermore, BM personnel may present a challenge to DT implementation in Nigeria, as some do not see the need to innovate in their work activities but prefer to adhere to their traditional methods (Emoh and Ndulue, 2021; Aghimien *et al.*, 2019). Six respondents believed that some colleagues would hinder their usage of a DT system. The following statement supports their claim:

"People would like to stick with what they already know, even though it is not working…… There are going to be issues at the beginning, like pushback and trying to repeal the digital twin innovation. That is going to be one of the challenges" – R11

In support of this response, Qoseem *et al.* (2024) spotlighted that challenges related to data ownership and data silos are concerns that hinder the use of DT in Africa. This challenge, stemming from a lack of awareness regarding the capabilities that DT offers for data management, has severely impacted organisational processes, rendering them less effective for maintenance management. Bello *et al.* (2024) highlighted that a lack of awareness regarding DT adoption in Nigeria could be due to an unclear understanding of its potential and benefits. These responses and findings suggest that awareness of the opportunities presented by technological innovations to BM organisations will pose an impending challenge in DT usage. Meanwhile, there are other reasons why some BM organisations might feel hesitant to implement a DT system. One respondent elaborated on why their colleagues might be uninterested in implementing a DT system for maintenance activities due to compatibility issues:

"Compatibility of a digital twin system would be one of the major challenges. ..We use our mobile phones to conduct maintenance activities. There is always an issue with application compatibility. How compatible will results from digital twin be with our mobile phones"–R10

This finding reveals that BM organisations will play a crucial role in the success of DT implementation. It suggests that they need to be more open to the principles of digital transformation, which would facilitate their work activities. Meanwhile, there are additional challenges to DT implementation, one of which is the type of building. Such a challenge arises because not all buildings and assets are suitable for management with a DT system, especially those lacking maintenance history and documentation (Section 6.4.2; Sub-theme III). One respondent believed that the building type and its assets might pose a challenge to the usage of DT for their management:

"I believe for digital twin, you need certain technologies in the building. So, you can get your data and all of that. Some existing buildings do not have all these components" – R11

It can be inferred from these findings that several challenges will hinder the implementation and use of DT for BM management in Nigeria. These challenges include financing, inadequate infrastructure, resistance from BM personnel towards technology, compatibility issues, and building type. Although these challenges may impose limitations, there are avenues to address some of them. Some respondents emphasised the need for assistance to overcome the challenges associated with implementing a DT system, particularly in the areas of funding, technological support, and training. One respondent believed that with sufficient funds, a DT setup is attainable:

"I think one of the ways assistants can be provided is much more on the side of funding because if funds are available, there is nothing that cannot be put in place" – R5

This response underscores the importance of funding for the implementation of a DT system. If this challenge is addressed, other challenges can be managed more effectively. Furthermore, financial assistance could help reduce the costs of equipment. Three respondents substantiated this point, and a statement in support is:

"I will rather say for some of those materials, due to financial issues such as exchange rates, the sensors and equipment are not far-reaching" – R2

Building on these responses, Bello *et al.* (2024) supported the idea that the government could introduce avenues such as partnerships with technology providers to mitigate the costs of DT-related infrastructure. Essentially, if key components of a DT system, including sensors, cameras, and high-performance processing computers, are made affordable, then its implementation becomes feasible. This is crucial as the technological components of a DT system are central to its setup and operations. Four respondents noted that assistance with technological support would facilitate the implementation of a DT system. A statement elaborating on their point is:

"There will be a need for things like, say, sensors and how to read information from the sensors. So, there will be a need on how to get those things that will be needed" – R11

While these responses highlight the necessity of technological support in implementing a DT system, user training plays a crucial role in optimising its effective use for maintenance activities. One respondent emphasised that technological support should include training, as maintenance personnel need to develop the expertise to operate a DT system:

"……. I will ask them to give me technology transfer, and that technology transfer means that they will have to provide personnel to train my maintenance personnel in the field" – R1

Three additional respondents affirmed that training is essential for the effective usage of a DT system, as maintenance personnel need to become familiar with its operations. A statement supporting their point is:

"You want to bring on board what people do not know or know little about. So definitely, to train them on what it is, how to go about it and the benefit it holds for them as well" – R11

In line with these responses, Bello *et al.* (2024) suggested that enhancing the skills of organisational staff through training is vital for successful DT implementation. This finding reveals that training BM personnel is as critical as acquiring DT system components. Therefore, adequate training through ongoing development workshops should be provided to help them better understand how to utilise a DT system for their maintenance activities.

In summary, implementing a DT system at the organisational level poses challenges such as financing, inadequate infrastructure, technological resistance, compatibility, and building type. While these challenges may seem like obstacles to DT implementation, they can be overcome with appropriate assistance, including funding, training, and technological support.

If these challenges are adequately addressed, then the implementation of a DT system will be seamless. The following section will explore the possibilities of promoting a DT system implementation.

Sub-theme IV: Promoting a Digital Twin System for Building Maintenance Organisational Management

This sub-theme explores avenues for promoting the implementation of a DT system for organisational management, particularly within BM organisations. The codes generated focus on promoting DT both globally and within Nigerian BM organisations. The effective promotion of any innovation is essential to its implementation and utilisation (Gulewicz, 2022; Jeschke and Grassmann, 2021; Jiang *et al.*, 2021). On the global stage, ten respondents identified various possibilities, including awareness, collaboration, case studies, the willingness of top management, policy support, and training, all aimed at promoting a DT system in organisations. Moreover, effective awareness serves as a viable means to inform individuals about the benefits and potential of any innovation. For DT, which is still evolving, effective dissemination will help potential users understand its advantages over existing systems, such as BIM (Delgado and Oyedele, 2021; Deng *et al.*, 2021). Three respondents asserted that awareness is an effective way to promote the use of a DT system in organisations. A statement in support of their view is:

"I think organisations really need to understand better the benefits of using a digital twin, so there is a knowledge gap that currently exists at the organisational level, which often is very important when an institution decides to adopt the digital twin solution" – R9

These responses indicate that raising awareness of the possibilities offered by DT to potential users, including BM organisations, will significantly aid in its implementation. This finding suggests that ongoing awareness is vital for uncovering the prospects of DT, which could be facilitated through avenues such as workshops and seminars, among others, as highlighted in Section 3.9.1.1. Collaboration with existing users or those involved in its research is another avenue to promote the use of DT. Such collaboration is crucial for exchanging valuable insights on a DT system, particularly since it is still developing within the AEC industry. To achieve this objective, stakeholders from various sectors, including manufacturing, offshore, and aerospace, could work together with those in the AEC industry to explore the advantages of DT and share the knowledge gained with potential users (Gulewicz, 2022; Eromonsele, 2021; Errandonea *et al.*, 2020). Two respondents emphasised the need for stakeholder collaboration to implement a DT system effectively. A statement in support of their view is:

"A strong collaboration between the companies, industry, academia, and funding agencies to implement the technological systems. The expertise.. is really important, as they have the test, trial, and error progress to see the benefits or the potential impact of the digital twin" – R18

This response highlights the value of collaboration in promoting a DT system. This finding implies that multi-disciplinary partnerships should be formed among DT stakeholders to harness the valuable potential of DT. Furthermore, the outcomes of these collaborations could be conveyed through avenues such as case studies. Employing case studies can provide an informative approach to promoting DT, as the saying "seeing is believing" often leads individuals to embrace innovation more readily than through mere verbal communication. Case studies will offer a significant platform to advocate for the use of a DT system, and its potential can be readily assessed by its anticipated end users. Four respondents believed that case studies are an effective method for evaluating the usefulness of a DT system, which, in turn, leads to its implementation by potential users. The following statement substantiates their claim:

"Case studies and using a pilot project on an existing building that the employees are familiar with to further their understanding and promote interest in the technology" – R16

This response suggests that case studies can serve as a visible avenue for promoting a DT system, allowing potential users to better appreciate its benefits over other systems that support their activities. This finding indicates that conducting additional case studies to demonstrate a DT system's prospects to potential users, particularly BM managers, would be beneficial in their operations. Furthermore, adopting a market strategy is another effective means of promoting the implementation of DT. If individuals recognise the usefulness of DT, it becomes ingrained in their thinking, thereby increasing the likelihood of adoption. One respondent elaborated that promoting a DT system through its usefulness would facilitate its rapid implementation:

"I would recommend promoting the value of digital twins from, perhaps, by starting by not marketing it as a digital twin but as a technology that addresses an important need" – R4

These responses illustrate that potential users may be more interested in how a DT system can assist them with their operations while saving time and costs. This finding suggests that a DT system should be promoted in ways that highlight its value and practicality, particularly regarding its ability to tackle various issues, such as maintenance-related issues, rather than being viewed merely as technology. Conversely, while these discussed strategies for promoting DT focus on advocacy for awareness, additional strategies are necessary at the organisational level. One such strategy is the commitment of top management. For successful implementation, top management needs to be committed. This commitment includes securing funding, establishing policies, and providing personnel training. Three respondents believed that top management's acceptance of a DT system would facilitate its effective implementation and subsequent usage in organisations. The following statement supports their assertion:

"I think the organisational CEO needs to be a role model in promoting these initiatives. I think strong leadership is definitely important, and it should be a top-down approach" – R18

This response shows that top management in organisations must play a crucial role in seamlessly implementing a DT system. This finding indicates the necessity of comprehensive top management buy-in for a DT initiative, enabling lower-level staff to recognise the value and potential of DT in enhancing their work activities. Furthermore, appropriate policies need to be established to promote the implementation of a DT system within organisations (Aliyu *et al.*, 2021; Gerber *et al.*, 2019). Three respondents highlighted that enacting the right policies would facilitate the implementation of a DT system, as it allows organisations to adhere to legislation. The following statement supports their claim:

"I guess it needs to be a policy-based strategy. I think the central authorities really need to formalise this better and, perhaps, adopt some legal-based strategy to influence how digital twins can be adopted and promoted at the level of an organisation" – R9

This response reveals that organisations should comply with existing legislation governing their operations, suggesting that the government should enact and enforce laws to encourage organisations to explore innovative solutions. Additionally, such legislation or policies might include mandatory training and retraining of personnel by top management on innovative approaches, such as DT, to enhance their operations. Gulewicz (2022) found that training organisational staff can improve awareness and implementation of DT. Such training will enable the staff, who are the BM personnel in this study, to stay current and competitive in employing a DT system for managing their activities. Four respondents affirmed that training would assist personnel, especially those with limited technological skills, in understanding the benefits and operational efficiencies of a DT system. A statement to support their point is:

"It is also very important for the organisational management to train the operating staff to use the digital twin, to understand how the data transmission is conducted, and how the virtual models can be utilised to support decision making" – R18

This response indicates that training and retraining staff are essential for organisations aiming to enhance productivity and efficiency. This finding implies that organisational management should prioritise staff development, as employees are the backbone of the organisation. Essentially, the more knowledgeable staff members are, the more effective they will be in their roles. Based on these findings, it can be concluded that promoting DT usage at the organisational level may be challenging, but it is achievable. Potential avenues include awareness, collaboration, case studies, a willingness from top management, policy development, and training. Therefore, if organisations utilise these avenues, they will find it easier to implement DT to support their organisational activities.

Sub-theme V: Promoting a Digital Twin System for Organisational Management of Building Maintenance in Nigeria

This sub-theme explores avenues for promoting the implementation of a DT system within the context of BM organisational management in Nigeria. While the global promotion of DT has been discussed in the preceding section, it is imperative to understand the specific avenues for DT's promotion within Nigerian BM organisations, as unique challenges may influence its implementation. These avenues are derived from the respondents' responses and coded as sensitisation, collaborations, case studies, government policy, and training. Sensitisation will serve as a crucial avenue for raising awareness of innovation, enabling BM managers and organisations to recognise the potential benefits of DT for maintenance activities. Nine respondents indicated that sensitising BM managers and organisations about the benefits of DT would encourage them to consider its implementation. The following statement supports this point:

"Sensitisation on what digital twin is… and how it can better activities of the industry" – R11

Three respondents suggested that sensitisation could be conducted through various avenues, such as advocacy, to educate BM managers and organisations on the specific advantages of a DT system compared to other approaches for their maintenance activities. A supporting statement is:

"It can be promoted by making people see the advantages, making people understand that it helps in making maintenance and management jobs easy for the clients, the building users and then the managers too" – R19

Another three respondents noted that sensitisation regarding a DT system could be facilitated through professional bodies, which oversee the registration and operations of BM organisations. The following statement substantiates this perspective:

"When we introduce it to people, for them to have the knowledge and practice it outside and even professionally, it needs to go through the Nigerian Institute of Building. The professional bodies will introduce it, like BIM, which is very common now and used" – R2

This response indicates that raising awareness among BM organisations will help them understand why DT is beneficial for managing maintenance activities. Findings by Bello *et al.* (2024) recommended that strategic communication of DT's potential and benefits through professional bodies in the Nigerian construction industry will facilitate its implementation process. They further highlighted that such communication could occur through seminars, courses, and workshops, incentivising attendance by offering points for continuous professional development. This finding suggests that ongoing sensitisation will be a valuable avenue for promoting DT, as BM organisations will be well-informed about its advantages for future implementation.

Furthermore, effective collaboration will serve as an excellent avenue to uncover the unique potential of a DT system tailored for managing maintenance activities in the Nigerian context. One respondent emphasised that research collaborations with developed countries for the utilisation of DT systems will aid its promotion, as such collaborations will better adapt its implementation to suit end users in developing countries:

"With assistance from other developed countries, we can conduct the research together and get certain things done to give a better understanding of the digital twin method, and then, we will be able to promote it and not limited to Nigeria alone, but even to other countries.." – R2

Meanwhile, two respondents emphasised that case studies are crucial for promoting the implementation of a DT system, as they enable end users to assess the system's relevance to their existing maintenance management approaches. A supporting statement is:

"The first thing would be to make sure that it works, and when it works, then you will be able to convince others. It will take a while, but if they find out that it is successful on one project and if it is going to save them money, they are going to embrace it at some point" – R3

These responses reveal that collaboration and case studies are essential for promoting a DT system, as they will enhance the understanding of how DT functions, making it more applicable for maintenance activities. These findings indicate that increased collaborations with developed nations will facilitate the fine-tuning of a DT system suitable for implementation in Nigeria, which could be demonstrated through continuous case studies.

However, while these avenues can effectively promote DT, others exist, such as legislation. The enactment of appropriate legislation by the government to encourage organisations to innovate in their operations will further promote the implementation of DT for maintenance activities. One respondent expressed that establishing the right policies would assist in fostering DT implementation:

"Policies can be put in place actually to encourage people to use the digital twin" – R11

Findings by Arowoiya *et al.* (2024) highlighted that DT can be better promoted in Nigeria when the government domesticates its usage. Bello *et al.* (2024) confirmed that effective policies and guidelines would propel the implementation of DT in Nigeria. Furthermore, two other respondents underscored that suitable policies would lead to initiatives within BM organisations, such as staff training, to gain relevant knowledge on utilising DT. This statement substantiates their point:

"Training will translate to personal development in the use of the digital twin" – R1

This response underscores the necessity of staff training for the organisational implementation of a DT system, as it will equip staff with a comprehensive understanding of its operations. Furthermore, such training can occur incrementally by instructing staff who demonstrate interest or possess technical expertise in DT. These individuals will become project champions, change agents, or facilitators, who will subsequently train other personnel within the organisation, as highlighted in Section 3.9.1.1. This finding suggests that for DT to be effectively harnessed and utilised, continuous training is essential to keep BM personnel well-informed about the best ways to utilise it for their activities.

Moreover, training staff on technological innovations like DT can be more impactful when initiated within educational institutions. One respondent elaborated that DT training should commence at universities. This training will prepare students on the functionality and practicality of DT before they graduate and enter the industry:

"Definitely, we have to start from the classroom and teach students how to use it so that the implementation will be very easy when they go out. We can practicalise it in the classroom as we use it in our environment. We will be able to transform many buildings through that process and then arrive at something proactive and have good data on maintenance" – R2

Supporting this response, Bello *et al.* (2024) corroborated that the introduction of emerging technologies, such as DT, into the Nigerian educational curriculum would enhance its promotion. Based on these findings, DT implementation can be promoted through various channels at the organisational level. These channels include awareness initiatives, collaborations, case studies, the willingness of top management, policy development, and training. While these avenues establish a foundation for promoting DT in Nigeria, BM organisations need to be innovative and inquisitive to leverage them effectively. This ensures that the potential of DT is strategically and proactively harnessed for maintenance management, ultimately improving the longevity of buildings and assets.

6.5 Summary

The continuous occurrence of maintenance-related issues necessitates effective management, achievable through the appropriate available data and the utilisation of technologies and systems such as DT. However, the successful implementation of DT for BM organisations requires careful consideration to meet its requirements and operational dynamics. Therefore, in-depth interviews were conducted to understand DT's operational dynamics, applicability, requirements, and potential avenues for its promotion in BM organisational management. Analysis of the interview dataset revealed that the development of DT comprises several components, with its core concept being the digital representation of a physical asset with data communication between them. These components include data-capturing devices, transmission devices, model development platforms, data integration mediums, data analysis tools, and implementation devices. The data types used for DT operations encompass static, dynamic, and system data of a physical asset, emphasising the pivotal role of data and its continuous availability in enabling the seamless functioning of a DT system.

The findings on the applicability of DT for BM management indicate its potential to manage certain maintenance issues related to physical asset data. DT leverages data to assess an asset's current status, optimise its performance, and predict its future conditions. With this potential, BM organisations can adopt a strategic approach in their maintenance activities and make informed decisions, thereby enhancing the asset's longevity. However, the utilisation of DT for maintenance activities is hindered by certain barriers, including issues related to data quality and technological infrastructure. Findings suggest that data quality issues can be mitigated by deploying appropriate technologies for data collection, which is then screened for the removal of uncertainties. Furthermore, the implementation of blockchain technology is recommended to enhance the security of data sharing. In essence, these findings underscore the necessity for BM organisations to undertake proactive measures to fully harness the potential of DT for effective maintenance management.

In terms of organisational requirements for DT implementation, findings reveal that the PPT dimensions of BM organisations are crucial. Hence, achieving a harmonious balance among these dimensions is essential for a successful DT implementation. Despite their importance, challenges related to inadequate infrastructure, technological resistance, compatibility issues, and building types pose challenges that BM organisations have to overcome to achieve a seamless DT implementation. Findings also suggest that addressing these challenges, particularly for BM organisations in Nigeria, necessitates comprehensive support mechanisms, such as funding, training, and technological assistance. Therefore, tackling these challenges will facilitate the anticipated seamless implementation of DT for organisational BM management.

While these findings have outlined some of the technological tools and devices necessary for DT implementation and the requirement for adequate human resources for its utilisation, there remains a need for an implementation process specifically for its application in maintenance activities. Consequently, a framework will be developed in the following chapter using the harmonised process mapping of the NBC and GDCPP, as discussed in Section 3.9.2.4.

Chapter Seven – Development and Evaluation of a Digital Twin Framework for Building Maintenance Management

7.0 Introduction

This section presents the development of a framework for implementing DT for organisational BM management through process mapping. As discussed in Section 3.9.2.4, Nigeria's NBC guidelines and the GDCPP were harmonised, with inferences drawn regarding their meeting point to develop the framework for this study (Table 3.7). While the methodology of the study was tailored to fulfil its objectives rather than specifically to understand how respondents utilise process mapping, an iterative approach was applied to draw inferences from the thematic analysis of qualitative data. The framework is structured into four primary phases at the top to highlight the various process layers and nine activities along the left side to emphasise the activity zone. Additionally, the top phases are subdivided into nine sub-phases and operationalised based on literature, utilising the core principles of the GDCPP, which are detailed in Table 7.1. On the left side, the core principles of the GDCPP are similarly applied and elaborated upon utilising the 5 W's ("When? Where? Who? What? Why?") guideline (Parton *et al.*, 2009). Consequently, the headings are designed to label the rows and are presented in Table 7.2. Figure 7.1 provides excerpts of these foundational components (process layers and activity zones), illustrating the processes involved in the development of the framework.

Table 7.1: Operationalisation of the Main Phases and Sub-Phases of the Generic Design and Construction Process Protocol for Building Maintenance Management

Phase	Sub-Phase	Phase themes
Data Acquisition Layer	0	Demonstrate the need for the maintenance of a particular building asset.
	1	Conceptualise the need for the maintenance of the building asset.
	2	Conduct a feasibility study and outline the maintenance activities.
	3	Identify the required data for conducting maintenance activities and financial approvals.
Transmission Layer & Digital Modelling Layer	4	Design a method for the transmission of acquired data.
	5	Develop a virtual model of the physical item.
	6	Clean and structure the transmitted data and check the accuracy or fidelity of the virtual model for seamless integration.
Data/Model Integration Layer	7	Integrate the virtual model with the screened data.
	8	Simulate the integrated virtual model.
Service Layer	9	Use the simulated result for maintenance activities through human intervention.

Table 7.2: Operationalisation of the Generic Design and Construction Process Protocol Activity Zone Using the 5 W's Guideline

W's		**Activity Zone**
When was the task done?	Time	Description of sub-phase
		Key Questions
Who did the task?	Person	Stakeholders
What aids or instruments were used for the task?	Actions/processes	Action needed at each sub-phase
	Tools	Tools to assist with the phase
Where was the task done?	Place	Task location
Why was the task done?	Reason	Outcome of sub-phase
		Decision of the sub-phase

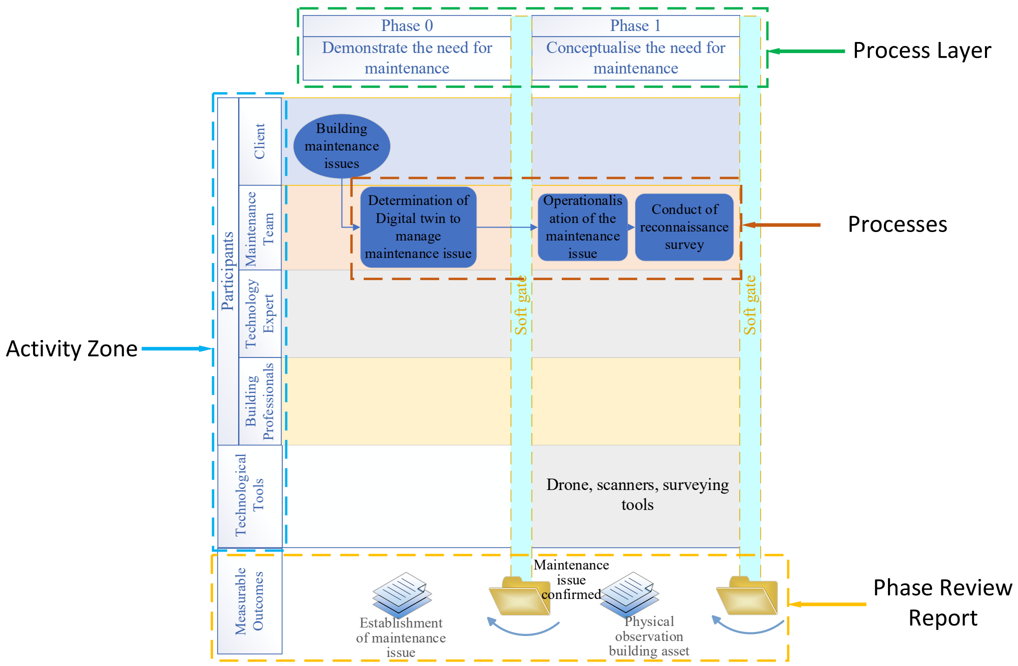


Figure 7.1: An Excerpt of the Underpinning Components of the Developed Framework

7.1 Process Framework Development

The framework is developed through an iterative process by mapping the findings of thematic analysis onto the various process layers and activity zones. Moreover, some respondents' responses substantiate the operationalised sub-phases; their quotes are provided in Appendix 4. The essence of these quotes is to validate the underlying reasons for the different sub-phases of operationalisation in relation to the DT development process. Thus, the sub-phases begin with establishing the maintenance issue and assessing its suitability for management with DT, continuing through to the final utilisation of the analysed data outcomes. These processes and activities are detailed in the subsequent sections.

7.1.1 Sub-Phase 0: Demonstration of Maintenance Need

This section outlines the necessity of utilising DT for BM management. As Kagioglou *et al.* (1998) highlighted, it is important to demonstrate whether an intervention approach is appropriate for addressing or managing any identified issue. Such a demonstration is essential because not all maintenance-related issues can be managed using DT. Studies emphasise that DT can be employed to manage maintenance-related issues interconnected with data (Lu *et al.*, 2020a; Peng *et al.*, 2020; Antonino *et al.*, 2019; Lu *et al.*, 2019; Stojanovic *et al.*, 2018). Moreover, findings from the qualitative analysis confirm that the maintenance issue needs to be identified to ascertain the suitability of DT for its management before development can commence (Section 6.4.3; Sub-theme I). Essentially, the issue needs to have previous histories of maintenance activities and the potential to acquire dynamic data for its management using DT.

To achieve this phase, BM stakeholders need to answer certain questions. These questions, along with other procedures, are outlined in Appendix 5. The building owner and the maintenance team have to evaluate the maintenance issue to answer these questions. The results of this evaluation will dictate the next phase of DT development. Therefore, confirmation of the usability of DT for a maintenance issue is essential for the development process to progress to the subsequent phase.

7.1.2 Sub-Phase 1: Conceptualisation of Maintenance Needs

This section discusses the conceptualisation of the need for maintenance. Following the determination that a maintenance issue can be managed with DT, it is crucial to understand the issue. Kagioglou *et al.* (1998) highlight that conceptualising an issue is a vital step towards addressing it. Such conceptualisation is fundamental, as it requires analysing the various components of the maintenance issue to identify the most suitable management approach. Findings from the qualitative analysis confirm that the maintenance issue should be broken down (Section 6.4.1; Sub-theme III).

Consequently, the conceptualisation of maintenance needs involves considering the issue at hand. The maintenance team is responsible for this, as they possess the necessary understanding to break down the issues into manageable parts. A field survey should be conducted to gather physical observations of the building and assets requiring maintenance (Emoh and Ndulue, 2021; Osuagwu *et al.*, 2021b; Chidi *et al.*, 2017). This survey includes conducting a reconnaissance assessment to ascertain the cause and severity of issues, along with other activities outlined in Appendix 5. Instruments such as drones, scanners, and surveying tools are employed to carry out this task. These tools assist the on-site maintenance team in accurately analysing the issue and collecting all relevant data for effective management. Therefore, if adequate data is collected, maintenance activities will progress to the next phase.

7.1.3 Sub-Phase 2: Conduct of Feasibility Study on Preliminary Maintenance Activities

This section outlines the feasibility of carrying out maintenance activities on the building and its assets. After clarifying the conceptualisation of maintenance needs, it is vital to delineate the preliminary maintenance activities and conduct a feasibility study on the building. Such a feasibility study examines the activities to be undertaken and identifies opportunities to incorporate DT. Findings from the qualitative analysis revealed that certain preliminary activities have to be carried out before the actual maintenance activities (Section 6.4.1; Sub-theme III). Hence, the maintenance team and technical expert outline preliminary maintenance activities based on the analysis of findings from the conducted field survey. These actions include identifying the various maintenance activities to be performed and evaluating the feasibility of employing DT, as presented in Appendix 5. The ultimate aim of these activities is to determine if the collected field data is sufficient and appropriate for the maintenance tasks to be executed. Therefore, if the data is adequate, the maintenance activities will proceed to the next phase.

7.1.4 Sub-Phase 3: Identification of Required Maintenance Data and Approvals

This section discusses the necessary maintenance documents and approvals for maintenance activities. Kagioglou *et al.* (1998) highlight that certain documents are crucial for carrying out any activities and obtaining approvals, including the financial requirements that need to be granted for seamless execution. When carrying out a maintenance activity, specific documents, such as maintenance manuals and as-built drawings, are essential alongside the actual field data collected from the building or asset (Section 6.4.1; Sub-theme II). The stakeholders involved in this phase include the client, building professionals, and the maintenance team. Therefore, these stakeholders have to take specific actions. The maintenance team is responsible for identifying all necessary data and assessing its suitability for executing the maintenance activities.

Moreover, findings from the qualitative analysis confirm that clients are responsible for providing documents, such as as-built drawings and maintenance manuals, which are developed and updated by a consortium of professionals (Section 6.4.1; Sub-theme II). Contract documents, like financial autonomy, must be agreed upon and signed off by both the maintenance team and the client. These documents, along with data from the field survey and dynamic data, are used to create a robust data pool or ecosystem. Meanwhile, devices such as drones, sensors, and thermal cameras, among others, assist in collecting this data. These activities are vital for acquiring the appropriate data sets. Thus, the main objective of this phase, which serves as a hard gate and the concluding phase of the physical layer, is to collect all relevant data concerning the maintenance issue and develop an effective DT system. The process for this phase activity is detailed in Appendix 5.

7.1.5 Sub-Phase 4: Transmission of Acquired Maintenance Data

This section outlines various methods for transmitting acquired maintenance data related to buildings and assets. This phase represents the connection layer between the physical and digital layers of the DT system. After all relevant maintenance data has been established and verified for usefulness, it is essential to transmit it to the digital layer of the DT system. Consequently, the technical expert and maintenance team will devise a suitable method for transmitting all relevant data. Certain parameters influence the development of the transmission method, including the data type and documents for transmission. Technological mediums such as fibre optics, Wi-Fi, and 5G, among others, can facilitate data transmission. The transmitted data can be stored in databases such as Microsoft Azure, Google Cloud, and Microsoft SQL, among others. The essence of this phase is to ensure that an appropriate method for data transmission and storage is developed to transfer acquired data, including historical and dynamic data, to the digital layer of the DT system. Thus, if all acquired data is effectively transmitted and stored, the development process can advance to the next phase. This phase activity is presented in Appendix 5.

7.1.6 Sub-Phase 5: Development of a Virtual Model for the Physical Asset

This section discusses the development of a virtual model of the physical building and its assets. This phase marks the commencement of the digital layer of the DT system. Therefore, all virtual models of the physical building and its assets must be developed with precision for usability. The stakeholders responsible for this task are the technical expert and the maintenance team, as they are the personnel involved in using the DT system for scenario analysis. Consequently, their contributions to developing an accurate virtual model replica of the physical asset will facilitate the subsequent integration of the acquired data.

Meanwhile, the virtual development process of the asset is influenced by certain actions, such as determining any existing 3D virtual model and identifying a suitable modelling technique for developing a 3D model in its absence. Findings from the qualitative analysis highlight various avenues for developing a virtual model, including 3D and numerical simulation modelling (Section 6.4.2; Sub-theme II). The quality and accuracy of the developed virtual model are critical to the usability of the DT system, as the model must accurately replicate the physical asset. Thus, if the virtual model is successfully achieved, the DT development process can then progress to the next phase. This phase activity is presented in Appendix 5.

7.1.7 Sub-Phase 6: Data Screening and Filtering

This phase emphasises the need to clean and structure the transmitted data while cross-checking the accuracy or fidelity of the virtual model. Findings from the qualitative analysis indicate that data is sometimes duplicated during acquisition, necessitating cleaning to ensure it does not compromise the accuracy of the final analysis result (Section 6.4.2; Sub-theme VI). The technical expert oversees this activity, as it involves computational data and model cleaning or ratification. Technologies such as AI and analytical models assist in executing this task. The ultimate goal of this phase, which serves as another hard gate, is to eliminate all unnecessary data and 3D model components that are not useful for analysis. This phase activity is presented in Appendix 5.

7.1.8 Sub-Phase 7: Integration of the Virtual Model with Screened Data

This section discusses the integration of the virtual model with the screened data. Data integration is crucial for developing a DT system, as both historical and dynamic data have to be integrated with the virtual replica of the physical building and asset. Consequently, the technical expert is the stakeholder responsible for effectively executing this task, as such personnel possess the requisite knowledge for data computation. Findings from the qualitative analysis revealed several methods for integrating the virtual model with the screened data (Section 6.4.1; Sub-theme IV). These include API, analytical model, and ontology, which encompasses IFC, Bricks, and COBie, among others. Therefore, if the activities in this phase are executed efficiently, the DT development process can continue to the next phase, with the process activity presented in Appendix 5

7.1.9 Sub-Phase 8: Analysis of the Integrated Data Model

This section presents the analysis of the integrated data model. This phase is regarded as the processing unit of a DT system, as all data analyses and various simulation activities related to maintenance issues are conducted here. These activities include performance, diagnostics, optimisation, and prognostic analyses (Section 6.4.3; Sub-theme I). The essence of these analyses is to adequately uncover the cause of the underlying maintenance issue and predict any potential reoccurrence. Hence, the technical expert is the stakeholder responsible for this task, which can be achieved through AI and ML.

Moreover, the findings from the qualitative analysis revealed that programming languages such as Python, Java, R, Julia, and Ruby on Rails can be utilised to develop scenario models for accomplishing this task (Section 6.4.2; Sub-theme II). The main goal of this phase, which serves as a critical gate, is to ensure that the maintenance issue is synthesised accurately using all available data and feasible solutions to manage the underlying issue. The process activities are presented in Appendix 5. Therefore, if the phase activities are fully executed, the DT development process advances to the next phase; if not, the process reverts to the previous phase or is repeated.

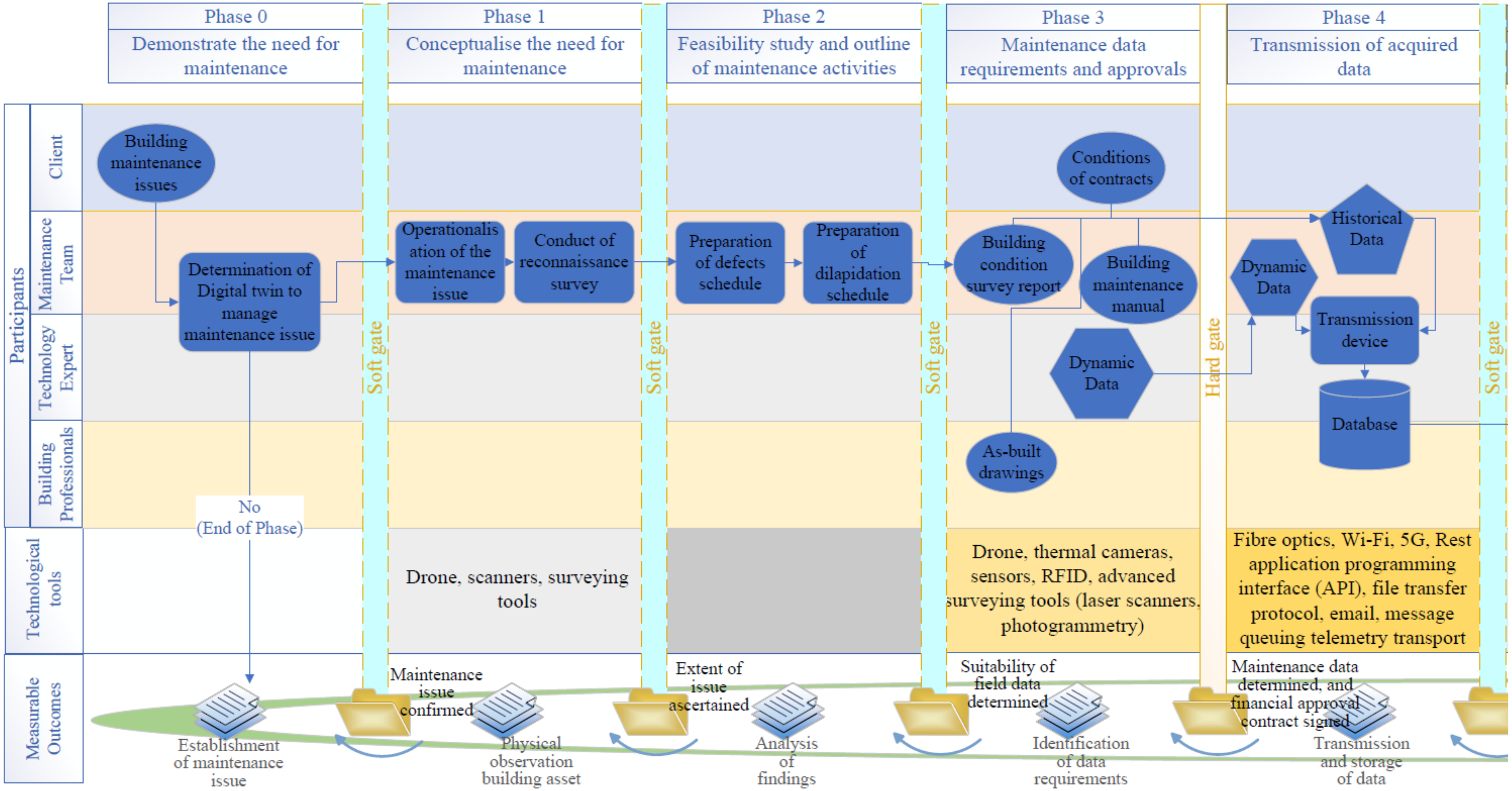
7.1.10 Sub-Phase 9: Action of Analysed Data Model for Maintenance Activities

This section discusses the execution of results derived from the data model analysis for maintenance activities. After the data model is analysed and the outcomes verified, it is essential to act on these outcomes to manage the underlying maintenance issue. Although DT involves bi-directional data flow between the physical asset and its virtual counterpart, the maintenance team is accountable for interfacing the physical asset with the analysed outcomes from its virtual replica in the context of maintenance activities. As Al-Sehrawy and Kumar (2021) highlight, there are two types of DT regarding the actioning of analysed outcomes: active and passive DT (Section 3.2). In this context, the passive DT approach is employed. Consequently, the stakeholders involved in these activities are the technical expert and the maintenance team. The technical expert provides an explanation of the outcomes and any additional information to the maintenance team for their seamless management of maintenance activities.

Moreover, the qualitative analysis revealed that AR and VR can assist the maintenance team's activities (Section 6.4.3; Sub-theme II). These technological devices enable the maintenance team to interact more effectively with the physical building and assets. The process activities are detailed in Appendix 5. Thus, this marks the final phase of the DT development process, closing the development loop back to the maintenance issue by acting on the analysed outcome for its appropriate management.

From the developmental discussion so far, the various process phases and the activity zones discussed represent a stepwise approach to utilising DT for the management of maintenance-related issues. If BM organisations diligently adhere to these steps in their maintenance activities, they can effectively plan their operations and identify the necessary human resources and technological tools or devices for execution. This will enhance the planning and management of maintenance activities for BM organisations.

In summary, it is apparent that implementing DT for BM organisational management necessitates an interconnection among the organisation's human resources, processes, and technological infrastructure. Such an interconnection is underpinned by the understanding that for an organisation to adopt any technological innovation, a balance among its people, processes, and technology dimensions is essential. Based on empirical findings and literature highlighting the absence of a framework for organisational DT implementation, particularly for maintenance activities, Figure 7.2 presents the proposed developed framework, which is an excerpt from Appendix 5. It outlines the process activities and identifies participants responsible for executing maintenance tasks with the aid of enabling technological tools or devices, along with measurable outcomes for each phase. This is based on the premise that DT is deeply rooted in data, specifically concerning maintenance issues that can be managed based on historical and dynamic data. Therefore, it is crucial to determine whether DT can be employed to manage a maintenance issue before proceeding with other processes that lead to its application. Consequently, this framework will serve as a process path to facilitate the utilisation of DT for maintenance activities by BM organisations and will be evaluated through focus group discussions with experts in DT and BM.


Phase 0
Demonstrate the need for maintenance
Phase 1
Conceptualise the need for maintenance
Phase 2
Feasibility study and outline of maintenance activities
Phase 3
Maintenance data requirements and approvals
Phase 4
Transmission of acquired data
Participants
Client
Maintenance Team
Technology Expert
Building Professionals
Technological tools
Measurable Outcomes
Building maintenance issues
Determination of Digital twin to manage maintenance issue
No (End of Phase)
Operationalisation of the maintenance issue
Conduct of reconnaissance survey
Preparation of defects schedule
Preparation of dilapidation schedule
Conditions of contracts
Building condition survey report
Building maintenance manual
Dynamic Data
As-built drawings
Historical Data
Dynamic Data
Transmission device
Database
Soft gate
Soft gate
Soft gate
Hard gate
Soft gate
Drone, scanners, surveying tools
Drone, thermal cameras, sensors, RFID, advanced surveying tools (laser scanners, photogrammetry)
Fibre optics, Wi-Fi, 5G, Rest application programming interface (API), file transfer protocol, email, message queuing telemetry transport
Maintenance issue confirmed
Extent of issue ascertained
Suitability of field data determined
Maintenance data determined, and financial approval contract signed
Establishment of maintenance issue
Physical observation building asset
Analysis of findings
Identification of data requirements
Transmission and storage of data

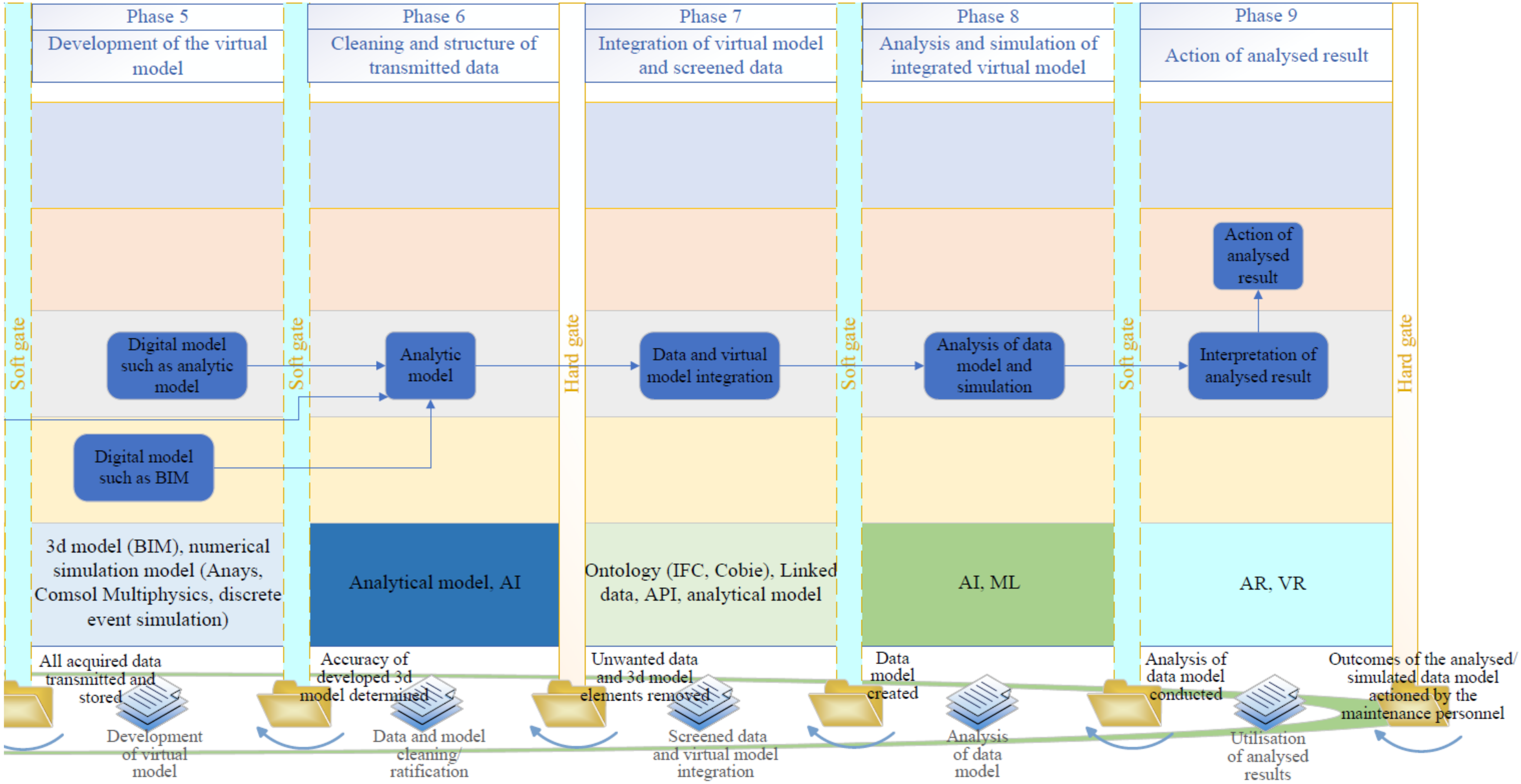


Figure 7.2: The Study's Proposed Developed Framework

7.2 Evaluation of the Framework

This section discusses the evaluation process of the study's developed framework. As mentioned previously in Section 4.7, research validity is essential for ascertaining the accuracy of data collection and analysis instruments in achieving the generalisation of findings (Babbie, 2007). Validity can be assessed through internal or external validity, which includes validation and evaluation (Saunders *et al.*, 2019; Kumar, 2011). Section 4.6.5 justifies the choice to use formative evaluation in assessing the developed framework, which involves experts' opinions regarding its applicability. Therefore, the evaluation process is elaborated in the subsequent section.

7.2.1 Formative Evaluation Process

The evaluation process outlines the procedure followed to evaluate the proposed framework. Following the development of the proposed framework in Section 7.1 using an iterative approach, it is necessary to evaluate its applicability to produce the final version. For this reason, a focus group discussion was conducted to accomplish this task, and expert opinions were solicited on the developed framework. The focus group setup, design, and participant selection techniques employed are discussed in Section 4.6.5. The use of a focus group for framework evaluation, particularly in the built environment, was supported by Domingos *et al.* (2024), Cotgrave and Wilson (2020), and Talebi *et al.* (2020). It is proven effective for eliciting expert opinions on evolving innovations, as it allows for comprehensive discussions that lead to an informative and acceptable conclusion that may complement or contradict the framework under review (Adu and Miles, 2024; Patton, 2015). Its advantages include diverse perspectives, in-depth exploration, interactive discussions, identification of inconsistencies, and enhanced trustworthiness from participants during the evaluation process.

Meanwhile, the parameters that constitute a focus group are a topic of debate in the literature. According to Domingos *et al.* (2024), the quotum of a focus group typically ranges from three to twelve participants. A study by Cotgrave and Wilson (2020) employed two focus group discussion sessions to evaluate their study's developed framework. One session included two participants, while the other had ten participants. Although the study highlighted the limited number of two participants in the focus group, their contributions provided valuable insights for refining the developed framework. The study then emphasised that a focus group of two participants could still make meaningful contributions to a study. Similarly, Talebi *et al.* (2020) also conducted two focus group discussion sessions to evaluate their study's developed framework, with one group session comprising six participants and the other four. Domingos *et al.* (2024) affirmed that six expert participants were more than sufficient for evaluating a framework.

Based on these studies, using six expert participants was appropriate for this study's framework evaluation. The six expert participants possessed substantial knowledge of DT and/or maintenance management, and they had not been involved prior to the evaluation stage of this research. Choosing a new set of participants was intended to elicit diverse perspectives, thereby ensuring the research process remains rigorous.

7.2.2 Focus Group Evaluation Procedure

The essence of the focus group session is to provide sufficient feedback on the applicability of the developed framework from an industry perspective. This feedback contributed to updating the final version of the developed framework. Consequently, selected participants were asked to confirm their availability, and consent forms, as well as the proposed framework and relevant questions, were sent to them to facilitate this task. After confirming the participants' availability, an online session was held. A study by Domingos et al. (2024)

also utilised an online session for their study's framework through a focus group approach, which justifies this study's choice. The session began with an explanation of the study's rationale and a description of the proposed framework to enlighten the participants, as none had been previously involved in the research process. Following the description of the framework, the discussion allowed participants to respond to questions regarding it. The essence of the sessions was to elicit participants' opinions, which complemented or contradicted the proposed framework, assisting with the iteration of the final version.

7.2.3 Profile of the Focus Group Experts

The demographics of the expert participants were analysed based on their job details and years of experience in their respective industries. As discussed in Section 6.3, highlighting the need to replace "expert" with "enthusiast" for clarity in terms of competencies, the results in Table 7.3 show that one of the participants, who works full-time in academia and part-time in industry, was knowledgeable in DT and maintenance management. The other participants were all employed full-time in the industry. One was an enthusiast in DT and facility management; two were enthusiasts in facility management, and another two were in BM management.

Table 7.3: Profile of Evaluation Participants

Participant	Participant Categories	Job Details	Years of Experience
P1	DT Enthusiast	Academics/Maintenance Management	15
P2	DT Enthusiast	Facility Management	6
P3	BM Enthusiast	Facility Management	9
P4	BM Enthusiast	Facility Management	11
P5	BM Enthusiast	Building Maintenance Management	10
P6	BM Enthusiast	Building Maintenance Management	14

7.2.4 Analysis of Focus Group Discussion

The collected data was qualitative and subsequently analysed in accordance with Section 4.6.4.6. NVivo software, known for its robust coding system, was employed to analyse the dataset. It facilitated an in-depth analysis of the focus group transcripts by organising them into a hierarchical coding structure. The additional recommendations for the refined framework are highlighted in green (Figure 7.4).

7.2.5 Evaluation Findings and Discussion

The overall findings of the focus group session are positive. From the analysis of the discussion, three themes emerged (Figure 7.3). Most participants affirmed that the framework was implementable and provided feedback along with recommendations for its improvement. Notably, all participants have over five years of experience in their respective disciplines (Table 7.3). This result suggests that the participants possess well-informed knowledge of DT and maintenance management, and their comments regarding the framework evaluation are substantial. Consequently, the findings from the focus group session are discussed below.

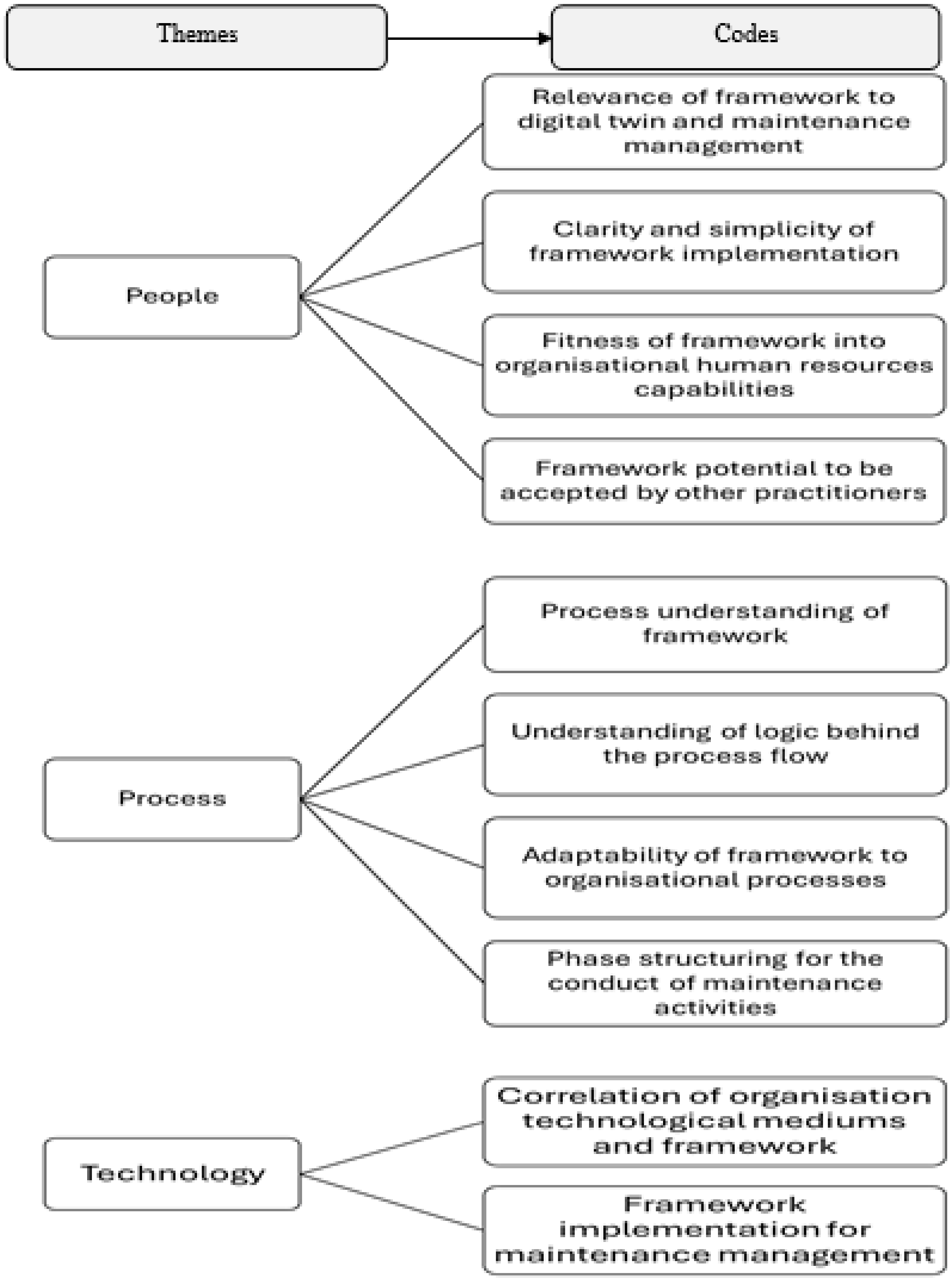


Figure 7.3: Focus Group Themes and Codes

Theme 1: People

The participants' feedback shows that the framework acknowledges the stakeholders involved in maintenance activities. When asked about the framework's relevance to DT and its usefulness for maintenance management, all participants confirmed that it was useful. Statements to substantiate their views are:

"Yes, the framework is important for maintenance management because it is predictive in nature and would help anticipate possible failure or need for maintenance" – P3

"I feel it is definitely useful because it offers an opportunity for preventive maintenance to be done using real-time data" – P6

The participants' views centred on the fact that the framework provides building organisations with better access to data. As a result, they can plan more effectively and adopt a more strategic approach to maintaining buildings and assets. With respect to the clarity and simplicity of the framework, five participants agreed that it was satisfactory. The following statements confirm their opinions:

"Yes, it is simple and clear enough for implementation" – P3

"The model will work. You just got to make sure the user manual is very straightforward" P2

However, one participant opposed the views of others. The participant's idea hinged on the data source:

"No, I believe this is not a simple approach. The authoritative source for the data has not been tapped to provide input at the point of creation of the data" – P1

While not all participants entirely agreed on the framework's clarity, most found it easy to implement. This finding suggests that the framework has potential for improvement. Furthermore, the participants were asked to evaluate their organisations' current human resources to determine if they are equipped to navigate the framework activities for maintenance. All participants acknowledged that the framework would suit their human resources but highlighted the necessity of upgrading or hiring more staff. Statements to support their comments are presented below:

"Well, it will definitely fit, but the challenge is getting people with adequately skilled" – P6

"With additional training of personnel, it fits into my organisation's human resources capabilities" – P3

Meanwhile, one participant elaborated that the complexity of maintenance being managed would necessitate hiring additional staff:

"I see no real issues with HR. However, it would be far better to understand the HR and FTE requirements for the asset prior to it being designed and constructed. Does it alight with the resources on hand or will additional resources and skills be required" – P1

These comments imply that the framework will not impose an additional burden on BM organisations. Moreover, it would aid in strengthening the human resources of BM organisations concerning the technicalities of managing complex maintenance-related issues using technology. While these comments were positive, the participants were asked if the framework has the potential to be embraced by other practitioners. All participants indicated that a broader audience might adopt the framework. The following statements reinforce their comments:

"Yes, it has the potential to be accepted, howbeit with some sensitisation" – P4

"Yes, with specific resources to set it up" - P2

These comments illustrate that the framework met the participants' expectations from the perspective of the people dimension of its implementation. While the framework appears positive based on participants' evaluations, recommendations were made for its effective use in maintenance management. Some of these recommendations included training and raising awareness among BM organisations regarding the usefulness of DT in fully utilising the framework.

Theme 2: Process

The feedback from the participants revealed that the framework took into account the organisational process dimension of maintenance management. Some questions were asked regarding the participants' understanding of the framework's process flow. All participants affirmed their comprehension, and supporting statements include:

"Yes, I understand" – P5

"Yes, I understand the workings of the developed framework based on your explanations" P4

Meanwhile, one participant expressed the opinion that maintenance management begins at the design phase:

"I do. However, I believe that going forward, we should not assume that maintenance begins at handover, but with design"- P1

This view was based on the observation that some maintenance-related issues can be traced to the neglect of building and asset maintainability during the design stage. Architects who design maintenance-prone buildings often create additional issues during their usage. To address this issue, maintenance professionals should be consulted during the design stage of a building project (Hauashdh *et al.*, 2020; Chidi *et al.*, 2017). Furthermore, the participants were asked about their understanding of the underlying logic behind the framework's process flow. All participants confirmed their comprehension of the rationale for the framework's process formation. The following statements reflect their understanding:

"Yes, the logic is suitable" – P4

"Yes, the framework is logical and achievable" – P3

These comments indicate that the participants understood the framework flow well. Consequently, they were asked about the adaptability of the framework to their current organisational processes. Five participants confirmed that the framework processes could be integrated into their existing practices, although some minor adjustments would be required. Statements in support of their comments are:

"Yes, it is applicable to our organisation process. Training will be needed though" – P4

"It is something that can fit into the process we have currently" - P5

These comments suggest that the framework is adaptable for organisations willing to implement it, but they need to meet specific requirements for smooth implementation. Additionally, the participants were asked about the phase structuring for maintenance activities. All agreed that the framework's phase structuring aligned with the conduct of maintenance. The following statements support their responses:

"Yes, the techniques are applicable" – P4

"Yes. The tools identified can be employed to support maintenance activities. But much of that data has already been collected, and this assumes significant duplicative effort" – P1

Meanwhile, one participant (P1) was of the view that phases 2, 3, and 4 were duplications of already existing data. While this view is valid in certain instances where an asset's data model exists, it is essential for the data model to be updated, particularly in the case of BIM data, where changes in building usage may render the existing model outdated. This comment serves as a recommendation for the framework and is discussed further in Section 7.2.6. With these advancements, BM organisations will be equipped with the appropriate data set to plan their maintenance activities effectively.

Theme 3: Technology

The feedback from the participants indicates that the technological tools and devices proposed in the framework were useful for maintenance management. Some questions were asked, such as whether the participants' organisations utilise or possess most of the technological mediums highlighted in the framework. All participants confirmed their use of technological tools and devices but expressed divergent views on the extent of their usage. The following statements expand on their comments:

"In my country, we are late adopters of technologies for our processes, but well, I will try to see how this can be used to enhance our operations" – P4

"I think it is going to depend on who the client is. If it is for a more sophisticated owner, we probably may have some of these capabilities" – P1

From the above comments, it can be inferred that the technological devices and tools highlighted in the framework are viable for BM organisations to conduct maintenance activities. The usage of these technological devices and tools depends upon the scope and strategies of the maintenance activities to be carried out by BM organisations. Moreover, the participants were asked whether the framework was implementable and comprehensive for maintenance management. All participants agreed that the framework is implementable. The following statements support their comments:

“Yes, it is implementable” – P4

“Yes, as an aspirational goal…… I would expect it to be implementable” – P1

These comments suggest that the framework is implementable for maintenance management from a technological perspective. Although some participants indicated that the adoption of technological devices and tools depends on the scope of the maintenance activities, utilising these devices is essential for effective and strategic maintenance management, such as condition-based or predictive strategies. In essence, BM organisations should make more efforts to use basic technological devices for their maintenance activities.

Overall, the participants’ expert opinions illustrate that the framework is both useful and implementable. Moreover, the literature reveals that the three PPT dimensions are crucial to the organisational implementation of innovation, such as DT (Tripathi *et al.*, 2023a; Papic and Cerovsek, 2019). While this is the case, the participants' comments underscore the need to place greater emphasis on people, particularly the process dimension, in the organisational implementation of DT. For this reason, BM organisations have to establish robust processes from data acquisition, as data is pivotal to the operations of DT, to the point of actioning outcomes when managing maintenance-related issues. Data acquisition can be achieved by collecting new maintenance data or utilising an existing data model, which may exist in COBie or IFC. Additionally, updating the existing data model is vital, as information on buildings and assets can become obsolete due to changes in their usage without a corresponding update. Thus, BM organisations have to ensure the accuracy of their datasets, whether new or existing, from the developmental phase to the point of action for maintenance management.

The people dimension is another essential aspect of the PPT, as competent and qualified personnel are needed to execute the processes. The participants acknowledged that although organisations like theirs may not immediately possess the requisite human resources for the framework implementation, they can enhance staff capabilities and employ various promotional approaches. Such promotional approaches to DT implementation, including training, are highlighted in Section 6.4.4. If organisations can overcome the challenges posed by insufficient human resources through the mentioned promotional strategies, the implementation of DT using the framework will be seamless. Consequently, if BM organisations can effectively address both process and human resource challenges, they will find it easier to utilise any of the technological devices and tools highlighted in the framework for maintenance management. In conclusion, while the participants provided positive feedback on the framework, they also offered recommendations for its improvement.

7.2.6 Recommendations and Refinement of the Framework

The participants recommended adding or modifying certain aspects of the framework processes. These recommendations are discussed below.

1. It was recommended that data validations be conducted where data models exist. P1 proposed re-ordering the phases to accommodate the existing data models. This recommendation pertains to scenarios involving data models, where documents such as Cobie were prepared before the handover of buildings and assets for effective maintenance management. Based on this scenario, the implementation of this study’s framework may

resemble a duplication of already existing data. However, in some instances, the existing data model is outdated and requires updates or validation of the actual status of the buildings and assets. To achieve this recommendation, P4 proposed a connection between Phases 3, 4 and 6, 7. With this suggestion, the framework is improved by retaining its structure while accommodating existing data models for validation.

"To me, it appears that a lot of effort is applied prior to the data gathering and that the data should inform the process going forward. Information about routine maintenance, preventive maintenance, spare parts, and other business processes depends on the specifics of what is delivered. I would order Phase 5, Phase 6, and Phase 7, then validate the data using Phase 3 and 4" – P1

"I think what you can do is maybe link Phases 6 and 7 together. Maybe the arrows should return back to phases 3 and 4, then before it goes to Phase 5" – P6

2. Another recommendation was for the addition of a new phase to accommodate more process activities. P1 recommended Phase 10 for the continuous updating of the DT framework, as maintenance activities are continuous:

"There probably also needs to be a Phase 10 due to work orders. You cannot close a work order until you have updated your digital twin because you will not be able to keep the digital twin up to date. Work orders are happening all the time, and that will make changes to the digital twin" – P1

This suggested recommendation is crucial for the framework, as it will help prevent the obsolescence of the DT framework. Therefore, the framework must undergo continuous data updates. To achieve this, data needs to be refreshed through different starting points at any phase requiring an update. Although this will ensure the framework remains up to date, the proposed Phase 10 activity must have access to other phases. For this reason, the recommended Phase 10 will have access to other phases through a continuous influx of required data at each phase. This recommendation has been incorporated into the revised version of the framework (Figure 7.4).

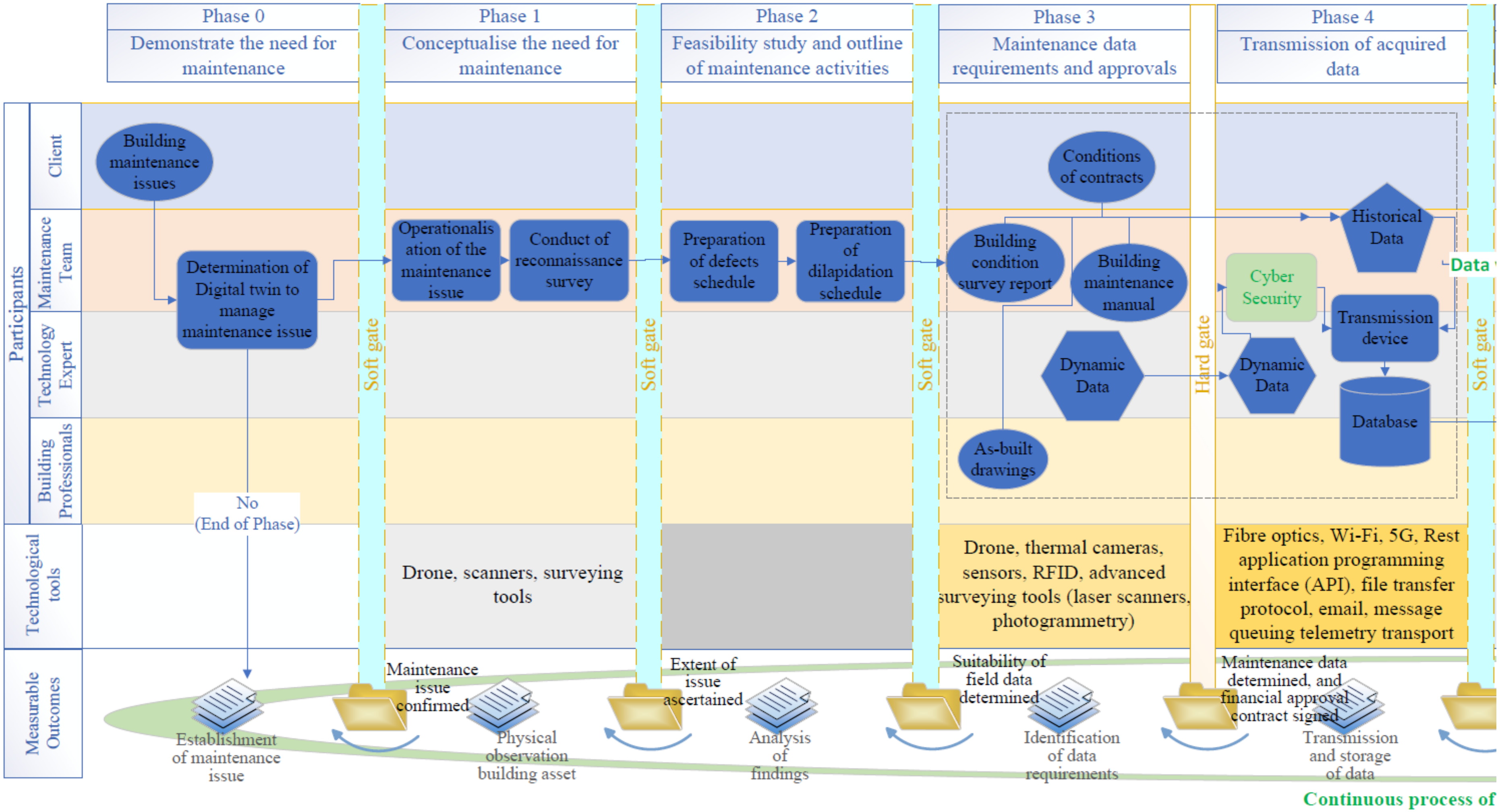
3. Data privacy and security issues were discussed to improve the framework. P2 raised concerns regarding data privacy from sensors and cameras, as well as AI utilisation for analysing the collected data. P1 suggested implementing cybersecurity measures to enhance data security during sharing. The incorporation of cybersecurity was recommended in Phase 4 to address this issue. Based on this recommendation, cybersecurity has been included in Phase 4 of the final version of the framework to improve data security. Additionally, P2 recommended an offline DT that can be accessed by certain personnel designated for its use.

"The government, for example, are going to put some policies to slow down artificial intelligence because it is getting to the point where it is quite dangerous due to data access and sharing" - P2

"Data sharing is fairly complex. Phase four is fairly complex also. One of the things we get into with phase four, your sharing and transmission of data, is that some data cannot be shared, and some data is sensitive. It should not be shared and should depend on who gets it. So, I think cybersecurity needs to be inserted there" - P1

"So, I think a backup might be a good idea: to have some sort of digital twin that you could have like a backup, which would be like what we call a closed protocol digital twin. So, you only share it with some people, and you do not put it live on the Internet backed up" - P2

In conclusion, the participants' recommendations have significantly improved the framework (Figure 7.4). With these recommendations, the framework has accommodated the validation of existing data models for BM organisations already employing technologies/systems, continuous updating of the DT framework to prevent obsolescence, and addressed security concerns stemming from data privacy.



Phase 0
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Maintenance data requirements and approvals
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Participants
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Technology Expert
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Operationalisation of the maintenance issue
Conduct of reconnaissance survey
Preparation of defects schedule
Preparation of dilapidation schedule
Conditions of contracts
Building condition survey report
Building maintenance manual
Dynamic Data
As-built drawings
Historical Data
Cyber Security
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Dynamic Data
Database
Data
Soft gate
Soft gate
Soft gate
Hard gate
Soft gate
Drone, scanners, surveying tools
Drone, thermal cameras, sensors, RFID, advanced surveying tools (laser scanners, photogrammetry)
Fibre optics, Wi-Fi, 5G, Rest application programming interface (API), file transfer protocol, email, message queuing telemetry transport
Establishment of maintenance issue
Maintenance issue confirmed
Physical observation building asset
Extent of issue ascertained
Analysis of findings
Suitability of field data determined
Identification of data requirements
Maintenance data determined, and financial approval contract signed
Transmission and storage of data
Continuous process of

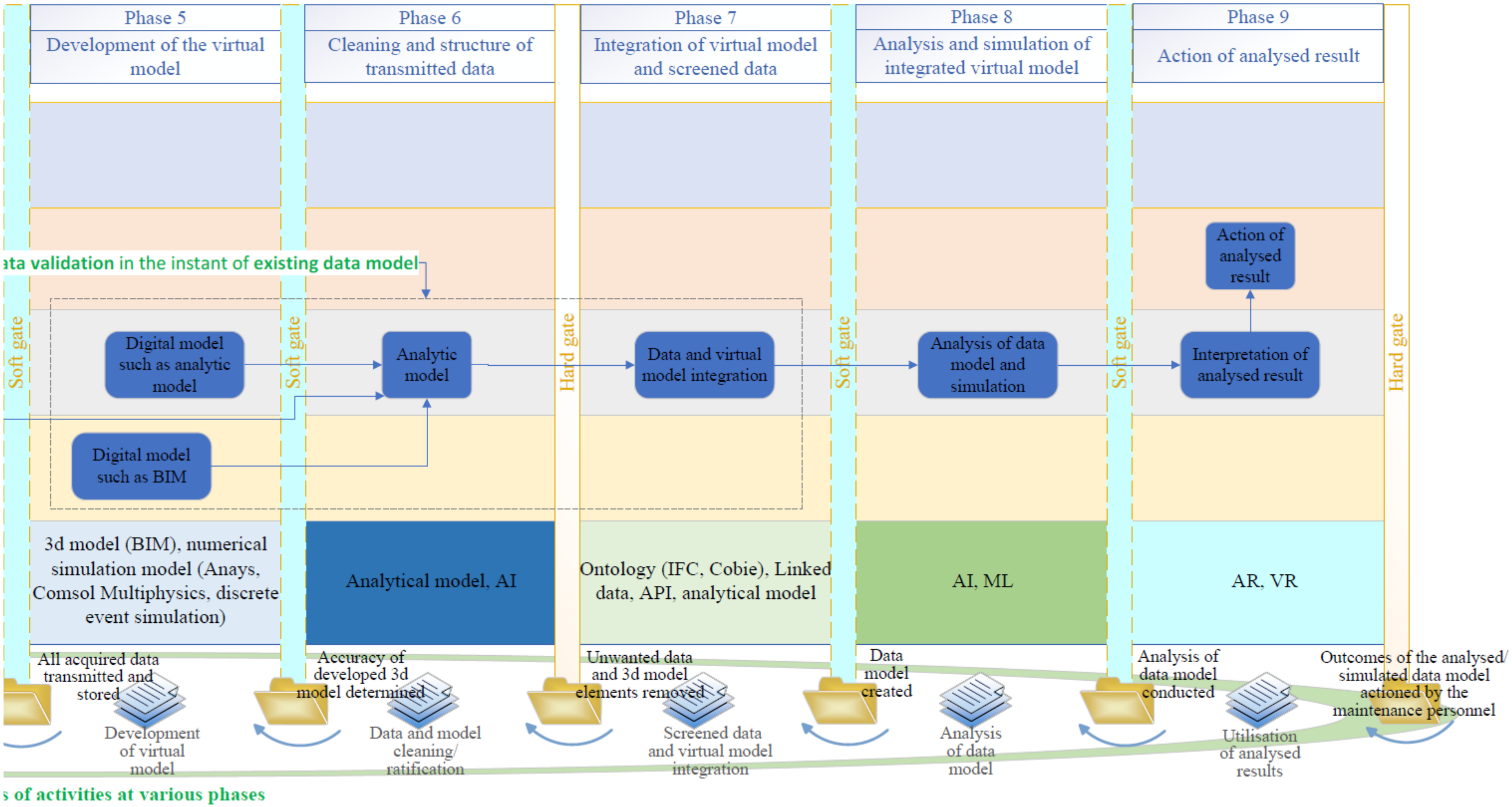

Figure 7.4: The Study's Refined Developed Framework

7.3 Summary

This chapter discusses the framework development for implementing DT for BM management at the organisational level through a process mapping approach. The NBC and GDCPP process mappings are utilised to develop the framework. Such mapping frameworks enable the researcher to operationalise maintenance activities and DT into four main phases and nine sub-phases along the horizontal dimension. Along the vertical dimension, the core principles of the GDCPP are applied and structured using the 5 W's ("When? Where? Who? What? Why?") guideline to elaborate on the activity zone. The framework was developed using an iterative approach based on literature and data analysis findings from interviews.

An overview of the framework, including all sub-phases and activity zones, is presented in Appendix 5. The framework is developed with the intention of providing a systematic approach to support BM organisations in implementing DT, regardless of their knowledge of technological advancements. Participants' comments indicate that the framework acknowledges the necessity of acquiring new data and validating existing data models for effective maintenance management. Overall, findings revealed that the framework is useful and implementable for maintenance management. The developed framework, in alignment with this study's definition of DT, is illustrated in Figure 7.5, demonstrating how it connects back to supporting BM organisations in managing any identified maintenance-related issues.

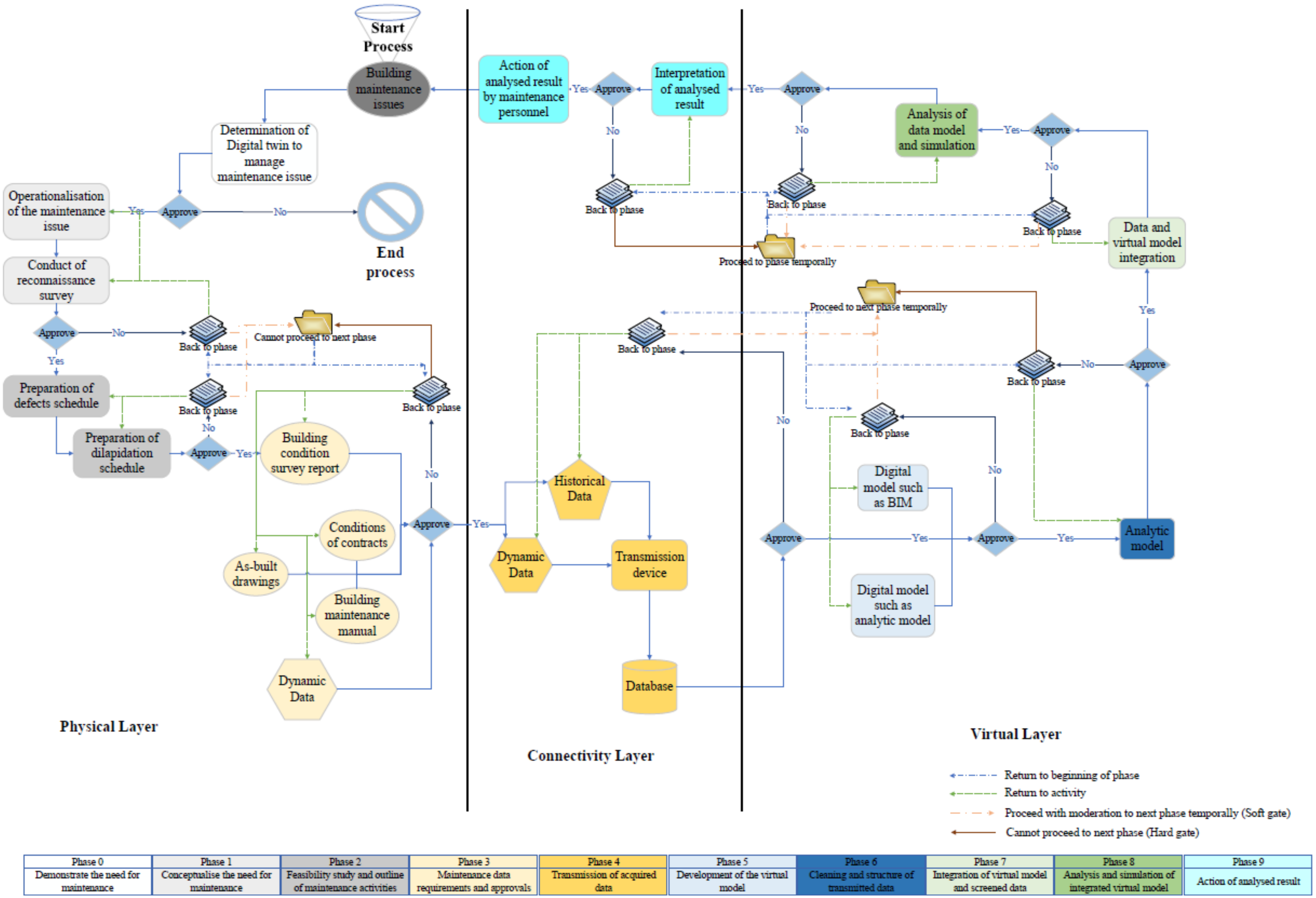

Figure 7.5: Developed Framework in Alignment with this Study's Definition of Digital Twin

Chapter Eight - Conclusion

8.0 Introduction

This chapter presents an overview of the study. It includes findings that provide evidence to answer the overarching research question while fulfilling the aim and objectives. The implications of these findings are discussed, followed by contributions to knowledge, limitations, and directions for further research.

8.1 Achievement of the Research Aim and Objectives

BM is a complex and multifaceted concern that manifests similarly across countries; however, it is managed using different approaches. By employing a sequential mixed research method (Chapter 4), this study developed a framework for implementing DT for BM organisational management, using Nigeria for contextual insight. Six research objectives were formulated to achieve the study's aim (Section 1.3). Through the literature review on BM, the first objective identified the causes and complexities of maintenance-related issues in Nigeria (Section 2.6). Additionally, it was important to uncover more causes and challenges that BM organisations encounter and the strategies adopted for managing these maintenance-related issues through empirical data collected from questionnaires and interviews. To propose a robust approach to managing these maintenance-related issues, the second objective explored the technologies and systems used for maintenance management in Nigeria (Section 2.7). The literature review indicated that DT has the potential to address the complexities of maintenance-related issues due to its real-time monitoring, data updates of buildings and assets, as well as scenario analysis. However, evidence of DT usage in Nigeria was lacking in the questionnaire and interview findings.

To further advance towards achieving the study's aim, the third objective investigated the applicability of DT for BM management by reviewing literature and conducting interview sessions on DT and maintenance in the built environment worldwide, prompted by evidence of its non-usage in Nigeria (Sections 3.6 and 5.4). It became evident that while DT was relevant for managing maintenance complexities, there was greater emphasis on its technical implementation than on its organisational aspects. To gain a deeper understanding, this objective was further explored through interview sessions on the applicability of DT for BM management. The interview sessions involved participants who were experts in DT and related activities within the built environment worldwide, as there was no evidence of its usage in Nigeria. The fourth objective was partially fulfilled through the use of the PPT framework to explore the organisational requirements for the implementation of digital innovations, encompassing DT (Section 3.9.1). The empirical data from the interviews expanded this objective to focus on the organisational requirements for DT. The fifth objective was achieved by developing the study's framework using GDCPP principles to explore points of intersection among organisations' people, processes, and technology dimensions concerning the use of DT for BM management (Section 7.1). Lastly, the sixth objective evaluated the developed framework for its usefulness and applicability through a focus group session (Section 7.2). The following subsections provide details of the findings related to achieving each objective in order to fulfil the study's aim.

Objective One: "To identify the challenges of building maintenance management in Nigeria"

This objective was achieved through literature review and empirical data collected from questionnaires and interviews. The literature established that maintenance-related issues are a worldwide issue, involving both human-related and natural-related issues. In Nigeria, the primary causes of human-related issues were traced to faulty design, the use of poor construction materials, users' misuse of building assets, and managerial practices (Section 2.6.1). Moreover, the questionnaire findings substantiated that the most prominent causes of maintenance-related issues stem from organisational dynamics, technical complexities, and user-related challenges (Section 5.5). To further uncover the challenges within the organisational dynamics of BM organisations in managing maintenance-related issues, the interview findings highlighted that inadequate tools and technologies, insufficient information dissemination, funding constraints, lack of proper documentation, and insufficient skilled personnel were the major challenges (Section 6.4.1).

For this reason, BM organisations need to adopt a proactive approach in their maintenance strategies to transition from reactive and preventive measures to predictive ones and manage these maintenance-related issues effectively. Faulty designs and substandard construction materials cannot be rectified once buildings are in use, nor can building users be expected to change their attitudes towards the use of buildings and assets. Therefore, BM organisations need to implement robust management techniques to manage these maintenance-related issues. This finding directed the research to focus on technologies and systems to assist BM organisations in managing maintenance activities.

Objective Two: "To explore the current technology and systems used for building maintenance management in Nigeria"

This objective was achieved through a review of literature and empirical data collected from questionnaires and interviews. The literature established that technologies and systems are crucial for managing maintenance activities, as they assist BM organisations in conducting these activities. These technologies include CMMS, EAM, CAFM, IWMS, and BIM (Section 2.7). In the Nigerian context, the available literature indicated that BM organisations utilise

CMMS and BIM to manage their maintenance activities (Section 2.7.2). Moreover, findings from the questionnaires revealed additional technologies and systems, such as CAFM, IWMS, BAS, and Microsoft programs (Section 5.4). The interview findings further substantiated certain aspects of the literature and questionnaire results, revealing the use of sensors, drones, and VR to assist BM organisations with their maintenance management (Section 6.4.1; Sub-theme IV). While it is noteworthy that BM organisations in Nigeria are proactively progressing from reactive to preventive maintenance practices by employing technologies and systems, there remains untapped potential in the area of predictive maintenance, which can be achieved through DT from a scholarly perspective (Sections 2.7.1.9 and 3.6). This finding directed the research to focus on the application of DT due to its potential to provide richer data through the real-time monitoring of buildings and assets, as well as enabling scenario analysis, thus allowing BM organisations to plan strategically and proactively in their decision-making.

Objective Three: "To explore the applicability of digital twin for building maintenance management"

This objective was achieved through a review of literature and findings from interviews. The literature established that DT is employed for maintenance activities such as effective data management, anomaly and defect detection, maintenance inspection, conservation, and optimisation (Section 3.6). The literature further revealed that DT has the potential to streamline issues related to maintenance documentation, requests, and decision-making processes. For this reason, from a scholarly perspective, BM organisations can harness the capabilities of DT to become more proactive and strategic in their operations. Additionally, interview findings suggested that DT can assist BM organisations with certain activities, including building operations, enhancing occupants' comfort, decision-making, operating costs, and fault prediction. Findings revealed an array of analyses, such as performance, diagnostic, optimisation, and prognostic that BM organisations can conduct to manage maintenance activities strategically (Section 6.4.3, Sub-theme II). However, despite the apparent benefits of DT for BM organisations in managing maintenance activities, no standard documentation specifies the requirements for DT implementation, particularly at the organisational level (Sections 3.8 and 6.4.4; Sub-theme I). Thus, this finding directed the research to examine the requirements for BM organisations to implement DT in their maintenance management.

Objective Four: "To determine the organisational requirements of implementing digital twin for building maintenance management"

This objective was fulfilled through the review of literature and interview findings. The literature revealed that two policy documents exist for the utilisation of digital technologies in the UK: Data for the Public Good and Gemini Principles, which have been adopted in various other countries for similar purposes (Section 3.8). Interview findings substantiated the use of these documents and underscored the absence of policy documents evidencing the requirements for DT implementation (Section 6.4.2). Moreover, the literature provided insights into several technologies and infrastructures necessary for the development and implementation of DT (Section 3.8). However, the literature was indicative of a lack of focus on the organisational implementation of DT, concentrating solely on its technical aspects. Therefore, the PPT framework was explored to identify the organisational requirements associated with the implementation of DT for BM management (Section 3.9.1).

Using the PPT framework, the organisational requirements associated with DT implementation were further drawn from the interview dataset. Concerning the people dimension, the literature and interview findings identified four key stakeholders: the building owner/client, maintenance team (Sections 2.5, 3.9.1, and 6.4.1; Sub-theme II), building professionals (Section 6.4.1; Sub-theme II), and technical staff (Section 6.4.4; Sub-theme I), who are pivotal in driving the adoption of DT by BM organisations for effective maintenance management. While these stakeholders are crucial to the people dimension of DT implementation, findings also highlighted certain challenges, such as employee resistance to change, conservative attitudes, technological literacy issues, and the commitment of top management to the adoption of DT in BM organisations. For BM organisations in Nigeria, Section 6.4.4 illustrated how these challenges can be addressed to facilitate the implementation of DT.

The literature revealed that the organisational process dimensions regarding technology usage encompass workflow integration through process mapping and data management, which includes data governance, integration, and analysis (Section 3.9.1.2). While data is central to the operations of DT, the literature indicated that, with the appropriate processes adopted in BM organisations, issues like data silos can be resolved through the decentralisation of decision-making and the promotion of centralised data integration. For this reason, applying the right processes for DT implementation by BM organisations will enable strategic planning and improved decision-making related to maintenance activities. Additionally, interview findings highlighted the importance of some BM organisations in Nigeria conducting their maintenance activities according to a defined procedure or framework (Section 6.4.1: Sub-theme II). If this practice is maintained and expanded, it will facilitate a smoother adoption of DT for maintenance activities among BM organisations.

Regarding technology, the literature indicated that organisations exploring technological advancements should prioritise clarity in digitising their work activities, particularly concerning data quality, security, connectivity, integration capabilities, and scalability

(Section 3.9.1.3). Interview findings further revealed that inadequate infrastructure and technological compatibility pose significant challenges for BM organisations, particularly those in Nigeria, attempting to digitise their work activities (Section 6.4.4; Sub-theme III). To overcome these challenges, BM organisations have to align their digitisation efforts with the principles of DT development by investing in relevant infrastructures (Section 3.8.1). Therefore, the challenges across the different PPT dimensions need to be addressed before DT can be successfully implemented in Nigerian BM organisations. These findings directed the research towards developing a DT framework for maintenance activities.

Objective Five: "To develop a framework for the organisational implementation of a digital twin for building maintenance management"

This objective was achieved through a review of the literature and interview findings. The literature established several mapping frameworks useful for the study's development of a DT framework (Section 3.9.2). These mapping frameworks facilitated the operationalisation of maintenance activities and DT model development into process phases and activity zones (Section 7.1). In doing so, the interconnection among the PPT dimensions of BM organisations regarding the use of DT for maintenance management was explored. Adopting an iterative approach, the GDCPP principles served as a guide to populate the framework with interview findings about the PPT dimensions on DT and maintenance activities. The application of the GDCPP principles aimed to identify the various responsibilities of BM stakeholders for maintenance activities, ascertain the technological tools or devices required to fulfil their tasks, and specify measurable outcomes at each process phase (Appendix 5). Section 7.1 detailed the framework development process. Hence, this phase directed the research to focus on the applicability of the developed framework for BM management.

Objective Six: "To evaluate the developed framework for the organisational implementation of a digital twin for building maintenance management"

This objective was achieved through a focus group discussion session. The session elicited expert opinions for the framework evaluation (Section 7.2). The findings from the focus group indicated that the framework accounted for maintenance processes and the responsibilities of BM stakeholders at each phase (Section 7.2.5). The experts provided recommendations, including incorporating cybersecurity in certain phases of development to address privacy and data acquisition infringements (Section 7.2.6). It was concluded that the developed framework acknowledged the PPT dimensions of BM organisations and was useful and implementable for maintenance activities.

8.2 Research Contributions

This research contributes to both theory and practice by developing a framework for implementing DT to support BM management. The theoretical contributions involve employing the PPT framework to situate emphasis on these three dimensions of BM organisations in the context of DT implementation. Additionally, the conceptualisation of DT through a mapping approach for BM management aims to bridge existing gaps in the literature. The practical contribution lies in the development of a framework to assist in the implementation of DT in BM management.

8.2.1 Theoretical Contributions

Determining the people, process, and technology-related considerations for DT implementations in BM organisations:

Understanding the organisational implementation of DT is as complex as understanding its technical implementation. The use of the PPT framework revealed the necessity for a balanced structure within BM organisations to implement innovations such as DT effectively. This balance cuts across the people, processes, and technology dimensions. As highlighted in the literature (Section 3.9.1), establishing organisational balance in DT implementation is crucial due to certain inadequacies within BM organisations (Section 6.4.3; Sub-theme III). Consequently, the PPT framework was employed to highlight these inadequacies, prompting BM organisations to take corrective measures.

Focusing on achieving balance among the people, process, and technology dimensions will facilitate the implementation of DT and assist the maintenance team in managing BM activities. To this end, BM organisations require human resources with technical expertise in digital technologies while addressing employee resistance to change, conservative attitudes, technological literacy, and top management's commitment to granting financial autonomy to operational staff. They also need a clear organisational workflow, effective data management processes, and technological infrastructure that aligns with the principles of DT. Thus, this study emphasises the importance of these PPT dimensions and the necessary considerations associated with them. In doing so, this research contributes to the existing literature by unravelling the organisational inadequacies that hinder BM organisations from effectively implementing DT and suggesting potential avenues for addressing them (Section 6.4.4).

Conceptualising of DT model development using a mapping approach for BM management

Utilising a mapping approach to address the complexity of maintenance activities associated with DT has led to a more comprehensive method for managing anticipated maintenance-related challenges (Section 7.1). By conceptualising DT model development alongside maintenance activities into distinct process phases, points of interconnection among the PPT dimensions of BM organisations were identified. The literature acknowledges that DT enhances the efficiency of maintenance planning and execution due to its capacity to deliver richer data (Section 3.6). However, this thesis introduces a structured mapping approach to manage these maintenance-related complexities (Appendix 5). Consequently, this mapping approach contributes a new perspective to the literature regarding how DT can be conceptualised, especially in the context of BM management. It highlights the involvement of various stakeholders in executing maintenance activities by utilising appropriate technological tools or devices to process data at the right stage, achieving measurable outcomes to address the complexities of maintenance management.

Therefore, this study adds to the literature by revealing the organisational inadequacies that impede BM organisations from effectively implementing DT, whilst proposing solutions to address these inadequacies (Section 6.4.4). Additionally, it has conceptualised DT using a mapping approach for better BM management (Appendix 5).

8.2.2 Practical Contributions

Developing a framework to support implementing DT for BM management

The developed framework serves to interconnect the PPT dimensions of maintenance activities within BM organisations. The process activities outlined in this framework create a template for BM organisations to explore various avenues for achieving targeted activities at each phase relevant to the utilisation of DT for maintenance management. Moreover, these conceptualised process activities are not tailored to the size, location, or level of digitisation of the BM organisations but are based on the principles of their operations, allowing them to commence at any point that aligns with their organisational procedures.

Spotlighting the usefulness of the developed framework for BM organisations, it provides a systematic approach for implementing DT in maintenance management. By simplifying complex maintenance activities into phase processes and activity zones, BM organisations can more easily determine whether DT is suitable for addressing a specific maintenance-related issue before initiating its model development and subsequent implementation.

Furthermore, the framework identifies various technological tools and devices that can assist BM stakeholders in carrying out their activities at each sub-phase. With this information, BM organisations can effectively plan their maintenance activities and make necessary technological purchases to address maintenance-related issues. Additionally, the framework provides vital information on measurable outcomes for each process phase activity, enabling BM organisations to make informed decisions regarding necessary actions as maintenance activities unfold, including obtaining essential documents from stakeholders and accurately documenting maintenance activities.

Overall, the developed framework provides BM organisations with crucial insights regarding the organisational requirements for implementing DT in BM management. For example, data management procedures acknowledged during the evaluation indicate that the developed DT framework outlines steps for collecting data from buildings and assets lacking existing data, as well as for validating data models associated with their respective buildings and assets. The collection and validation of data are essential for preparing the correct data model for comprehensive analysis, which, in turn, yields actionable results for strategic maintenance management. For this reason, the framework supports BM organisations in transforming their practices to adopt a more proactive stance, such as a predictive strategy, by establishing interconnections among the PPT dimensions in which they should invest for optimal maintenance management.

8.3 Research Limitations and Future Studies

This study provides insight into the reoccurring maintenance-related issues and complexities, focusing on Nigeria. It reveals that DT is a potential solution for managing these issues; however, BM organisations need to balance their PPT organisational dimensions to facilitate its implementation. While the study developed a DT implementation framework to support BM organisations in maintenance management, it encountered some limitations that future studies could address. These limitations include the following:

- The modest response rate from experts in BM management during the questionnaire survey was a concern. Such a rate was likely due to the busy schedules of BM managers. While the survey was preliminary in nature to establish clarity in the gaps in the literature, future studies should involve a broader population of organisations engaged in BM management to provide further insight and validate the presented findings.

- There were no accessible participants who specialised in using DT for BM management. Moreover, the number of participants who specialise in the use of DT for other construction-related activities was limited during the interview sessions. The low number of participants is likely attributed to the infancy of DT in the AEC industry compared to others, such as manufacturing. Future studies should investigate the usage of DT, particularly in BM management, with a broader audience to achieve saturation.

- Additionally, there was no available case study of DT usage for maintenance activities to analyse for more in-depth information. Therefore, future case study approaches are necessary to elicit a comprehensive understanding of DT usage for BM management.

- The developed DT framework proposes a strategic approach to managing maintenance-related issues by considering the PPT dimensions of BM organisations. However, due to the study's time constraints, the framework has yet to be implemented to manage a real-life maintenance-related issue. Hence, its true validation is essential. More studies are required to validate the framework's efficacy and usefulness for BM management.

- Future studies should investigate the impact of emerging technologies beyond DT for BM management. It is crucial to understand the challenges of technology adoption in developing countries like Nigeria and compare them with those of developed countries. Such studies could provide invaluable insights into the utilisation of emerging technologies for effective BM management.

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Appendices

Appendix 1: Questionnaire Data Collection Instrument for Maintenance Managers

General Instruction

Please respond to the following questions by writing or marking the appropriate answers. You should select only one answer.

Section A: Participant's Particular

1. What is your job title? Please select one from the options below:

   Building Manager [ ] Building Executive/Supervisor [ ]

   Building Technician [ ] Others, please specify: …………………

2. How long have you been involved in the building maintenance industry? Please select one from the options below:

   Less than 5 years [ ] 6 – 10 years [ ] 11 – 15 years [ ]

   More than 15 years [ ]

Section B: Building Maintenance Patterns: Types and Strategies

3 Which type of building does your organisation maintain the most? Please select one from the options below:

Public Office Buildings [ ] Private Office Buildings [ ]

Hotels [ ] Hospitals [ ] Tertiary Institution [ ] Monuments [ ]

Public Residential Buildings [ ] Private Residential Buildings [ ]

Religious Buildings [ ] Others, specify …………………

4 Which of these types of buildings is the most problematic to maintain? Please select one from the options below:

Public Office Buildings [ ] Private Office Buildings [ ]

Hotels [ ] Hospitals [ ] Tertiary Institution [ ] Monuments [ ]

Public Residential Buildings [ ] Private Residential Buildings [ ]

Religious Buildings [ ] Others, specify …………………

5 What type of strategy is most commonly adopted for maintenance management? Please select one from the options below:

Corrective [ ] Emergency [ ] Preventive [ ]
Condition-based [ ] Predictive [ ] Others, specify …………………

Section C: Technologies and Systems

6 Which of the following software does your organisation utilise the most for maintenance activities? Please select one from the options below:

Computerised Maintenance Management Systems [ ] Building Automation Systems [ ] Integrated Workplace Management Systems [ ] Maintenance Management Information Systems [ ] Computer Aided Maintenance Management [ ] Building Information Modelling [ ] Digital twin [ ] Others, specify ………………………

Section D: Causes of Building Maintenance

Please indicate the extent to which each statement reflects the causes of maintenance. Tick or select the appropriate cell or box for each statement.

7.	**Organisational-related causes**	**Not at all**	**To a minimal extent**	**To a moderate extent**	**To a large extent**	**To a very large extent**
a	Improper planning and scheduling					
b	Unclear organisational structure and job description					
c	Selecting an unqualified maintenance contractor					
d	Lack of collaboration between stakeholders					
e	Substandard maintenance works					
f	Lack of planned maintenance and regular upkeep inspections					
g	Incomplete strategic management plan					

h	The issue of maintenance policy implementation					
i	lack of timely response to maintenance requests					
8.	**Technical-related causes**	**Not at all**	**To a minimal extent**	**To a moderate extent**	**To a large extent**	**To a very large extent**
a	Lack of maintenance consideration at the building design stage					
b	Inaccessibility of building maintenance activities due to faulty design					
c	Lack of ICT adoption and maintenance software tools					
d	Lack of advanced techniques and tools to detect building defects					
e	Faulty construction					
f	Non-availability of maintenance materials					
g	Poor quality of building materials					
h	The remoteness of the building					
9.	**Human resources-related causes**	**Not at all**	**To a minimal extent**	**To a moderate extent**	**To a large extent**	**To a very large extent**
a	Lack of work experience					
b	Training is not adequate to carry out work tasks effectively					

c	Lack of courses and workshops to improve staff skills					
d	Recruitment of employees without any context training					
e	Lack of adequate staff, engineers, and specialist					
10.	**Financial-related causes**	**Not at all**	**To a minimal extent**	**To a moderate extent**	**To a large extent**	**To a very large extent**
a	Lack of a standard to define the exact cost					
b	Insufficient budget to maintain the buildings					
c	Poor economy					
d	Systemic corruption					
11.	**Building user-related causes**	**Not at all**	**To a minimal extent**	**To a moderate extent**	**To a large extent**	**To a very large extent**
a	Lack of awareness among the building users					
b	Misuse of building facilities					
c	Lack of signage to guide users to use the facilities					
d	Delayed report of building defects					
e	Poor maintenance culture					
12.	**Natural-related causes**	**Not at all**	**To a minimal extent**	**To a moderate extent**	**To a large extent**	**To a very large extent**
a	Normal wear and tears due to the constant usage					

b	Natural factors arising from unforeseen circumstances					
c	Death of the proprietor of a building					
d	Age of the building					

Appendix 2: Interview Questions for Experts on Digital Twin and Related Construction Activities

No	Questions	Focus
Q1	A - What are your job title and professional affiliations? B - What does your job entail? C - How many years of experience do you have in the industry? D - Are you involved in maintenance?	To assess the participants' demographics (excluded from coding)
Q2	A – What constitutes a simple digital twin? B – What are the technological requirements for a digital twin system? C – What data is required for a digital twin system? D – How can other software applications or platforms integrate data into a digital twin system? E – Have you used digital twin for maintenance activities or related activities such as facility management, structural analysis, and urban planning, among others?	To explore the fundamental components of a digital twin and its applicability for activities such as maintenance.
Q3	A – In your opinion, what maintenance issues can be addressed using a digital twin system? B – How can a digital twin system address these maintenance issues?	To comprehend the sequential order of digital twin development, including the

	B1 – What steps should be taken to utilise a digital twin system for maintenance activities? B2 – What are the drivers/enablers to utilise a digital twin system for maintenance activities? B3 – What are the barriers to utilising a digital twin system for maintenance activities? C – What type of analysis can be conducted for maintenance on a digital twin system? D – What are the organisational requirements for a digital twin system for maintenance activities?	drivers/enablers, barriers, and its organisational requirements.
Q4	A – How can digital twins be further promoted at the organisational level for maintenance activities?	To explore how digital twin can be promoted for organisational usage

Appendix 3: Interview Questions for Experts on Building Maintenance

No	Questions	Focus
Q1	A - What are your job title and Professional affiliations? B - What does your job entail? C - How many years of experience do you have in the industry?	To assess the participants' demographics (excluded from coding)
Q2	A - What factors are considered when conducting a maintenance survey? B - What challenges do you encounter? C - What are the causes of maintenance-related issues in buildings? D - Are building asset and facility maintenance manuals sufficiently documented and provided to building maintenance managers for their duties? E - Does your organisation have a written document outlining the data requirements for its maintenance activities? F - How do you carry out maintenance for your building projects? G - Does your organisation adhere to any process approach (protocol, framework, guidance, among others) for building maintenance activities?	To explore how maintenance activities are conducted in managing maintenance-related issues

Q3	A - What are the client's responsibilities regarding maintenance activities? B - Do you have financial autonomy in carrying out maintenance activities? C - Do you believe that collaborating with other building professionals will enhance maintenance activities? D - What types of documents and records should be provided for maintenance activities, and by whom?	To determine the client's responsibilities and maintenance data requirements
Q4	A - Which software, digital tools, or systems have you used or observed colleagues using for building maintenance management? B – On a global scale, what technological improvement methods do you know are being employed for building maintenance activities? C – Have you heard of digital twin or similar technologies like BIM? D – What is your perception of digital twins and BIM? E – How advantageous do you believe these technologies are for building maintenance activities? F – Have you used or are you currently using BIM or digital twin?	To explore the technological tools or systems used for BM management
Q5	A - If you understand the workings of a digital twin and its benefits for building maintenance, will you implement it? B - If not, what will be the main reason for not implementing digital twin for maintenance practices?	To explore the viability of implementing digital twin for building

	C - If yes, do you believe digital twin technology is feasible for maintenance activities based on your present organisational practice? D - In your opinion, what challenges will you likely encounter when implementing digital twins for maintenance activities? E - What technological infrastructures does your organisation have that can support a Digital Twin system? E1 - Will there be a need for an upgrade?	maintenance activities
Q6	A – How can digital twin be further promoted in the Nigerian built environment, particularly in building maintenance practices? B – What support would you like to receive if your organisation chooses to proceed with implementing digital twin?	To explore ways to promote digital twin for BM management

Appendix 4: Examples of Quotes that Substantiate the Operationalisation of the Generic Design and Construction Process Protocol Framework's Nine Sub-Phases

Sub-Phases	Phase Themes	Quotes Extracted from Respondents
0	Demonstrate the need for the maintenance of a particular building asset	*"Without understanding the business problem, we cannot apply the digital twin concept. So, the first part would be to understand the business problem. If the business problem requires a digital twin-based solution, only then should we proceed. Otherwise, there is no point" – R7*
1	Conceptualise the need for the maintenance of a particular building asset	*"You need to identify what effect you are looking for, what you are trying to predict or what you are trying to estimate, and what the factors which contribute to that effect" – R17*
2	Conduct a feasibility study and outline the maintenance activities to be conducted	*"The first and foremost is trying to get information on the states of the system" – R17* *"First, you have to go for a reconnaissance survey" – R15* *"You need to know the level of defects, and that is where you need to do a lot of work establishing the state of those defects and their causes" – R2*
3	Identify the required data for the maintenance activities to be conducted and	*"You need data to capture and describe the system" – R6* *"We look at the kind of BMS system. Some historical data that are recorded over time…. We need also dynamic data, which is something we collect from the environment" –*

	financial approvals	*R12* *"Until the data ingestion aspect is extremely clear and accurate, there is no point in going forward and trying to create a digital twin. So, the major hurdle for a digital twin is not the requirement of more technical expertise to execute the project, but instead, it is the data acquisition stage in the first place" – R17*
4	Design a method for the transmission of acquired data	*"Well, you have to define what data goes into the digital twin at the beginning" – R6* *"You need a communication layer. So, a sophisticated communication system needs to be developed which could fetch data from sensors and ultimately transmits this data maybe with a wireless mode of transmission" – R7* *"You would need some sort of way to connect to the building data loggers" – R16*
5	Develop a virtual model of the physical item	*"You start by having a design model that reflects what needs to get built" – R4* *"You need to model your asset or system and then try to understand the key variables which govern the operation of that asset or system" – R7* *"To create a digital twin, you essentially need to build it from a digital model of the facility" – R6*
6	Clean and structure the transmitted data and cross-check the accuracy or fidelity of the virtual model	*"You try to understand the key variables which govern the operation of that asset or system. ………. Once you identify the data, then you also need to identify whether the data you have collected is sufficient enough or not" – R7*

	for seamless integration	*"You would compare the data sets from the built model as well as sensor data and be able to identify discrepancies" – R4* *"It would then need to be formatted correctly and then set up in a way for the data to be sent over periodically and visualised in a way which can indicate the differences between DT simulation outputs and the live data being fed in" – R16*
7	Integrate the virtual model with the screened data	*"When you have the virtual model ready, you have to connect the virtual model with the data communication protocols" – R18* *"You need to be able to match data models" – R6* *"I guess geometric data can be combined with sensory data through the use of Analytical models or simulation models" – R9*
8	Simulate the integrated virtual model	*"You identify those variables and then select appropriate techniques within the digital space so that the entire analytics-based process where you try to understand your business problem" – R7* *"You get your machine learning model ready into this data and it will predict whether the machine requires maintenance right now or not, or probably will require maintenance in the near future or not" – R17*
9	Use the simulated result for maintenance activities through	*"It depends on what you use for action. If you have robotics on site, you can push the data straight to the robot, give it a new set of actions, and update the set of actions. If it is more like a manual kind of activity, then you*

	human intervention	*can communicate with workers and send them an update on what they need to do through mobile apps, for example" – R6* *"The role of a digital twin in maintenance would be to have sensors on equipment, to receive those readings…, you call out the maintenance team to go and do an inspection or a repair. So, the actuator part could be not directly from the facility, but it could be for you to notify the maintenance department" – R13*

Appendix 5: An Overview of the Developed Digital Twin Approach for Building Maintenance Management Framework

Main Phase	Data Acquisition Layer				Transmission Layer & Digital Modelling Layer			Data/Model Integration Layer		Service Layer
Sub-phase	**Phase 0**	**Phase 1**	**Phase 2**	**Phase 3**	**Phase 4**	**Phase 5**	**Phase 6**	**Phase 7**	**Phase 8**	**Phase 9**
Description of sub-phase	Demonstrate the need for the maintenance of a particular building asset	Conceptualise the need for the maintenance of the building asset	Outline of Preliminary Maintenance Activities	Identify the required data for the maintenance activities and financial approvals	Design a method for the transmission of acquired maintenance data	Develop a virtual model of the physical asset	Clean and structure the transmitted data and cross-check the accuracy or fidelity of the virtual model	Integrate the virtual model with the screened data	Analyse and simulate the integrated data model	The action of outcomes from the analysed data model for maintenance activities
Key Questions	- What circumstances will necessitate maintenance activities for a specific building or its assets? - Is a digital twin maintenance approach suitable for addressing the maintenance issue?	- What maintenance issue needs addressing?	- What maintenance activities need to be conducted? - How can a digital twin approach address the maintenance issue?	- What are the data requirements for the maintenance task? - How can this data be collected?	- What steps should be taken to transmit the collected data? - How can the collected data be transmitted to the virtual model?	- How can the virtual model be developed in a situation where there is no existing model?	- What measures will be taken to screen the transmitted data and check the virtual model's accuracy?	- How can the screen data and virtual model be integrated?	- What types of analysis are to be conducted?	- Are the simulated results suitable for addressing the identified maintenance issue? If they are, proceed to execution. If they are not, return to the simulation layer for further analysis.

Main Phase	Data Acquisition Layer				Transmission Layer & Digital Modelling Layer			Data/Model Integration Layer		Service Layer
Sub-phase	**Phase 0**	**Phase 1**	**Phase 2**	**Phase 3**	**Phase 4**	**Phase 5**	**Phase 6**	**Phase 7**	**Phase 8**	**Phase 9**
Stakeholders	- Client - Maintenance team - Technical expert	- Maintenance team	- Maintenance team - Technical expert	- Client - Building professionals - Maintenance team - Technical expert	- Maintenance team - Technical expert	- Building professionals - Technical expert	- Technical expert	- Technical expert	- Technical expert	- Technical expert - Maintenance team
Action needed at each sub-phase	Establishment of the need to manage the maintenance issue using digital twin	Physical inspection of the building and asset by the BM personnel (field survey)	Analysis of findings from the field survey	Identification of data requirements for the conduct of maintenance activities	Transmission and storage of both historical and dynamic data data	Development and modelling of the virtual model	Data and model cleaning and ratification	Integration of screened data and virtual model	Simulation of the virtual model	Utilisation of the outcomes from the analysis/simulation model

Main Phase	Data Acquisition Layer				Transmission Layer & Digital Modelling Layer			Data/Model Integration Layer		Service Layer
Sub-phase	**Phase 0**	**Phase 1**	**Phase 2**	**Phase 3**	**Phase 4**	**Phase 5**	**Phase 6**	**Phase 7**	**Phase 8**	**Phase 9**
Action needed at each sub-phase (Details)	- Determine the context of the maintenance issue. - Assess the availability of previous maintenance histories and data. - Evaluate whether the maintenance issue can be managed using a digital twin.	- Assess the physical condition of the building asset. - Carry out a reconnaissance survey. - Identify the root cause of the maintenance-related issue. - Evaluate the severity of the maintenance issue.	- Identify the maintenance actions and activities that require execution. - Prepare defect and dilapidation schedules. - Identify the external building professionals who will participate in the maintenance activities. - Assess the feasibility of accommodating a digital twin.	- Identify the data requirements. - Confirm the availability of as-built drawings and building manuals. - Assess the relevance of the collected field data. - Explore options for collecting additional data when necessary. - Determine the contract details and any need for modifications regarding their use for DT.	- Identify the appropriate data and documents to be transmitted. - Identify avenues for the transmission of collected data. - Determine an appropriate database for the storage of the transmitted data.	- Assess the availability of any existing 3D virtual models. - Identify an appropriate modelling technique for developing a 3D model in the absence of one.	- Determine the area or section of the data and model that requires cleaning. - Select a suitable method for cleaning the data and model.	- Identify a suitable medium for the integration of the virtual model and data.	- Identify a suitable technique for simulating the data model.	- Identify an appropriate method for actioning the analysed/simulated model. - Determine the possibility of outcome actions by robots. - Determine mediums for the action of outcomes by maintenance personnel.

Main Phase	Data Acquisition Layer				Transmission Layer & Digital Modelling Layer			Data/Model Integration Layer		Service Layer
Sub-phase	**Phase 0**	**Phase 1**	**Phase 2**	**Phase 3**	**Phase 4**	**Phase 5**	**Phase 6**	**Phase 7**	**Phase 8**	**Phase 9**
Tools to assist with phase		Drone, scanners, surveying tools		Drones, laser scanners, thermal cameras, RFID technology, sensors, and advanced surveying methods tools	**Transmission devices** encompass fibre optics, Wi-Fi, 5G, REST API, file transfer protocol, email, and MQTT. **Storage solutions** include Microsoft Azure, Google Cloud, Amazon Web Services, Google Firebase, and Microsoft SQL.	3D model (BIM), numerical simulation model (Ansys, Comsol Multiphysics, discrete event simulation)	Analytical model, AI	Ontology (IFC, Bricks, Cobie); linked data; API; analytical model.	- AI, ML - These are developed using programming languages such as Python, Java, R, Julia, and Ruby on Rails.	AR, VR
Task location	- Building maintenance site - Building maintenance organisation office	- Building maintenance site	- Building maintenance organisation office	- Building maintenance site - Building maintenance organisation office	- Building maintenance site	- Building maintenance organisation office	- Building maintenance organisation office	- Building maintenance organisation office	- Building maintenance organisation officee	- Building maintenance organisation office - Building maintenance site

Main Phase	Data Acquisition Layer				Transmission Layer & Digital Modelling Layer			Data/Model Integration Layer		Service Layer
Sub-phase	**Phase 0**	**Phase 1**	**Phase 2**	**Phase 3**	**Phase 4**	**Phase 5**	**Phase 6**	**Phase 7**	**Phase 8**	**Phase 9**
Outcome of sub-phase	To determine if the maintenance issue can be addressed using digital twin	To assess the maintenance issue or extent of defects and collect data.	To analyse if the collected data is sufficient for the maintenance activity.	To determine the necessary maintenance data requirements.	To transmit the maintenance data into a database.	To develop the 3D virtual model of the physical asset due for maintenance.	To clean the data and 3D virtual model for unwanted data and elements that are not useful.	To integrate the cleaned data and 3D virtual model of the asset to be maintained.	To analyse and then simulate the data model of the physical asset.	To take action on the outcomes of the analysis/simulate the data model of the asset.
Decision of sub-phase	- If yes, the maintenance activities may proceed. - If no, it will be terminated at this point phase.	- If the collected data are sufficient, the maintenance activities may proceed. - If not, the maintenance task may proceed but with the intention of collecting more data.	- If the data are sufficient, the maintenance activities may proceed. - If not, the maintenance task can proceed, but with the aim of collecting additional data.	- If the data are sufficient, the maintenance activities may proceed. - If not, the maintenance task cannot advance to the next stage phase.	- If all data transmission is achieved, maintenance activities may proceed. - If not, the process can continue, but with the aim of consolidating transmitted data.	- If the 3D virtual model is achieved, the maintenance activities can proceed. - If not, the process can proceed with the view to develop the asset 3D model.	- If the cleaned data and model are achieved, the maintenance activities can proceed. - If not, the process cannot proceed to the next phase due to data/model unreadiness.	- If data and models are integrated, the maintenance activities can proceed. - If not, the process can proceed with the view to integrate the data and model.	- If the analysis and simulation of data are achieved, the maintenance activities can proceed. - If not, the process can proceed with the view to analyse/simulate the data model.	- If the outcomes of the asset's analysis/simulated data model are usable, the maintenance activities can proceed. - If not, the maintenance activities cannot be executed due to inadequate information.

Main Phase	Data Acquisition Layer				Transmission Layer & Digital Modelling Layer			Data/Model Integration Layer		Service Layer
Sub-phase	**Phase 0**	**Phase 1**	**Phase 2**	**Phase 3**	**Phase 4**	**Phase 5**	**Phase 6**	**Phase 7**	**Phase 8**	**Phase 9**
Measurable outcome	Maintenance issue must be confirmed	The extent of maintenance issue ascertained	Appropriateness of collected field data determined and suitable for the maintenance activities	All relevant maintenance data must be determined, and financial approval contract documents signed	All available acquired data should be suitable for transmission.	The quality and accuracy of the developed 3D virtual model should be assessed for its usefulness	Unwanted data and 3D model elements that are not useful must be ascertained and removed.	Appropriate data and 3D virtual models should be integrated	Analysis of the integrated data model should be conducted.	The outcomes of the analysed/simulated data model must be suitable for maintenance personnel to take action.

Appendix 6: Focus Group Evaluation Questions

No	Questions	Focus
Questions Set 1:	A: Given your profession, do you understand the process of the developed framework? B: Is the framework adaptable to your current organisational processes? C: Is the underlying logic behind the flow of activities (i.e., the sequence of steps) appropriate? D: Based on your experience, are the phases outlined in the framework applicable to maintenance conduct activities?	To assess the applicability of the framework to fit into the process dimension of the participants' organisations
Questions Set 2:	A: In your view, is the framework relevant to digital twins and useful for maintenance management? B: Will the framework align with the human resources capabilities of organisations? C: Is the framework straightforward to implement regarding clarity and simplicity? D: Does the proposed framework hold the potential to be embraced by practitioners and to be utilised in the industry?	To assess whether the people dimension in the participants' organisations can accommodate the framework.
Questions Set 3:	A: Does your organisation utilise most of the technological mediums highlighted in the framework? B: Is the framework implementable and comprehensive for maintenance management?	To evaluate the technological infrastructure dimension within the participants' organisations could accommodate the framework.