UNIVERSITY OF BIRMINGHAM

Adoption of Building Information Modelling for Assessing the Life Cycle Cost of Sustainable Buildings: A Case Study in Saudi Arabia

By

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List of Abbreviations

(2D): Two Dimensional

(3D): Three Dimensional

(4D): Four Dimensional

(5D): Five Dimensional

(6D): Six Dimensional

(7D): Seven Dimensional

(AEC): Architectural, Engineering and Construction

(AECO): Architecture, Engineering, Construction and Operations

(AGCA): Associated General Contractors of America

(BDS): Building Description Systems

(BIM): Building Information Modelling

(BIWG): Building Information Modelling (BIM) Industry Working Group

(BPM): Building Product Model

(BS ISO): British Standards and International Organisation for Standards

(CAD): Computer-Aided Design

(ERG): Efficiency and Reform Group

(GBM): Generic Building Model

(GCC): Gulf Cooperation Council

(GDP): Gross Domestic Product

(GLIDE): Graphical Language for Interactive Design

(IDM): Information Delivery Manual

(IFC): Industry Foundation Classes

(IFD): International Framework for Dictionaries

(ISO): International Organisation for Standards

(KSA): Kingdom of Saudi Arabia

(LCC): Life Cycle Cost

(NBIMS): The National BIM Standard

(UK): The United Kingdom of Great Britain and Northern Ireland

(WLC): Whole-Life Cost

List of Publications

The publications can be found below:

	Publication	The Status	Chapter
1	**Building Information Modeling (BIM) towards a Sustainable Building Design: A Survey** (Conference paper). Alasmari, E., Martinez Vazquez, P. and Baniotopoulos, C., 2022. Building Information Modeling (BIM) towards a Sustainable Building Design: A Survey. *Proceedings of the CESARE22, 3rd Coordinating Engineering for Sustainability and Resilience, Irbid, Jordan*, pp.6-9.	Published	**2**
2	**A systematic review of the impact of adopting Building Information Modeling (BIM) on Life Cycle Cost (LCC).** (Journal paper), Journal (Buildings). Alasmari, E., Martinez-Vazquez, P. and Baniotopoulos, C., 2022. A Systematic Literature Review of the Adoption of Building Information Modelling (BIM) on Life Cycle Cost (LCC). *Buildings*, *12*(11), p.1829.	Published	**2**
3	**Adopting BIM to Enhance Sustainability. The Saudi Arabia Construction Projects case study.** (Conference paper). Alasmari, E., Martinez-Vazquez, P. and Baniotopoulos, C., 2023, June. Adopting BIM to Enhance Sustainability. The Saudi Arabia Construction Projects case study. In *IOP Conference Series: Earth and Environmental Science* (Vol. 1196, No. 1, p. 012111). IOP Publishing.	Published	**4**
4	**Enhancing Life Cycle Costing (LCC) in Circular Construction of Buildings by Applying BIM: Literature review.** (eBook Springer). Alasmari, E., AlJaber, A., Martinez-Vazquez, P. and Baniotopoulos, C., 2023. Enhancing Life Cycle Costing (LCC) in Circular Construction of Buildings by Applying BIM: A Literature Review. *Creating a Roadmap Towards Circularity in the Built Environment*, pp.407-417.	Published	**2**
5	**Life Cycle Cost in Circular Economy of Buildings by Applying BIM: A State of the Art.** (second author), (Journal paper), Journal (Buildings). AlJaber, A., Alasmari, E., Martinez-Vazquez, P. and Baniotopoulos, C., 2023. Life Cycle Cost in Circular Economy of Buildings by Applying Building Information Modeling (BIM): A State of the Art. *Buildings*, *13*(7), p.1858.	Published	**2**
6	**An analysis of the qualitative impacts of Building Information Modelling (BIM) on Life Cycle Cost (LCC): A qualitative study on Saudi Arabia.** (Journal paper). Journal (Buildings). Alasmari, E., Martinez-Vazquez, P. and Baniotopoulos, C., 2023. An Analysis of the Qualitative Impacts of Building Information Modelling (BIM) on Life Cycle Cost (LCC): A Qualitative Case Study of the KSA. *Buildings*, *13*(8), p.2071.	Published	**5 and 6**
7	**Utilising BIM on LCC to Enhance Sustainability of Saudi Residential Projects Through Simulation. A Case Study at the Kingdom of Saudi Arabia.** (eBook Springer). Alasmari, E., Martinez-Vazquez, P., Baniotopoulos, C. (2024). Utilising BIM on LCC to Enhance the Sustainability of Saudi Residential Projects Through Simulation. A Case Study at the Kingdom of Saudi Arabia. 4th International Conference. "Coordinating Engineering for Sustainability and Resilience". CESARE 2024. Lecture Notes in Civil Engineering, vol 489. Springer, Cham.	Published	**7**

Abstract

This doctoral research has investigated the use of Building Information Modelling (BIM) on the life cycle cost (LCC) and sustainability of construction in the context of Saudi Arabia. Addressing a significant deficit in region-specific studies, it conducted a comprehensive review of extant BIM-related research in the Saudi construction industry. Utilising a mixed-methods approach, the study integrated extensive literature reviews, empirical research, and advanced BIM tools to achieve its objectives. The primary goal was to survey the current research landscape, revealing a profound scarcity of studies specifically focused on the challenges and opportunities of BIM in Saudi Arabia. Subsequent goals included identifying enablers and constraints to BIM technology adoption, quantifying the extent of BIM utilisation, analysing its application during the design phase, assessing impacts on building life cycle costs and sustainability, exploring contractual practices and construction technologies in the Saudi market, and developing a strategic framework for BIM application in government projects. The study aims to systematically review existing literature on BIM implementation within Saudi Arabia, identify key enablers and constraints affecting BIM adoption, quantify the current extent of BIM usage in the industry, explore its impact on building life cycle costs and sustainability, comprehend the integration of contracts and building technologies within the Saudi Arabian construction sector, and propose a strategic framework for BIM application in government projects.

Findings revealed that despite the global insights provided by extant literature, there is a pressing need for more localised research tailored to Saudi Arabia's unique socio-economic and regulatory contexts. The use of sophisticated BIM tools such as Autodesk® Revit 2023, Autodesk® Insight, and Autodesk® Green Building Studio markedly improved the study's

precision and efficiency, underscoring the critical role of BIM in enhancing construction practices for better sustainability and cost-efficiency. The application of One Click LCA demonstrated the advantages of integrating circular design principles. A significant discovery was the potential for substantial cost savings and environmental benefits through optimised design and lifecycle analysis. For instance, Scenario 4, developed through an interactive optimisation process, demonstrated a 39.53% reduction in life cycle costs over 30 years compared to Scenario 1, translating to potential savings of approximately $25 million for a project of 900 residential units. Additionally, design adjustments in Scenario 4 led to a 48.8% reduction in CO2e emissions, according to the comprehensive LCA, Scenario 4 led to a 48.8% reduction in CO2e emissions, according to the comprehensive LCA, while the social cost of carbon decreased to €9,453.

The integration of green BIM tools like Autodesk Insight and Green Building Studio directly supported design decisions promoting energy efficiency and lower life cycle costs with minimal environmental impacts. At the conclusion of Scenario 4, a 21% reduction in Energy Use Intensity was recorded relative to Scenario 1. The deployment of One Click LCA also enhanced the study's analytical capabilities, enabling the evaluation of circularity metrics such as material recovery potential, advocating for the early adoption of circular economy principles in design.

Critically, the results indicate that an integrated BIM approach can significantly influence construction projects in Saudi Arabia. Establishing a BIM standard, educating personnel, raising stakeholder awareness, and developing supportive regulations are crucial for accelerating widespread BIM adoption across the region.

The conclusions of this research highlight the importance of context-specific knowledge in developing effective BIM adoption strategies in Saudi Arabia. Future research should investigate regional variations, advanced BIM applications, dynamic simulation models, and strategies related to the circular economy.

Keywords: Building Information Modelling (BIM), Life Cycle Cost (LCC), Construction, Kingdom of Saudi Arabia (KSA), Saudi Arabia, Sustainability, Circular Economy.

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This research is also a success because of the contributions of various stakeholders in the Saudi Arabian construction industry. Heartfelt thanks to the research participants who shared their experiences and opinions, contributing to the success of this study.

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I would also like to express my appreciation to the University of Birmingham for providing me with the study resources and academic environment.

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1 Chapter One: Introduction

The purpose of this chapter is to give a brief background of the study concepts. Moreover, this chapter sets the stage for readers to understand the overall concept of this thesis. The chapter begins with background information, which highlights the role of building information modelling at organisational levels. Then, the chapter highlights the overall research problem, which lays the foundation for the research questions and objectives. The overall research methodology is then discussed. Moreover, this chapter also highlights the study's scope and possible contributions in terms of practice and academia.

1.1 Study Background

Since the beginning of the 21st century, the construction industry in the Kingdom of Saudi Arabia (KSA) has experienced a surge in economic growth, with a focus on expansion and investment policies. As a result of these policies, both local and international construction companies have been compelled to compete fiercely to secure their market share in the industry. This has created a need for working organisations in this field to have a more comprehensive grasp of Building Information Modelling (BIM) methodology as well as the imperative of ensuring the long-term sustainability of construction projects. Moreover, the construction industry in Saudi Arabia has witnessed an increase in productivity and economic growth as a result of the government’s investment in housing, infrastructure, and development projects (Naim, 2019).

Although there has been consistent growth in construction projects, there have been variations in the strategies used to execute these projects. This can be attributed to the rise in the execution of contracts and the reduction in implementation time, coupled with insufficient study during the design or implementation phase. According to Bavafa (2015), an analysis of reports indicates that 83 percent of a project timeframe in the construction sector is consumed by reviewing project drawings.

In academia, Building Information Modelling (BIM) is considered a critical element. BIM is highly valued in the construction and engineering sectors because it enables collaborative work to eliminate mistakes and oversights in building design and construction. Moreover, the inclusion of performance measurement and scheduling elements not only presents cost-saving opportunities, but also provides an added advantage for project quality control. Azhar, Khalfan and Maqsood (2015) argued the technological aspect of BIM allows project stakeholders to visualise potential design, construction, and operational issues in a simulated environment, promoting the integration of all stakeholders' positions. In the same vein, Li, Xu and Zhang (2017) affirmed that geometric structure formation and managing quality and quantity based on information handling related to the whole project are added by using BIM. The widespread utilisation of BIM in the construction industry is believed to require the integration of all elements involved in a construction project.

Over the last three decades, the concept of BIM has undergone significant development and gained increasing recognition for its relevance (Zuppa, Issa, and Suermann, 2009). The increased adoption of BIM in the construction industry can be attributed to the realisation of its positive impact on overall construction value. The use of BIM has led to greater precision in design, fewer errors, and improved communication, which have all benefitted architects and engineers. From a theoretical perspective, Singh, Gu, and Wang (2011) reported that by prioritising quality and reducing costs, construction projects can achieve better structure and minimise the occurrence of disputes, which are commonly associated with building projects.

Researchers predict a promising future for BIM as engineers and technicians in the construction industry continue to increase its usage. This thesis enhances the understanding of BIM applied to LCC analysis in the Saudi Arabian construction sector. It investigates how BIM can be integrated into LCC to promote sustainability and cost-efficiency, specifically within the unique socio-economic and regulatory contexts of Saudi Arabia. Unlike previous studies, which have generally considered BIM's impact across various global settings, this research narrows its focus to Saudi Arabia, pinpointing the distinctive drivers and frameworks that affect BIM adoption. This tailored approach aims to develop strategies that align closely with the specific needs and characteristics of the Saudi construction industry.

1.2 Overview of BIM

Over the past decades, the term BIM has constantly evolved. The term was first coined by Charles Eastman as "Building Information Model" in the 1970s. According to Eastman *et al*. (2008), "*BIM as a modeling technology and associated set of processes to produce, communicate, and analyse building models.*" According to the National Institute of Building Sciences in the United States, BIM is "*a digital representation of physical and functional characteristics of a facility creating a shared knowledge resource for information about it forming a reliable basis for decisions during its life cycle, from earliest conception to demolition*" (US National Institute of Building Sciences, 2007).

Mesároš, Smetanková and Mandiák explained BIM principles in their 2019 study. They shared data of an environment dividing it into seven dimensions of a facility as 3D is used for engineering and can show a virtual 3D drawing. Also, 4D is used for time, which can provide data through which the project time is monitored and operated during the project life cycle. 5D is used for costs and can estimate building costs. 6D is used for sustainability and can analyse facility data and evaluate its efficiency and determine energy consumption and building performance. Lastly, 7D is used for facility management and operational data to maintain conditions throughout the building life cycle.

However, the definitions of 6D and 7D BIM are not fully established and they occasionally overlap. 'nD' BIM stands for specifying various dimensions in general. GhaffarianHoseini *et al.* (2017) suggest that diverse knowledge hierarchies and their potential users interact throughout a development's flexible lifecycle stages. Figure 1 shows an in-depth picture of BIM.

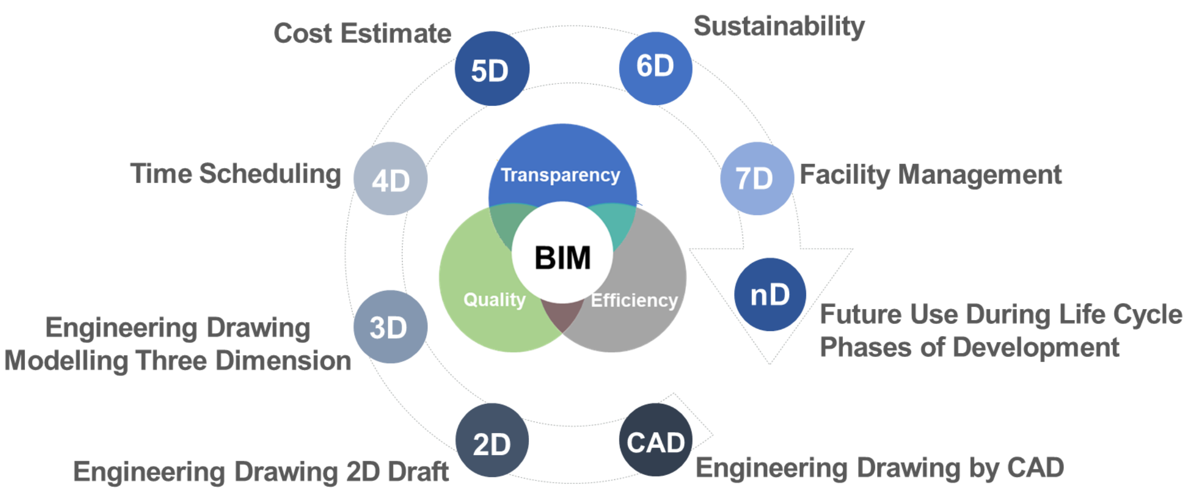


Figure 1: Dimensions of a BIM shared data environment (Alasmari, Martinez Vazquez and Baniotopoulos, 2022a)

Eadie *et al*. (2015) found that there is a global movement towards BIM adoption due to its ability to enhance building efficiency by minimising losses. In 2011, the UK Efficiency and Reform Group (ERG) introduced a BIM initiative with the aim of implementing Level 2 BIM in all government-funded projects in the country by 2016. Eadie et al. (2015) reported that the Building Information Modelling (BIM) Industry Working Group (BIWG) established BIM levels in their Strategic Plan (2011). Level 0 involves the use of CAD programs and 2D designs, while level 1 uses CAD 2D and 3D layouts. Level 2 involves the use of 4D data for project scheduling and 5D data for cost-related information. Finally, level 3 BIM is an advanced system that significantly enhances information sharing. The scenario is shown in Figure 2.

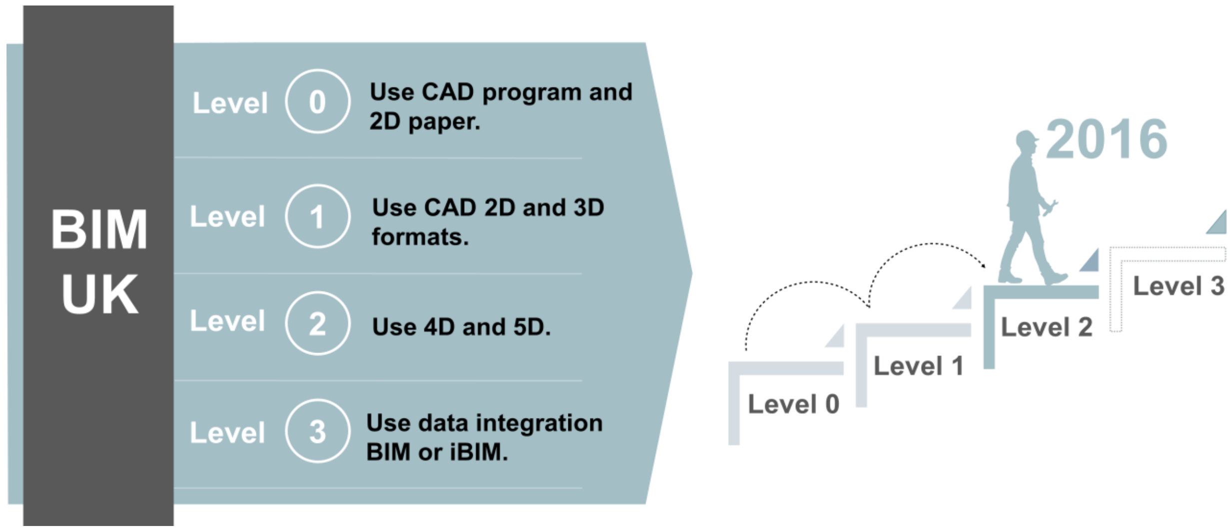


Figure 2: Current state of BIM in the United Kingdom

The life cycle cost, as defined via BS ISO 15686-5, 3.1.1.7, is the "cost of an asset or its parts throughout its lifecycle, while fulfils the performance requirements" (Marzouk, Azab and Metawie, 2018, p. 219). The international standard ISO 15686-5 has defined LCC and developed a methodology to clearly describe the term; it outlined the difference between the whole-life cost (WLC) and LCC - WLC has a broader perspective meaning and includes the LCC as part of it: the definition of WLC is "all significant and relevant initial and future costs and benefits of an asset, throughout its life cycle, while fulfilling the performance requirements" (ISO 15686-5:2017, 2020).

Although it had been accurate information, the decision-making of building outcomes throughout the life cycle, from design to present state, is based on shared knowledge data for a building (Ding and Xu, 2014). Figure 3 illustrates this as shown below.

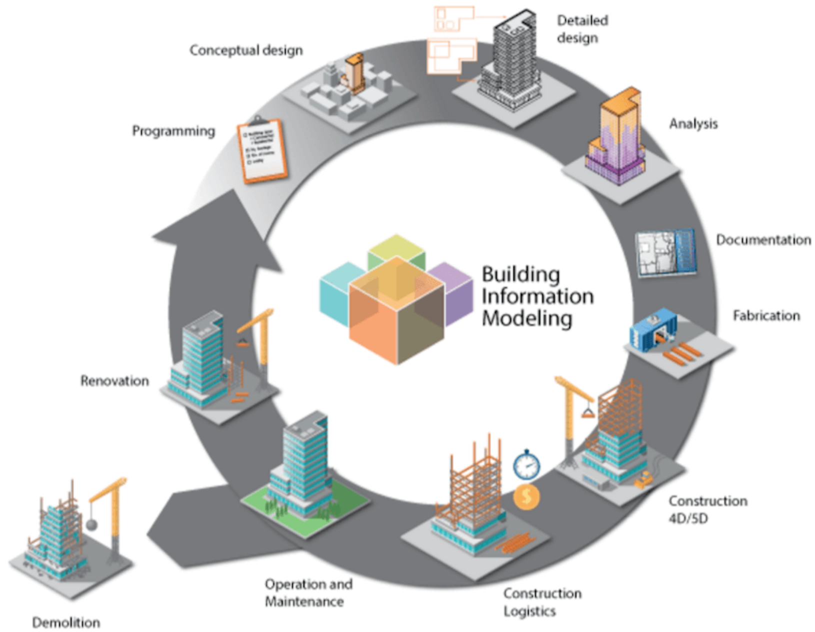


Figure 3: Life cycle cost of BIM (Lifecycle BIM and smart FM, 2020)

According to Lewis, Riley and Elmualim (2010), the operational phase of the construction is a long-life phase of construction and is more expensive for the building life cycle, with operating costs accounting for 60-80 per cent of the life cycle cost; design and construction accounting for 5-10 per cent; and restoration and modification accounting for 5-35 per cent. As a result, proactive maintenance has a favourable effect on lowering building life cycle costs (LCCs). Over the last several years, certain governments have accelerated the implementation of BIM systems, recognising the value of this technology in lowering building costs; this is due to their desire to reduce building costs, improve operational efficiency, and reduce LCCs. For example, Bavafa (2015) summarised the UK construction sector as 7% of the gross domestic product and spent annually at 11 billion pounds.

1.3 The Advantages of BIM

BIM represents modern software technology utilised by engineers in the construction sector. It shows a three-dimensional representation of the whole building system and its subsystems. 3D digitalisation is a cutting-edge technique that may give an exact visual of facilities thanks to a comprehensive database containing all the information about an engineering system that is linked to the database. BIM is seen as a platform for promoting multidisciplinary cooperation at all levels to offer complete and relevant information for all systems throughout the facility's life cycle. BIM can utilise the process of creating, maintaining, and utilising building resources to guide the construction and maintenance of buildings throughout the operational life cycle of an Organisation (Alshibani and Alshamrani, 2017).

Facility managers can benefit from BIM's ability to establish a life cycle by improving building management, achieving optimum and efficient energy usage, and better facility management throughout the working cycle, leading to increased efficiency in conducting required facility upgrades (Liu and Issa, 2016). Furthermore, BIM provides facility managers with a comparative analysis of various alternative energy options by considerably reducing energy usage used in the building operation, thereby decreasing negative impacts on the environment. It can also assist facility managers in providing the same support to users, but in a more advanced and effective manner without substantial energy consumption (Abanda and Byers, 2016).

Rogers, Chong and Preece (2015) stated that 3D technology, which designers utilise to examine the architecture professionally and adequately, can assist BIM to analyse energy usage and compare construction designs. In addition, 4D may be linked with time analysis via simulation, allowing it to anticipate project activities, cost, quality control, and schedule development. BIM is utilised in the operational stage for intelligent supervision and maintenance services, allowing operators to conduct maintenance at low prices and track project operations throughout the project life cycle (Ding and Xu, 2014).

It seems that 2D cannot be used to control the design stage's productive dimensions. The distinction between 2D and BIM is that it is only concerned with technical drawing. On the other hand, drawings are treated as structural components with a set of specified data characteristics in BIM. Nevertheless, thanks to the functionality of 4D, which generates four-dimensional models in Revit software for Navisworks Simulate software, the BIM model may give the user all the tables of quantities and specifications needed for implementation. Furthermore, the procedure guarantees that all the stakeholders and organisations engaged are aware of the construction plan, enabling them to become more creative and successful. Furthermore, the 5D element is concerned with the follow-up of cost as well as the effect of project delays on the project value. For example, Revit software can analyse information and modify properties between engineering systems, as shown in Figure 4.

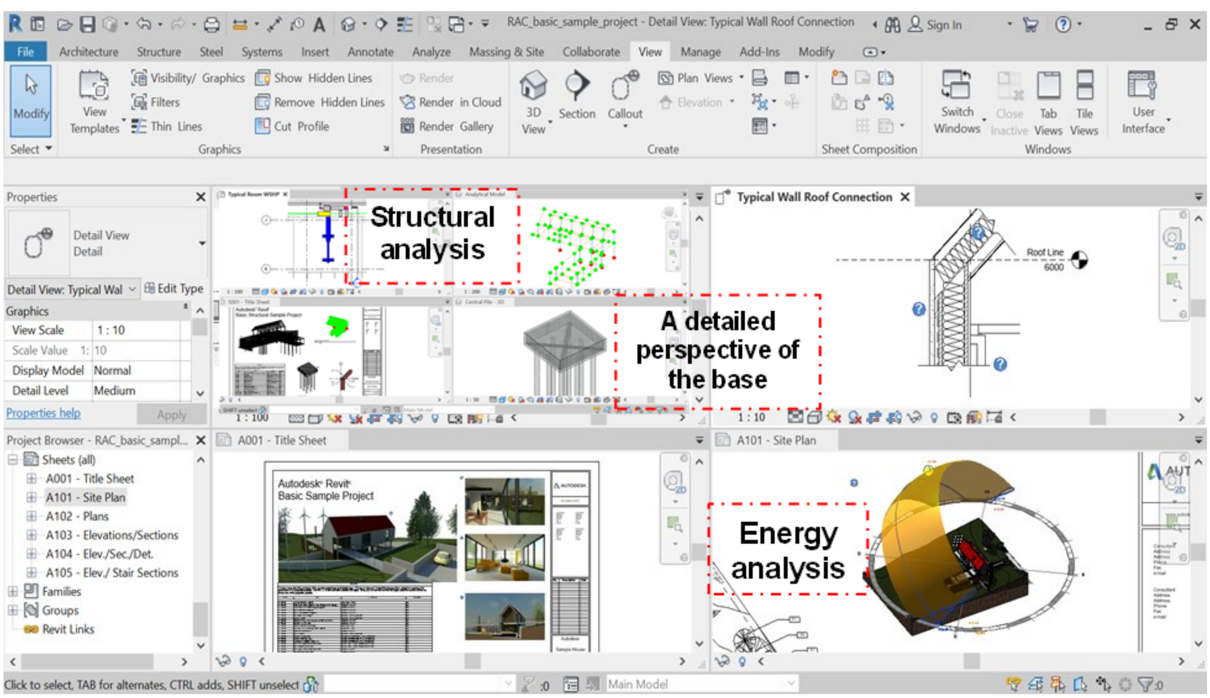


Figure 4: Screenshot of Autodesk Rivet 2020 software showing the program's ability to display multiple systems and analyses of a virtual project.

When compared to the obsolete design method, BIM can obtain information for team designing and this data could be utilised more precisely to assess better sustainability of the building. For instance, daylight analysis, water resources management, and thermal design may all be done while collecting data that can be used to assess Building Research Establishment Environmental Assessment Method (BREEAM) (Harding *et al.,* 2014). Eadie *et al.* (2015) concurred also that enabling comprehensive management processes may save building owners up to 70% of the cost of building maintenance information if integrated adequately into BIM. Marzouk, Azab and Metawie (2018) indicated that constructing a LCC evaluation is an economic study to improve decision making. As a result, the LCC is the premier cost of implementation plus half of the total expenses throughout the building life cycle (Wang, Chang and El-Sheikh, 2012). The total estimated costs of building projects, such as the preliminary construction phase cost, operation and maintenance costs, cost of repairs of a building component, and the life cycle of the built environment, or even just the overall costs of a building throughout its entire life cycle, can be significantly decreased by using a sustainable building strategic plan.

Khosrowshahi and Arayici (2012) illustrated that the project lifecycle information is also beneficial for forecasting maintenance and operating expenses to optimise present investment. Furthermore, BIM assists in creating the maintenance program by inputting the required information about the construction and assets that need frequent maintenance activities. McArthur (2015) notes that BIM facilitates the planning of entire maintenance schedules for each facility, organising maintenance activities, processes, and timetables efficiently, thereby significantly reducing the effort required for building maintenance. Whenever specialised maintenance or extra work is needed, the building original design plans are challenging to utilise. Because the data has not been maintained, the usage of BIM is critical. In addition, the BIM-enabled 3D illustrated maintenance guideline adds to complete facility information being readily available to the maintenance staff and adds value so that facility information is readily available (Diao and Shih, 2019).

Several studies have indicated the benefits of BIM (Autodesk, 2020; Azhar, 2011; Diao and Shih, 2019; Ghaffarianhoseini *et al*., 2017; Harding *et al*., 2014; Jiang, 2011; Kehily, 2016; Marzouk, Azab and Metawie 2018; Zou, Kiviniemi and Jones, 2017), which can be summarised as: time-saving, cost estimation, minimising changes, sustainability analyses, removal of omissions, quality management, logistics management, established life cycle, life cycle cost, operations and maintenance, efficient use of energy, facility management, daylight analysis, thermal design, transparency cost, quantity surveying, quantity take-off, and risk management.

The most potent argument for restricting BIM usage is that CAD operations are simple to execute. The BIM technique, on the other hand, has more complex procedures and requires much information. It is not only challenging, but also little is advertised about its benefits. Also, another problem is management staff has limited knowledge of BIM.

1.4 Research Problem

The construction industry in Saudi Arabia is one of the most complicated and inefficient in sticking to organised plans for project completion, with approximately 44% of projects being delayed (Control and Anti-Corruption Commission KSA, 2015). In addition, time, cost, and quality are just a few of the construction industry's constraints in contrast to other industries.

The Control and Anti-Corruption Commission KSA (2015) has indicated that the authority has monitored many delayed and stalled projects due to insufficiency of follow-up for implementation, as the number of projects that were followed up and examined reached 1526 projects, with a stumbling and delayed ratio of 44% (672 projects). According to Assaf *et al.* (2019), revealed that the main causes of claims and disputes in construction projects in Saudi Arabia are a change or variation in orders due to new client requirements (78%), variations in quantities due to new client requirements (74%), delays caused by contractors (74%), design errors or omissions (72%), and inconsistencies in the drawings and specifications (70%).

There are several reasons for stumbling and delayed projects; the most important are lack of planning, lack of clarity of vision and project documents during the study and design phases of projects, failure to study the nature of the project in terms of location and implementation requirements, the weak information base of the competent authorities on infrastructure, and repeating of change of orders during the project progress process.

Financial estimates for project implementation are considered an essential part of the design work. Also, they are considered an essential part of the necessary documents if they are built on sound foundations and methods. The level of design and its efficacy are directly related when estimating implementation costs. As a result, the consultant designer or engineering department is responsible for cost estimation.

Cost estimation refers to determining the project expected cost in advance of contracting and before implementation of the work, based on the designs developed and the owner's and project requirements. It is uncommon for this anticipated cost to match the project final cost, but the smaller the difference, the more accurate the cost estimate and the degree of competence of the cost estimator. Therefore, the value of Building Information Modelling resides in obtaining an accurate cost estimate, with minimal variations between the actual and predicted costs.

One of the pivotal contributors to these issues is the fact that the project information convenience is not being overseen via an integrated track covering all the various building stages from design to construction to operation and maintenance. Conventional approaches to the collecting and processing of data as well as the estimation of costs usually provokes number of mistakes, confrontations and waste, leading to the increase of the life cycle costs (LCC) of the building projects, particularly if one refers to sustainable ones.

The implementation of Building Information Modeling(BIM)technology can possibly address detected challenges through providing a collaborative space that is used for data sharing and management among the stakeholders involved. BIM aids in precise cost estimation onscreen during the design stage, resulting to lesser differences between actual and expected outlays. However, BIM plays the key role in the fully and integrated capable of delivering sustainable design concepts and materials, helping to reduce the negative environmental impact and ultimately make projects greener.

Nevertheless, BIM has been hesitantly accepted by the construction industry of the kingdom for various practical reasons including protection against change, standardisation, and building the workforce with enough training and capacity. It is the goal of this paper to examine the adoption of BIM by construction companies in Saudi Arabia and the situations involving the building of new projects promoted for sustainibility and life cycle costs reductions. In the context of the Saudi Arabian construction sector, there is a critical need to evaluate how the integration of BIM with LCC methodologies influences the effectiveness, accuracy, and sustainability of construction projects. Despite the recognised potential of BIM to revolutionise project planning and execution, its application in enhancing LCC for the purpose of achieving sustainable construction outcomes remains underexplored in Saudi Arabia. This gap is significant given the country's ambitious sustainability targets and the construction industry's pivotal role in achieving these goals. The problem is compounded by a lack of comprehensive understanding of the specific barriers that impede the effective integration of BIM in LCC practices, and how these hurdles can be overcome within the unique regulatory, environmental, and economic context of Saudi Arabia. Addressing this knowledge gap is essential for developing targeted strategies that leverage BIM technology to optimise LCC analyses, thereby promoting sustainability in the construction sector. The central problem addressed in this thesis is the underutilisation of Building Information Modeling (BIM) in new construction projects within Saudi Arabia, despite its proven benefits in improving efficiency, reducing costs, and enhancing sustainability. The research explores whether similar benefits can be extended to renovation projects, a topic not sufficiently covered in existing research. This lack of comprehensive adoption hinders the achievement of Saudi Arabia’s Vision 2030 goals related to sustainable development and technological advancement in the construction sector."

The research objectives are threefold:

Firstly, the research aims to assess the current state of BIM adoption in construction projects within Saudi Arabia. This involves evaluating the extent of BIM implementation, identifying barriers to adoption, and understanding the impact of BIM on project performance and outcomes.

Secondly, the research seeks to evaluate the impact of BIM usage on reducing life cycle costs (LCC) and improving sustainability in building projects across Saudi Arabia. This involves analysing case studies and empirical data to quantify the benefits of BIM in terms of cost savings, resource efficiency, and environmental impact.

Thirdly, the research aims to propose effective strategies to mitigate the increase in LCC for sustainable building projects through the adoption of BIM technologies and practices. This includes identifying best practices, developing guidelines, and recommending policy interventions to promote BIM adoption and utilisation in the Saudi Arabian construction industry.

1.5 Research Questions

This thesis aims to evaluate the application of BIM during the design and operation phases, to optimise the respective LCC of the building and improve sustainability in governmental projects in Saudi Arabia. In addition, the significance of this research lies in its potential to transform construction practices in Saudi Arabia through the adoption of BIM. By focusing on new construction projects, this study provides empirical evidence on the benefits of BIM, including enhanced project efficiency, cost reduction, and improved sustainability. These outcomes directly support Saudi Arabia's Vision 2030 objectives of economic diversification and sustainable development. The findings could guide policymakers, industry stakeholders, and academia in formulating strategies that leverage technology to optimise construction processes. The following research questions have been proposed to attain this aim:

a. What are the significant challenges of adopting BIM in the Saudi Arabian construction industry and what is the current BIM level in the country?
b. What is the impact of engineers' awareness on minimising the impediments to adopting BIM in Saudi projects?
c. Why do so many Saudi Arabian construction projects have such a high life cycle cost?
d. What are the cost implications of not using BIM technology on the cost, time, and LCC in Saudi Arabian construction projects?

e. How can the BIM environment support the estimated cost analysis of LCC better than is currently practised in Saudi Arabian projects?
f. What could persuade engineers and stakeholders of projects to adopt BIM to save operational and maintenance costs and what are the motivational factors for key stakeholders that encourage the use of BIM?
g. What are the risks of different types of contracts and what is the impact of the final cost of the project?
h. To what extent do signed project contracts in the KSA allow for the successful use of BIM models?

1.6 Research Objectives

In order to answer these questions, the following research objectives have been identified, as follows:

1. To conduct a review of research literature to identify the research gap in knowledge on BIM in Saudi Arabia.
2. To determine enablers and constraints associated with the use of BIM technology in governmental projects in Saudi Arabia.
3. To quantify the extent to which BIM technology is used in Saudi Arabia.
4. To explore the programs currently used during the design phase of construction projects in Saudi Arabia and their compatibility with BIM programs.
5. To study projects in Saudi Arabia that used building information modelling and impact identification to reduce building LCC and enhance sustainability.
6. To understand the types of contracts and building technologies utilised in the Saudi Arabian construction industry and their influence on the implementation of BIM.

7. To define a strategic framework within which BIM can be applied to government projects.

1.7 Proposed Methodology

This thesis exclusively investigates the adoption of BIM in new construction projects within the Kingdom of Saudi Arabia. The focus on new constructions is driven by the current boom in infrastructure and residential development projects aligned with economic expansion plans. While the potential application of BIM in renovation projects is acknowledged, they are not included in this study due to different regulatory and operational challenges that warrant separate investigation. Each research question and objective is crafted to explicitly address the unique aspects of BIM adoption identified as novel in this study. This targeted approach ensures that the research outcomes will provide specific insights and actionable recommendations tailored to the needs of the Saudi Arabian construction industry. The research study will use an exploratory sequential mixed type of research method. In doing the exploratory research, the research will identify the nature of the issue. However, it is not intended to offer compelling proof, but it does assist the researcher to better understand the situation. To achieve the aims of the research, a mixed-method research approach is appropriate; thus, a method is chosen according to the research questions and the methods of data collection and analysis. This will be divided into four phases:

Phase 1: Includes a comprehensive review of the research literature and systematic review. Forms a base of authentic in-depth concepts through which the entire scope of the research can be covered with information related to BIM.

Phase 2: Questionnaires are utilised to measure the extent to which engineers use BIM in Saudi Arabian projects in addition to identifying deficiencies in their non-use.

Phase 3: Includes conducting interviews with expert engineers in the KSA to know the factors affecting the result of using BIM to reduce the operating costs of the LCC.

Phase 4: Undertake a case study and simulation then compare buildings, one of which uses BIM to measure the impact on the LCC. See Figure 5.

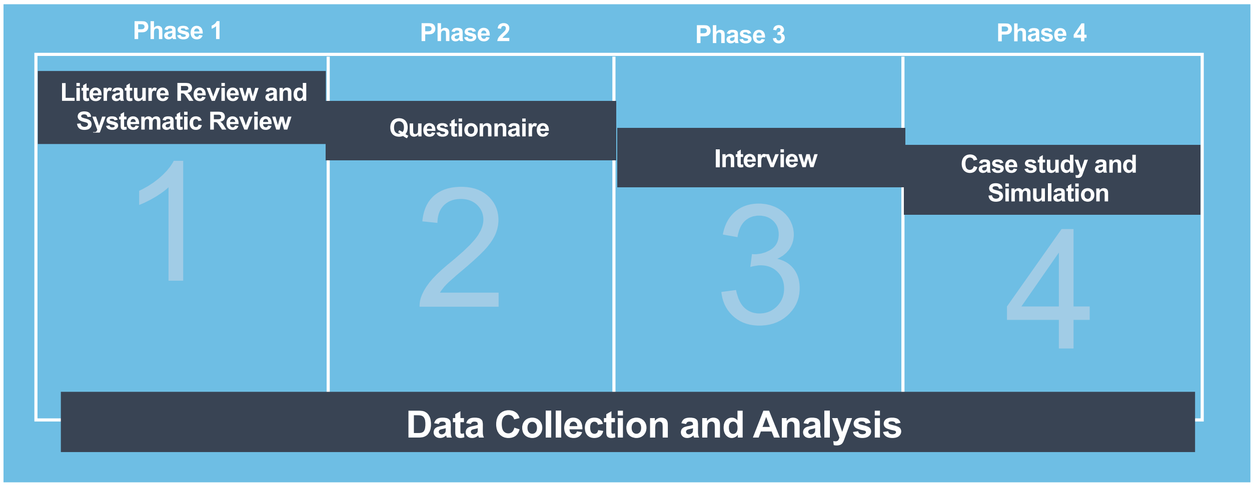


Figure 5: Methodology of the thesis

To achieve the above methodology, a survey questionnaire will be conducted to measure the awareness of engineers in the Kingdom of Saudi Arabia. Furthermore, the first part of the study will be devoted to distributing the questionnaire, using a random sample, and the size of the target population for the field survey is the Saudi engineers registered with the Saudi Council of Engineers. According to Cohen, Manion and Morrison (2018), it is suggested that the larger the sample, the more preferable because it not only increases reliability, but also allows for the application of more complex statistics. Also, the size of the study sample will be determined according to the following Yamane (1967:886) formula (Israel,1992):

- **Calculating the sample size:** n = N / (1 + N e2)

  n = the sample size

  N = the population size

  e = confidence level (1- per cent confident)

For example, the total number of workers in the engineering sector registered with the Saudi Council of Engineers up to the year 2020 reached about 55776 Saudi engineers and this represents the size of the study population. If the number of people in the sample represents 55776 Saudi engineers in the KSA (according to the council of Engineers), the margin of error is 5%, and the confidence level is 99%, then the result will be the required sample size of respondents needed, 656.

After receiving the opinions of the respondents, the relative importance index (RII) for some questions will be applied to determine the order of effect of the features according to the following mathematical formula (Chan and Kumaraswamy, 1997):

- **relative importance index** $\boldsymbol{RII}$ = $(\sum \boldsymbol{W})$ / $(\boldsymbol{A} * \boldsymbol{N})$

  $\boldsymbol{W}$ = the weighting given to each element by the respondents (from 1 to 5).

  $\boldsymbol{A}$ = the highest weight.

  $\boldsymbol{N}$ = the total number of respondents.

An interview, according to Cohen, Manion and Morrison (2018), is a versatile method for data gathering and a valuable tool for academics. Semi-structured interviews will be conducted with BIM experts in Saudi Arabia after obtaining the survey results; 30 BIM experts will be interviewed.

Cohen, Manion and Morrison (2018) highlighted the benefits of case studies offering research data in a more public-facing format than other types of research studies and a range of users may use them. As a result, it lessens the reader's reliance on unspoken theoretical frameworks and keeps the research system more flexible. In order to access the case studies, a group of government departments that supervise government projects will be visited to determine the available projects through which information can be obtained.

As a result, 4 projects will be identified that meet the criteria for the difference between their estimated cost and the actual cost. Consequently, data will be collected for the case study from four cases, involving two projects, each of which includes two recently finished BIM-assisted projects and two older projects undertaken without BIM. Decisively, the successive use of qualitative, quantitative, and exploratory research techniques is anticipated to provide more robust and trustworthy outcomes. See Figure 6.

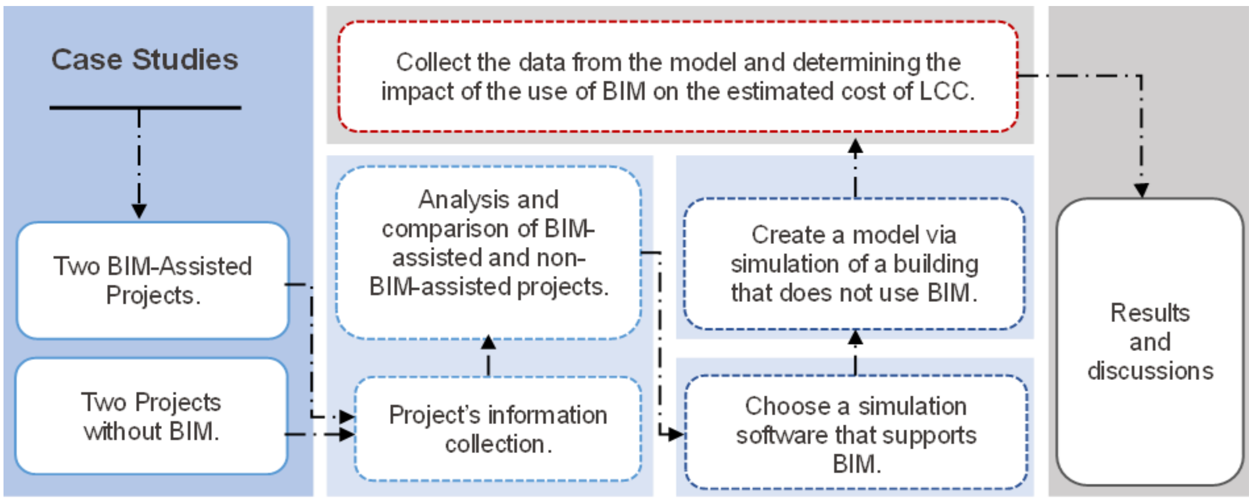


Figure 6: Research techniques.

1.8 Originality of Research and Contribution

According to a comprehensive literature review about BIM, the researcher found that one of the most significant results to come out of this data is that a considerable amount of literature has been published on BIM in most countries worldwide. However, there has been relatively little literature published on BIM in the KSA. Consequently, strong evidence of the knowledge gap was found when the results of the data analysis appeared, so research with a more consolidated approach is needed to cover this gap.

The absence of specific academic literature on integrating BIM with LCC in Saudi Arabia's construction sector underscores a significant gap, offering a prime opportunity for original research contributions. Exploring this integration could produce essential insights and methodologies that not only propel Saudi Arabia's construction industry forward but might also resonate with and influence sustainable construction practices globally.

In addition, published research has examined the integration of BIM into LCC analysis. Most of these studies explained multiple ways of integrating LCC methods through BIM. Moreover, there are limited studies on the method of organising and managing information between project phases utilising BIM during the project life cycle. There is a lack of information clarity surrounding the information management of construction in the KSA while utilising BIM through LCC to maximise the likelihood of obtaining the desired benefits of BIM.

The most significant reason for choosing this field is the presence of an apparent problem in the Saudi projects represented, in that there is no standard for BIM implementation in the KSA that is commensurate with the project implementation process. In addition, there is a lack of a clear standard and framework through which data on the construction can be transferred between all phases of the project, which will increase the LCC. Consequently, these problems will increase the life cycle costs of the project as a result of the poor automation of building sector regulations. This indicates a gap in this field's knowledge base, which this research intends to address.

The researcher will implement the BIM framework via LCCs in the KSA projects in order to enable a clearer understanding of project complexity, assist in the management of coordination and building information, and provide clearer data sources for stakeholders. Moreover, this research will measure the effect of the type of construction contract on the use of BIM in projects in the KSA. Furthermore, the BIM framework supports stakeholder engagement by creating a collaborative environment for sharing and updating project information in the KSA and optimising the effectiveness of the LCC. The field of BIM is still at a nascent stage compared to other fields and needs more research to confirm and develop its concepts.

The knowledge contribution to this field will increase the awareness of engineers of the importance of BIM and will support the mechanism of applying the principle of sustainability through reducing costs, which is one of the goals of sustainability. This thesis introduces a novel framework that integrates BIM with LCC specifically designed for the Saudi Arabian regulatory and economic context, using a mixed-methods approach that combines quantitative data with qualitative insights from local industry experts. This approach not only enhances the understanding of BIM's potential in Saudi Arabia but also provides actionable strategies tailored to local needs, which are not addressed by the currently available global research.

1.9 Structure of the Thesis

Chapter 1: Introduction

This chapter introduces the research topic and outlines the significance of BIM in sustainable construction. It also presents the research objectives and provides a roadmap for the entire study. Additionally, the chapter highlights the research methodology and structure of the thesis.

Chapter 2: Literature Review

The chapter conducts a comprehensive review of global literature and systematic review on BIM, its applications, and sustainability in construction. Thereafter, the chapter identifies research gaps, emphasising the need for localised studies in Saudi Arabia. It also lays the foundation for the research by discussing BIM's global trends and challenges.

Chapter 3: Research Methodology

Chapter three details the research approach including the data collection and analysis methods. It also discusses the case study approach, data sources, and tools used for modelling and analysis. Later, the chapter explains the selection of residential projects as the focus of the case study.

Chapter 4: Quantitative Data Analysis

This chapter focuses on the quantitative analysis of survey data, examining the awareness of BIM dimensions and enablers and constraints in the KSA. It also quantifies the extent of BIM technology usage and explores program compatibility during construction design phases.

Chapter 5: Qualitative Data Analysis - BIM on LCC in the KSA

Chapter 5 presents qualitative data analysis based on interviews, exploring BIM's impact on LCC, contracts, risks, challenges, and advantages in the KSA context.

Chapter 6: Qualitative Data Analysis - Case Studies and Simulation

Chapter 6 focuses on case study analyses, covering a range of projects in the KSA, and introduces simulation. It provides insights into diverse construction scenarios and outlines the methodology for simulation and optimisation.

Chapter 7: Simulation and Optimisation - Residential Project (900 Units) in the KSA

This chapter specifically focuses on the residential project in the KSA, detailing the methods of simulation, energy cost and life cycle cost analyses, and sustainability assessments. These are achieved using tools like Autodesk® Insight 360 and One Click LCA.

Chapter 8: Discussion and Conclusion

Chapter 8 analyses the study's results including the achievement of the research objectives and presents a discussion on the impact of BIM tools and circular economy principles on sustainability. The chapter acknowledges the study's limitations and provides recommendations for future research. The chapter concludes the thesis by emphasising the significance of energy-efficient design and BIM integration for sustainable construction practices in the KSA. See Figure 7.

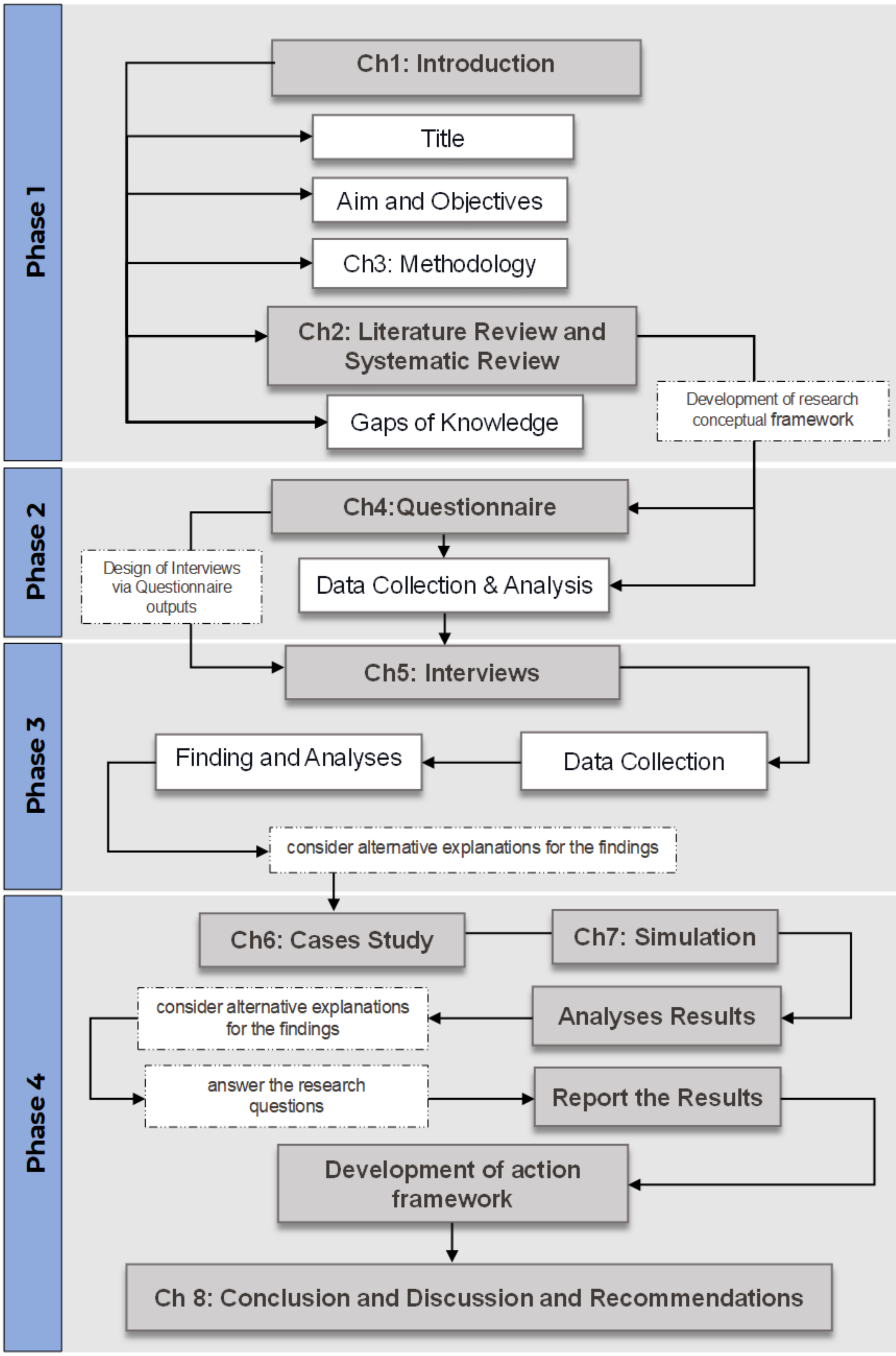


Figure 7: Research phases

1.10 Chapter Summary

Overall, the purpose of this chapter is to shed light on BIM, particularly in the construction industry. More specifically, this chapter highlights the main research problem in the study context that lays the foundation for the research questions and objectives. This chapter also provides a base for the literature review section.

The next chapter provides in-depth knowledge relating to BIM in the form of its history and the role of BIM in other domains. Chapter 2 will provide a comprehensive understanding of the landscape that surrounds BIM, further contextualising its importance within the construction industry and also highlighting the critical gaps in the literature.

Chapter 2

Literature Review

Content from this chapter has been published:

Building Information Modeling (BIM) towards a Sustainable Building Design: A Survey
Alasmari, E., Martinez Vazquez, P. and Baniotopoulos, C., 2022. Building Information Modeling (BIM) towards a Sustainable Building Design: A Survey. *Proceedings of the CESARE22, 3rd Coordinating Engineering for Sustainability and Resilience, Irbid, Jordan*, pp.6-9.

A systematic review of the impact of adopting Building Information Modeling (BIM) on Life Cycle Cost (LCC)
Alasmari, E., Martinez-Vazquez, P. and Baniotopoulos, C., 2022. A Systematic Literature Review of the Adoption of Building Information Modelling (BIM) on Life Cycle Cost (LCC). *Buildings*, *12*(11), p.1829.

Life Cycle Cost in Circular Economy of Buildings by Applying BIM: A State of the Art.
AlJaber, A., Alasmari, E., Martinez-Vazquez, P. and Baniotopoulos, C., 2023. Life Cycle Cost in Circular Economy of Buildings by Applying Building Information Modeling (BIM): A State of the Art. *Buildings*, *13*(7), p.1858.

Enhancing Life Cycle Costing (LCC) in Circular Construction of Buildings by Applying BIM: Literature review.
Alasmari, E., AlJaber, A., Martinez-Vazquez, P. and Baniotopoulos, C., 2023. Enhancing Life Cycle Costing (LCC) in Circular Construction of Buildings by Applying BIM: A Literature Review. *Creating a Roadmap Towards Circularity in the Built Environment*, pp.407-417.

2 Chapter Two: Literature Review

2.1 Introduction

This chapter highlights past and present trends in BIM and provides a critical evaluation of the literature relevant to the concept. Furthermore, it presents the necessary information to allow the reader to understand the background of the construction industry including the economic position of the KSA. Furthermore, this chapter demonstrates the situation of BIM, definitions of BIM, and provides a critical analysis of the literature review relevant to BIM on the LCC. Based on the past literature, the study gaps will be identified.

2.2 Construction Industry

There is no doubt that the construction industry has contributed effectively to global economic growth by creating multiple jobs. Therefore, the construction sector worldwide consumes 40% of the primary energy needs, and 80% of the energy use is operating energy for buildings occupied by humans (Huang *et al.,* 2018). Besides, both of the European Union and the United States of America consider the construction sector a considerable cause of greenhouse gas emissions approximately 36-38% (Santos *et al.,* 2019). Therefore, the construction sector has a significant impact on energy and water needs over the next 50-80 years (Bauer, Mösle and Schwarz, 2010). On the other hand, the construction sector is a major financier of the economies of many countries, despite a significant impact on the environment in recent years. Indicated Zutshi and Creed (2015) that human-made buildings and industrial activities led to the degradation of the natural environment, and focused on the need to preserve the environment through the wise use of raw materials for construction or industry compatible with sustainability in order to preserve the environment by using recycled materials. However, it is thought that the process of manufacturing and transporting building materials, the construction process, and the use of the building by its occupants are all energy and natural resource-consuming processes. They often cause air, water, soil, sound and light pollutions and other pollutants. It can be said that buildings make essential changes, mostly negative, at the level of the local climate, as well as the level of natural surroundings or construction.

According to Dakhil (2017), there is evidence that growth in population has a positive effect upon the future of the construction industry, the population expected that by the year 2050 it would be 9 billion, also the construction sector represents about 11% of Global Gross Domestic Product (GDP), and by the year 2020, the construction sector is expected to grow until it reaches 13.2%. As shown previously, there will be an expansion in the construction cycle in the coming years, which foretells the construction sector a bright future. Global Construction 2030 (2020) indicated that it is expected that by the year 2030, about 212 trillion dollars will be spent on the construction sector. However, the most critical question remains regarding the mechanism that countries will take in the construction process, which will effectively influence the decision to implement building information modelling.

In Saudi Arabia, the construction sector ranks second in the economy, contributing 8% to domestic GDP, with significant investments and reliance on this sector. The Kingdom's commitment to construction is evident in its 43% income allocation to construction, surpassing the Gulf Cooperation Council (GCC) projects cost index. This is shown in Figure 8.

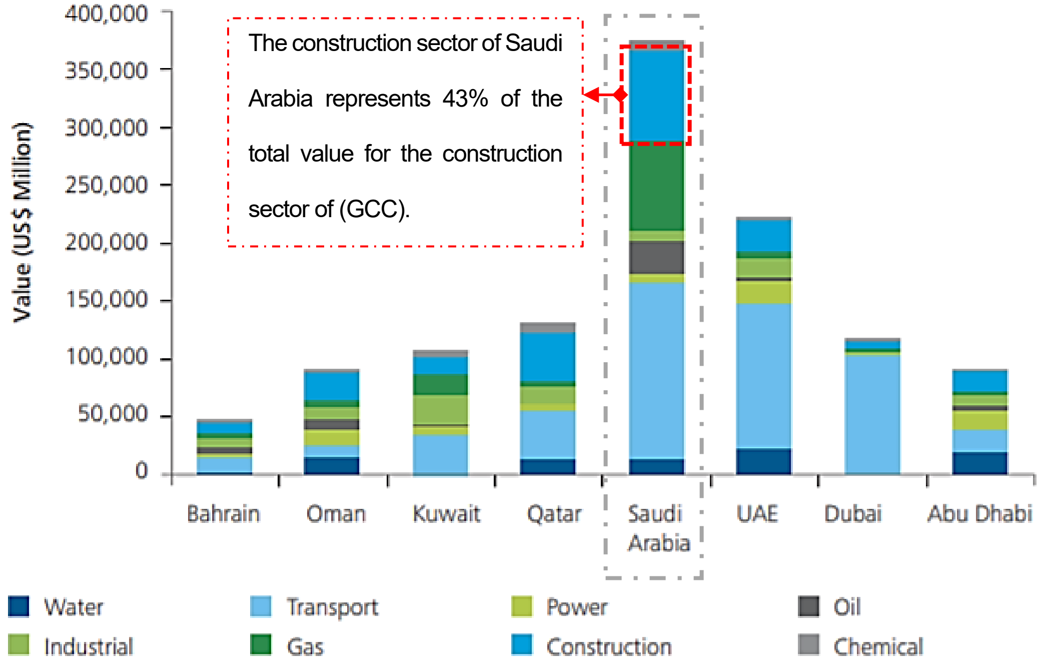


Figure 8: Index of the cost of projects during the period 2014-2020 in the GCC (Elhendawi, 2018)

From the practical perspective, Deloitte's (2018) report indicated that the decline in oil prices during the period of 2016 and 2017 clearly affected the spending for projects as the value of expenditures decreased during that period. The graph in Figure 8 shows that the cost of project contracts amounted to $79 billion for the year 2018 compared to 2017 that amounted to $124 billion. For 2016, it reached $116 billion. In contrast, 2014 and 2015 showed increased value than the years that followed because the economy had fluctuated in those periods. One question that needs to be asked, however, relates to the extent of the continued growth of the construction sector in the Kingdom; is it related to the rise in oil, or will there be other trends to invest in the construction sector as a significant income for the KSA?

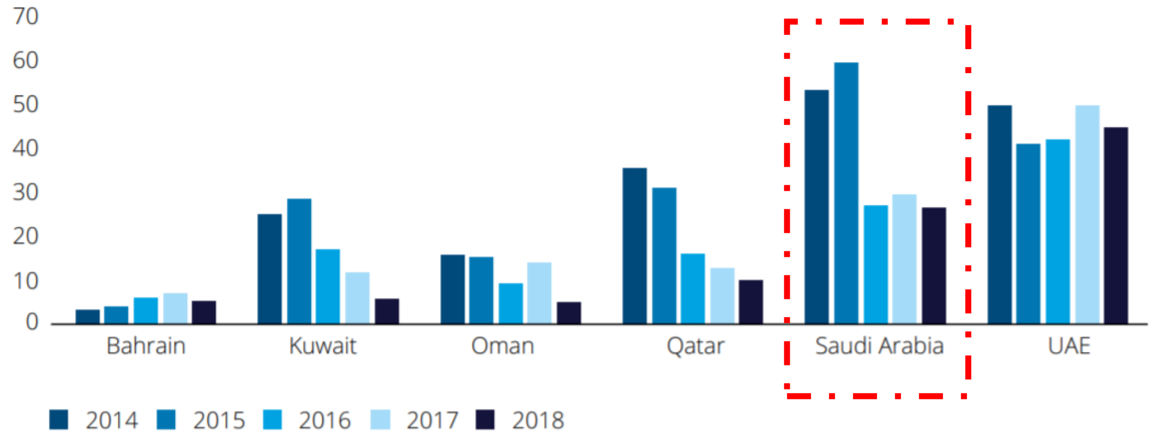


Figure 9: Value of contracts for projects during the period 2014-2018 in the GCC (Deloitte, 2018)

Figure 10 shows that the construction sector still has the largest share of the value of contracts compared to other sectors despite the decrease in the value of contracts during the period 2014-2018.

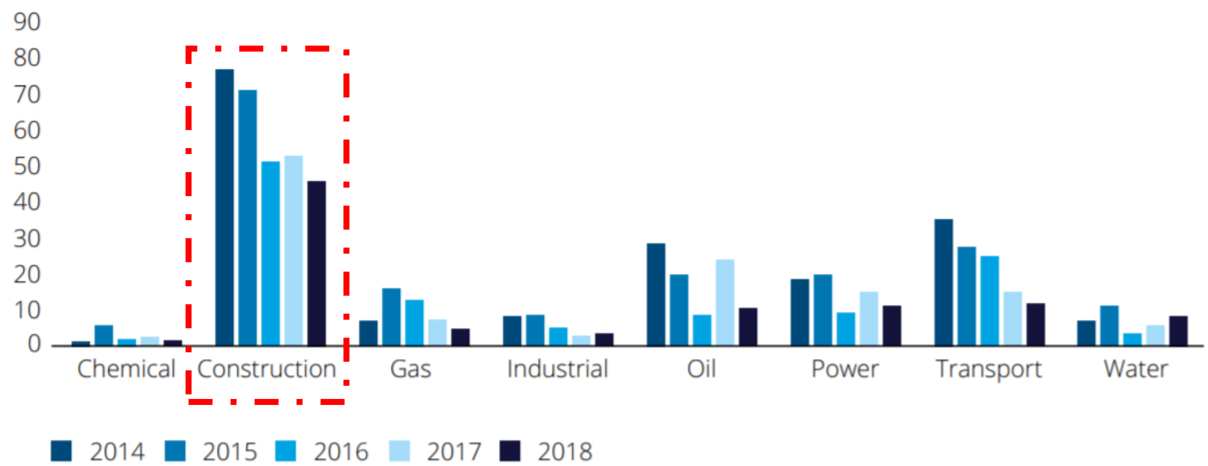


Figure 10: Value of contracts by sector during the period 2014-2018 in the GCC (Deloitte, 2018)

The Ministry of Economy and Planning's (2018) report indicated that the growth rate of the construction sector in the KSA is expected to be 7.2% annually under the ninth development plan, which is higher than the growth rate of 4.7% in the previous plan (see Figure 10).

However, Saudi Vision 2030 is working to invest, reviving the construction industry and attracting international companies to invest in this field. In this context, it is worthwhile considering the size of the major projects implemented in the Kingdom of Saudi Arabia, which is estimated at a total value of $272,400 million, as shown in Table.1.

Insufficient attention to the design phase due to an overload of project implementation can lead to the omission of important implementation items. However, the success of those projects is determined by cost, time, and quality. As a result, before beginning the project execution, it is essential to use BIM to minimise omissions or redundancy, save time, and benefit the return-on-investment study to help stakeholders decide before embarking on the implementation of the project. It confirms the importance of applying BIM to those projects, which will show its benefits from the design, through the implementation, up to the operation and maintenance stage.

Table 1: Major projects planned for implementation in Saudi Arabia (MEED Projects, 2020)

Largest projects in Saudi Arabia		
Project name	**Budget ($m)**	**Completion date**
Neom: Infrastructure and Utilities	100,000	2025
Dahiyat Alfursan	20,000	2025
Mecca Metro	16,000	2030
Jeddah Metro	13,000	2023
Red Sea Project	10,000	2030
Makkah Region Development - Al Faisaliah City	10,000	2025
GACA - KAIA: Phase 2	10,000	2026
REPDO - Renewable Energy Program: Round II	10,000	2023
Jeddah Metro: Orange and Blue Lines	8,000	2023
Mecca Metro: Lines B and C	8,000	2024
Saudi Landbridge	7,000	2023
Third Phosphate Fertiliser Manufacturing Facility	6,400	2024
New Jeddah Downtown	5,000	2029
Mixed Feed Cracker and Derivatives Complex	5,000	2024
Yanbu Jeddah Jizan and Taif Khamis Mushayt Abha Rails	4,200	2025

Mecca Metro: Line D	4,000	2024
Mecca Metro: Line A	4,000	2024
Jubail 3 IWPP	4,000	2022
Mecca Metro: Phase 1 (Lines B, C): Part 1: Package 3	3,547	2024
Jeddah Metro: Red Line	3,500	2023
Solar PV Project at Sudair	3,000	2023
Riyadh Storm Water Drainage Project	2,900	2022
The Avenues Riyadh: Mixed Use Development	2,700	2021
Mecca Metro: Phase 1 (Lines B, C): Part 1: Civil: Package 1	2,653	2024
Al Rayis Development	2,500	2027
Shuqaiq Power Plant Expansion: Phase 1	2,500	2022
Jeddah South Power Plant: Phase 2 Expansion	2,500	2023
Kaaki Development in Mecca	2,000	2022
Total budget of projects ($m)	**272,400**	

The General Authority for Statistics of Saudi Arabia (2018) prepared a report on the characteristics and components of construction work for buildings and civil engineering works and concluded that the total operating revenue for construction activity for the year 2018 reached about $ 87,963,583.46, an increase of 54% over the year 2017 with the value of revenue reaching $56,830,723.31, as shown in Table 2.

Table 2: Operating revenues by construction activity in Saudi Arabia from 2017-2018 (The General Authority for Statistics, 2018)

Economic Activity		2017	2018
1	Construction of buildings	30,153,964.50	49,588,897.62
2	Civil engineering	6,960,508.36	12,092,023.10
3	Specialised construction activities	19,716,250.45	26,282,662.75
Total $		**56,830,723.31**	**87,963,583.46**

The 2018 report of the Ministry of Finance of Saudi Arabia indicated that the financial challenges in the environment of operation and maintenance contracts are because of a lack of financial credentials due to the lack of information and automation, the insufficiency of an automated system for preventive maintenance to improve the operational performance of buildings, and reduction of maintenance costs. In 2018, total government spending on operation and maintenance was estimated at $ 20.77 billion, as shown in Figure 11.

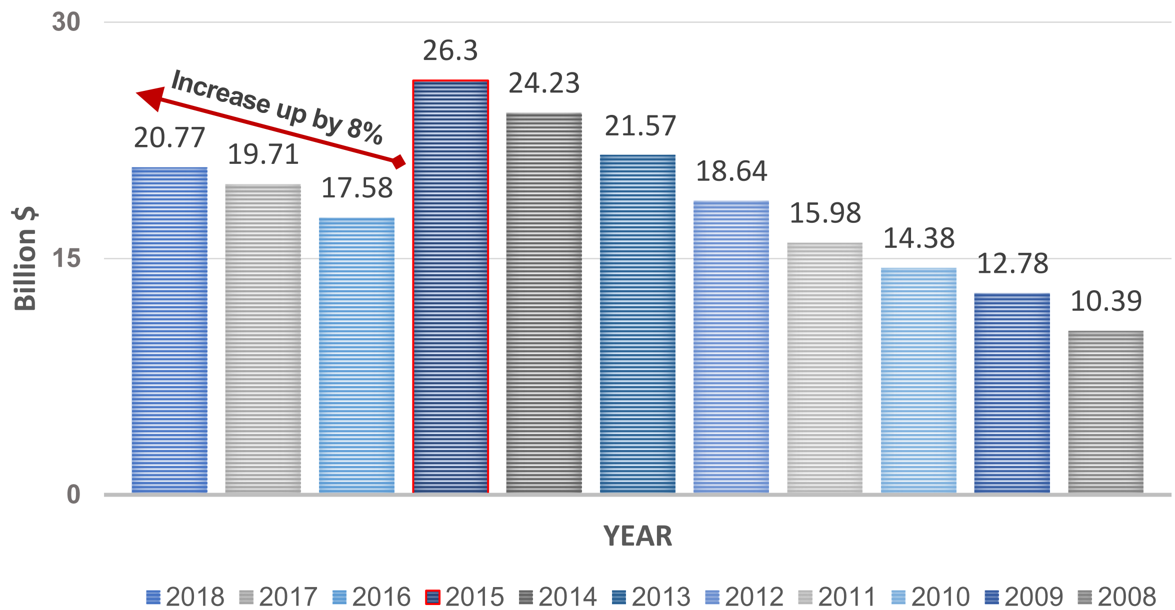


Figure 11: Value of the operation and maintenance expenses during the period 2008-2018 in the KSA (Ministry of Finance, 2018)

Figure 11 illustrates the operation and maintenance expenses within the budget of the Kingdom of Saudi Arabia during the ten years from 2008-2018. It can be clearly seen that a decrease in operating and maintenance expenses within the budget of the Kingdom began in the year 2015 and started to grow slowly in line with the total government budget. However, the spending rate in the last three years increased by more than 8% in operation and maintenance. Consequently, the importance of applying BIM became clear, to reduce the costs of operational maintenance, which is observed to rise annually.

The increasing expenditure in the construction sector in the KSA highlights the growing importance of managing the building life cycle costs. However, productivity in the construction industry remains a major challenge due to high costs, which can be mitigated with the use of technology. The process of activating the application of building information modelling systems has become essential due to the high operating costs of buildings. However, it is necessary to start implementing the activation of building information modelling from the design stage to convert the implementation into a digital format through which it is easy to reduce operating and maintenance costs. Besides, data on the enterprise life cycle is also useful for anticipating maintenance and operational expenditures to enhance current capital.

2.2.1 Saudi Arabia - Construction Industry

Since 2015, the Saudi construction industry has experienced significant growth and has become the largest in the Middle East. Shash and Habash (2020) argued that the construction industry contributed to a total gross outcome of 6.35% between 2011 and 2015, and rose to 7.05% in 2020, implying a jump from a value of US$105.6 billion in 2015 to US$148.5 billion in 2020. The most common types of contracts used in Saudi Arabia are the lump sum and unit price, with owners and contractors using both contracts in about 94% and 91% of their projects, respectively (Shash and Habash, 2020). Government owners typically use these two types of contracts. In essence, the government purchasing regulations demand that all governmental agencies should use lump sum or unit prices in their purchases, which includes construction projects (Alhazmi *et al*., 2021). Their popularity is due to how owners allocate budgets for building investments; owners believe that the allotted budgets are sufficient and desirable to obtain commitment from contractors, but due to poor quality and ambiguity, numerous change orders typically drive costs higher, thereby developing conflicts and disputes. For instance, increasing funding for government projects is difficult and time-consuming (Alhazmi *et al*., 2021). The majority of contractors (60%) and the majority of owners (60%) experience disputes at least monthly, but most government owners (55.89%) report a dispute each month (Shash and Habash, 2020). Contractors also tend to subcontract, which further creates room for more conflicts and disputes. In addition, private owners break their projects into various packages, awarding each package to a contractor and this also creates room for more disputes and conflicts. In addition, there are ambiguities in project documents, which are exacerbated by poor project management practices (Shash and Habash, 2020).

Figure 12 illustrates the implementation phases of construction projects in the Kingdom of Saudi Arabia, which include planning, design, construction, and operation and maintenance, regardless of the type of contract selected. During the planning stage, the feasibility of the project is conducted as well as developing objectives and goals (Alhazmi *et al.,* 2021; Hamida and Hassanain, 2020; Cao, Kamaruzzaman and Aziz*,* 2022). The design phase entails designing the blueprint for the project, which includes coming up with the project implementation process including engineering specifications (Alhazmi *et al*., 2021; Hamida and Hassanain, 2020; Cao, Kamaruzzaman and Aziz*,* 2022). The construction phase is the actual construction process, and this entails implementing the design of the project. It entails the actual implementation and team involvement in accomplishing the project goals, tasks, and milestones (Alhazmi *et al.,* 2021; Hamida and Hassanain, 2020; Cao, Kamaruzzaman and Aziz, 2022). The operation phase happens once the project implementation has been completed and served the purpose it was intended for. For instance, a building will house businesses and bridges will be used for providing vehicle transit. The operation phase allows the investor to recoup the initial cash outlays (Albogamy and Dawood, 2015; Badran, AlZubaidi and Venkatachalam, 2020; Tomek and Matějka, 2014; Wetzel and Thabet, 2015). If there are flaws, then the renovation phase is initiated, which helps rectify the flaws.

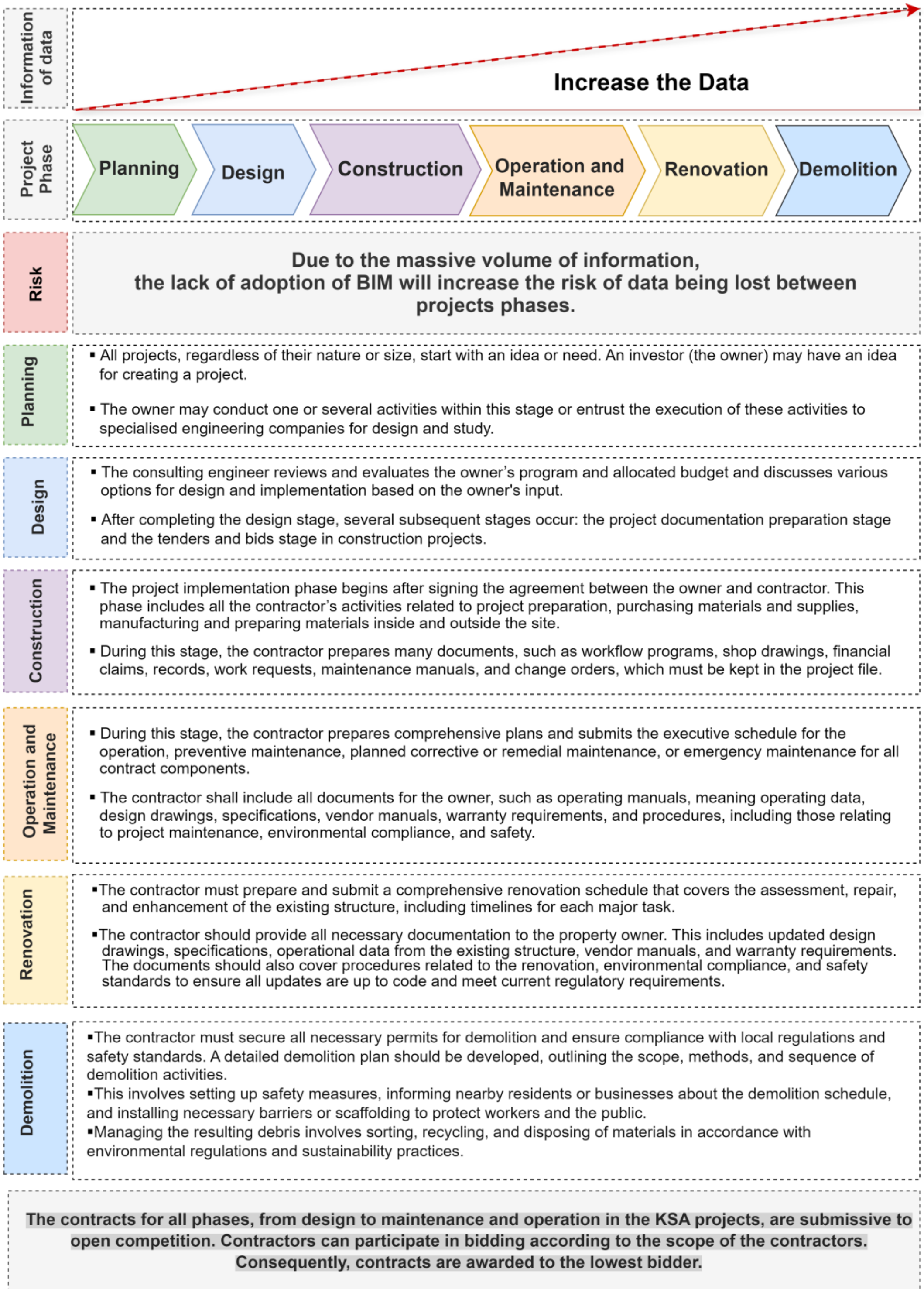


Figure 12 : Process of implementation for projects in the KSA

2.3 Current Situation of BIM

In recent decades, BIM has emerged as a promising innovation in the construction industry, addressing performance challenges in project implementation. Even though modelling of 3D geometry has a history dating back six decades (Eastman *et al*., 2008), the concept of BIM started in the 1970s and saw widespread adoption in the mid-2000s with the United States leading the way. Professor Charles M. Eastman laid the foundation for the BIM concept in the 1970s (Forbes and Ahmed, 2011). Initially, 3D representation methods were developed in the late 1960s and contributed to the creation of computer-aided graphics in 1987. The development of 3D solid modelling, in 1973, involved independent groups from Cambridge University, Stanford, and the University of Rochester (Eastman *et al*., 2008).

Buildings description systems (BDC) development began in 1975, focusing on creating a database for building design and specifications, facilitating analysis and cost reduction through data analysis. The evolution of design through computer systems introduced programs, like GLIDE (Graphical Language for Interactive Design), in 1977 for performance analysis and precise design (Eastman and Henrion, 1977).

Software development continued, leading to the emergence of Building Product Model (BPM) in 1989, designed to integrate with CAD (Latiffi, Brahim and Fathi, 2014). Subsequently, Generic Building Model (GBM) was established in 1995 to enhance information integration with BPM throughout the design and construction lifecycle (Latiffi, Brahim and Fathi, 2014). Recognising the construction sector's need to keep pace with technological advancements, building information modelling applications were applied in the year 2000 (Schlueter and Thesseling, 2009).

As noted earlier, computer software development continued in the construction sector; in 1987, the effective beginning of BIM was through the ArchiCAD software program of design, and 2004 saw the beginning of an application, the Bentley Systems software program, to activate BIM (Logothetis, Delinasiou and Stylianidis, 2015). Besides, the first product from BIM was started by Revit Architecture™ in 2002 via the company Autodesk (Jiang, 2011). However, based on the evidence and examples shown above, a time-line showing the history of BIM can be seen in Figure 13.

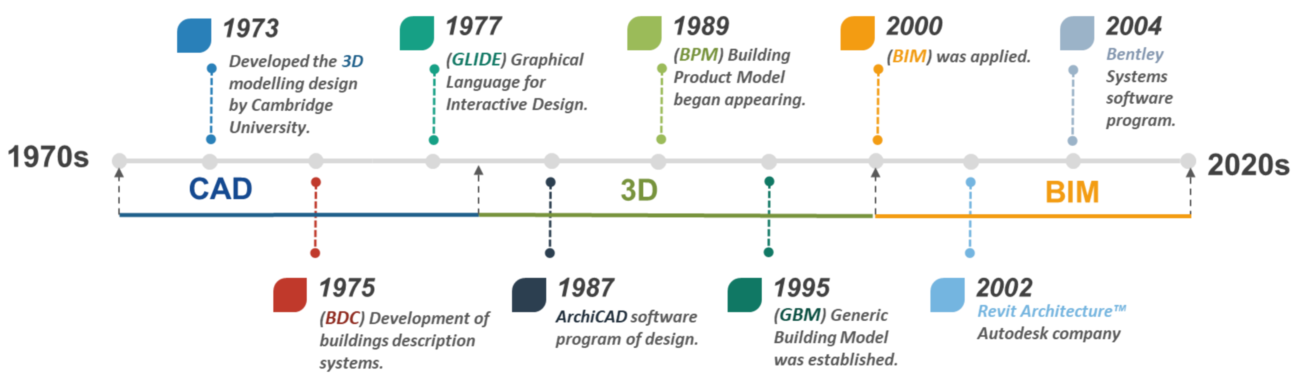


Figure 13: History of the development of BIM from the 1970s to 2020s

The concept of BIM is not a modern one as it has existed since 1970; however, the original concept differs from its current state. This concept has evolved over three stages: starting with CAD, it evolved into 3D, spawning automated BIM programs such as Revit and Bentley. The idea of BIM was experiencing many challenges, the most important of which is the overlap and sharing of information for several specialities simultaneously. However, this challenge led to open new horizons to uncover problems, faults, and overlaps between the different engineering disciplines during the design phase.

In 2008, Bew and Richards introduced the BIM Maturity Model in the UK. Level 0 is used to create the engineering drawing using the (CAD) program, and the information is printed on paper - that information is exchanged through the engineering team; level 1 is used to optimise

(CAD) information by 2D and 3D to represent information of the building, such as the British Standard BS1192:2007; level 2 is used to analyse information of the building such as the time and cost management; and level 3 is used to collect and integrate information via iCloud BIM models to manage the life cycle by data of the Industry Foundation Classes (IFC), the process of the Information Delivery Manual (IDM), and the terms of the International Framework for Dictionaries (IFD) (Bavafa, 2015), as illustrated in Figure 14:

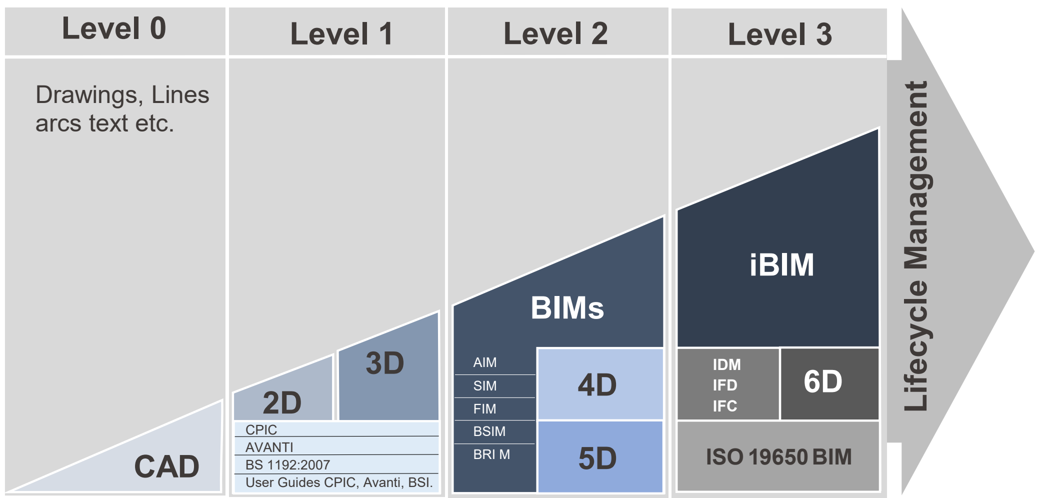


Figure 14: BIM Maturity Model as proposed by Dowd and Marsh (2020)

In 2007, both the Norwegian and Danish governments requested adoption of BIM in all projects (Smith, 2014). Thus, according to research by Kjartansdóttir (2011), from a survey conducted in Iceland, it was found that around 40 per cent of engineers used BIM. In addition, three McGraw Hill publications indicated that there had been significant growth in the use of BIM in the United States, with BIM projected to have been utilised in 75 per cent of projects between 2007 and 2009 (Eadie *et al.*, 2015). In addition, Singapore's government began adopting BIM in public projects in 2015 (Smith, 2014). The Australian government decided to adopt BIM in the public sector and took the initiative in 2016 without interfering with industry procedures or technical specifics (Eadie *et al.*, 2015). Autodesk (2020) indicated that the authorisation of BIM initiated its application across the world, and this is due to the expected rise of the world population reaching 7.9 billion by 2050 according to the United Nations report. The importance of activating BIM is the need of the projects' sector to transfer project information and data during implementation to benefit from it in the period of operation and maintenance. The countries that currently adopt BIM Autodesk mandates are: the United States, Brazil, Chile, UK, Norway, Denmark, Germany, Finland, Latvia, UAE, Kazakhstan, Japan, South Korea, Vietnam, and Australia, and the countries in the accreditation planning stage are: Mexico, Colombia, Peru, Argentina, Uruguay, France, Italy, Spain, Czech Republic, China, Indonesia, Singapore, and New Zealand. Figure 15 depicts the adoption of BIM worldwide.

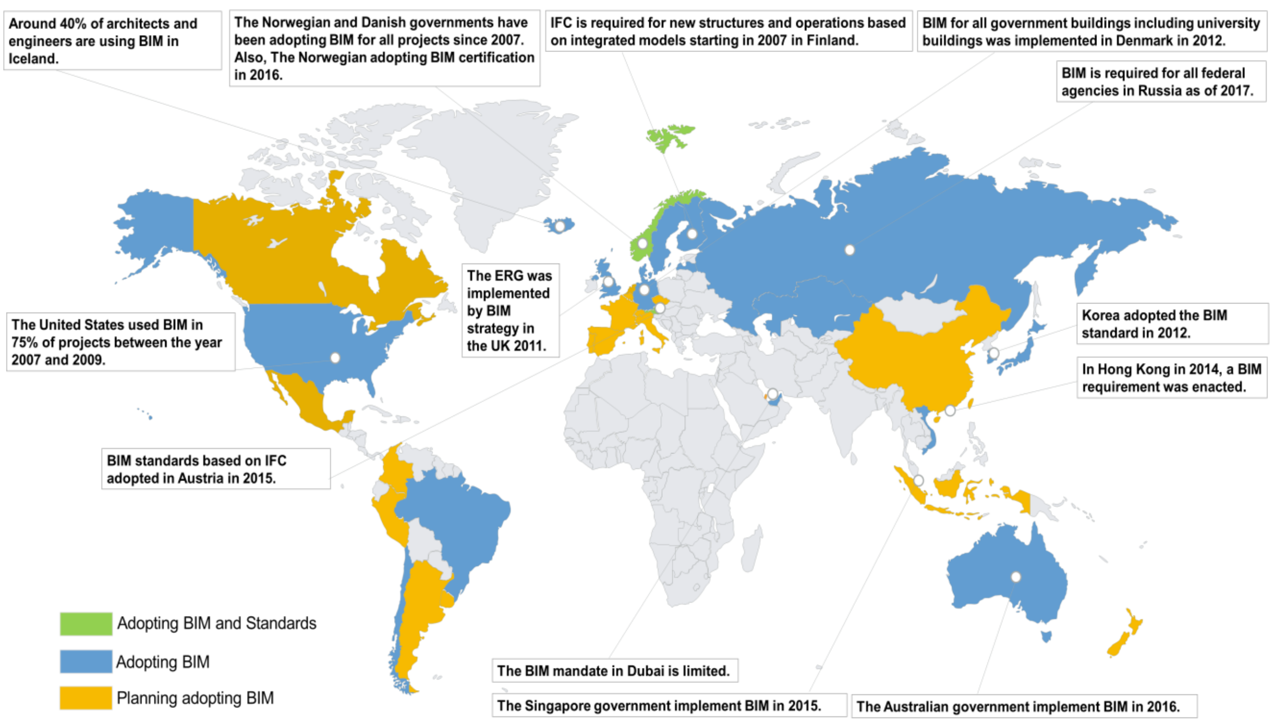


Figure 15: Current situation of BIM adoption around the world (Smith, 2014; Eadie *et al.*, 2015; Autodesk, 2020; Paul, 2018)

A careful analysis reveals a substantial growth in the use of BIM, particularly in the United States where it is more prevalent compared to Europe. While interest in BIM has surged in recent years, its widespread adoption remains in its early stages in some countries.

This technology shift in the construction industry has transformed how engineers approach design and information communication. BIM facilitates the transition from traditional CAD engineering drawings to a comprehensive 3D approach, offering a wealth of data on design, quantities, sizes, dimensions, and building components.

BIM has expanded the scope of the construction process, encompassing design, construction, the building entire lifecycle, and performance evaluation from start to finish. Realising the full potential of BIM necessitates a well-trained workforce and is driven by factors like the growing demand for construction projects, expedited construction schedules, artificial intelligence, and the capacity to assess sustainability and energy efficiency (Eastman *et al*., 2008).

2.3.1 Definition of BIM

BIM, a progression from CAD (Computer-Aided Design), originated in the 1980s with 2D drawing. CAD primarily relies on computer-assisted design drawings, operating in a 2D linear manner, lacking three-dimensional understanding. This results in redrawing entire building elements when changes occur. Initially viewed as a software tool simulating engineer input, BIM has evolved into a multifaceted concept. Multiple definitions of BIM exist, but they share core elements like technology, data sharing, building stage analysis, and development. Table 3 summarises numerous BIM definitions from various experts and organisations, highlighting common terms like software, data, structure, process, and analysis for preliminary comparison and exploration.

Table 3: Different definitions of BIM with analysis of common factors

	Economic Activity	Common Factor
1	"BIM is the development and use of a computer software model to simulate the construction and operation of a facility. The resulting model, a Building Information Model, is a data-rich, object-oriented, intelligent and parametric digital representation of the facility, from which views and data appropriate to various users' needs can be extracted and analysed to generate information that can be used to make decisions and improve the process of delivering the facility" (Associated General Contractors of America, 2005).	Computer software A data-rich Intelligent Construction Operation Analysed Improve
2	"BIM is a digital representation of physical and functional characteristics of a facility. As such it serves as a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle from inception onward. A basic premise of BIM is collaboration by different stakeholders at different phases of the life cycle of a facility to insert, extract, update or modify information in the BIM process to support and reflect the roles of that stakeholder. The BIM is a shared digital representation founded on open standards for interoperability" (NBIMS, 2007).	A digital A facility Information life-cycle Support Software
3	"BIM is a collaborative tool used by any member of the architectural, engineering and construction (AEC) industry based upon a number of software solutions" (Robinson, 2007).	Collaborative tool Solutions
4	"BIM as a modelling technology and associated set of processes to produce, communicate, and analyse building models" (Eastman *et al.*, 2008).	Technology Analyse
5	"BIM is an emerging technological and procedural shift within the Architecture, Engineering, Construction and Operations (AECO) industry" (Succar, 2009).	Technological Emerging

6	"BIM is a digital representation of the physical and functional characteristics of a building over its life cycle" (BS 8536 Facility management briefing, 2010).	**A digital** **life-cycle**
7	"BIM is a shared digital representation of physical and functional characteristics of any built object (including buildings, bridges, roads, etc.) which forms a reliable basis for decisions" (BS ISO 29481-1, 2010).	**A digital** **A shared** **Built object**
8	"A building information model characterizes the geometry, spatial relationships, geographic information, quantities and properties of building elements, cost estimates, material inventories, and project schedule" (Azhar, 2011).	**Characterises** **Information** **Estimates**
9	"BIM is construction of a model that contains the information about a building from all phases of the building life cycle" (ISO 16757-1, 2015).	**Information** **life-cycle**
10	"BIM is an intelligent 3D model-based process that gives architecture, engineering, and construction (AEC) professionals the insight and tools to more efficiently plan, design, construct, and manage buildings and infrastructure" (Autodesk, 2020).	**Intelligent** **Efficiently**

An objective of the analysis for the definitions of BIM was to investigate the extent to which the definitions of BIM are compatible with each other. It has been clearly shown that most definitions agree that BIM is a software tool, except some definitions determine that BIM is a process or information (Azhar, 2011; ISO 16757-1, 2015; Autodesk, 2020).

According to the definitions of BIM by Associated General Contractors of America (2005) and NBIMS (2007), BIM can be conceptualised as a representation of data in a digital form. The digital representation is assisted by simulation software that acquires data, analyses it, and supports decisions based on user requirements. Therefore, BIM methodology is a knowledge resource for improving various aspects of building performance. In addition, according to

Robinson (2007) and BS ISO 29481-1 (2010), BIM is a digital data resource with sharing capabilities. The ideas are a reflection of BIM's intelligent data capabilities to support decision making within a collaborative environment.

There is a vast difference in the ways to define the definition of BIM. However, there is an agreement in some determinants such as the life cycle of operating, which is a significant component in this field of research that is mentioned by the Associated General Contractors of America (2005), NIBS (2007), BS 8536 Facility management briefing (2010), and ISO 16757-1 (2015), which will effectively contribute to defining design perception, cost estimation, construction process, assets, facility life cycle, asset and operating performance, and areas that can change. After careful analysis of all definitions, it can be concluded that BIM has been presented as a software program, processes, information, and analysis that share data to obtain the end product. See Figure 16.

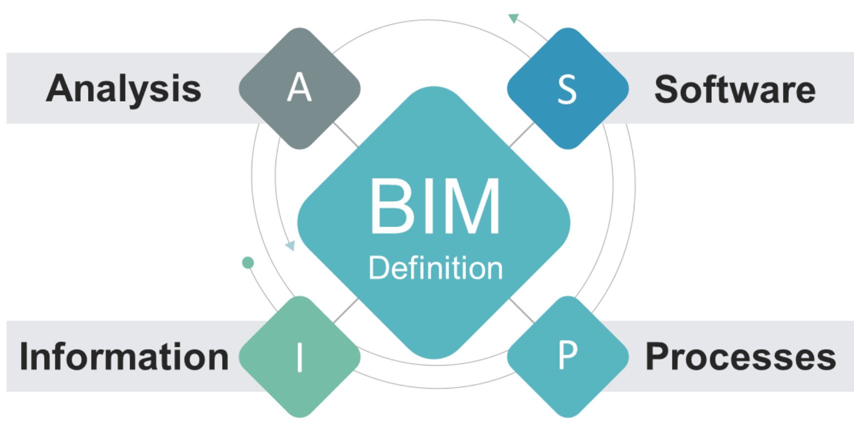


Figure 16: Principal dimensions of BIM definitions

In general, it can be clearly seen that BIM is transacting with elements separately and the model is created by specifying its characteristics, not by specifying its lines. Consequently, the outcomes will be clearly defined, as all projections and sectors are represented in a three-dimensional model, which simplifies to defining each element individually, rather than repeatedly illustrating them in multiple floor plan drawings. BIM provides an integrated information store with three-dimensional elements of the physical representation of the building. In essence, BIM is a practical way to construct a building before actually executing it. It is a numerical simulation of the physical and functional building properties using smart elements. In addition, it is an important element of transparency and support to make the project less prone to collusion when having a change order of project specifications and elements.

One of the most important research topics is the adoption and implementation of BIM in the real estate industry (Abanda and Byers, 2016). These studies were conducted from following the principles of over numerous theoretical models and conceptual frameworks. The TAM thinking is just one of the most applied theory that accounts the issue of user’s willingness to apply new technology. With TAM theory assuming that perceived usefulness and that effortlessness of use, are the two biggest factors for technology acceptance (Abanda and Byers, 2016). In the field of BIM, in addition to traditional research on TAM, scholars are also exploring the effects of additional factors like executive support, training, and education, as well as compatibility of workflows during the adoption process.

Another person's theory should be mentioned, that is the Diffusion of Innovations (DOI) which was also suggested by (Alaboud and Alshahrani, 2023). DOI describes how innovations are allowed to penetrate the social systems of the people over time, and that such factors like relative advantage, compatibility, complexity, trialability and observability directly influence the pattern and rate of adoption of such innovations (Alaboud and Alshahrani, 2023). The importance of digital skills diffusion in fostering the architecture, engineering and construction (AEC) industry has been highlighted for more than a decade. The extent to which this objective can be achieved depends on several factors. An augmented BIM adoption stems from, but is not restricted to, government policies and initiatives (Karampour, Mohamed, Karampour, and Lupica Spagnolo, 2021). Among the works of BIM researchers involving DOI are the works that try to comprehend the spreading patterns and motivators of BIM adoption in organisations as well as in projects.

Alongside the theoretical models, several conceptual frameworks which are principles based are also being advocated for to guide the BIM implementation in organisations and projects. An example is the Integration BIM Maturity theory that put forward gradually maturity levels denoted ranging from ad-hoc to full BIM adoption (Altaf *et al.,* 2020). Other than these frameworks, for example, the BIM Capability Maturity Model and the BIM Competency Assessment Scheme do exist which provide structured methods of evaluating an organisation's capabilities in the area of BIM and give way to refinement roadmaps (Ansah et al., 2020).

Thus, built-environment scholars have developed strategic approach proposals to better integrate BIM's capacity to optimise LCC, energy efficiency (EE) and life cycle assessment (LCA). Consequently, BIM can be combined with LCC analysis and sustainable design principles to build a systematic framework (Ansah *et al.,* 2020). Utilising the BIM environment with data rich features, they develop algorithms to perform accurate cost estimates for the entire life cycle of the building regarding both carbon footprint and green materials (Aletaiby, 2018).

In the same light, (Amos and Pearse, 2008) introduced a comprehending model that combines BIM, LCC and LCA techniques. They adopt BIM modeling which allows them to pull out this information among commensurate materials descriptions and then use that data for analysis in the field of LCC and LCA in terms of economic and environmental aspects. To include the economic and environmental features from designing times, this model targets to provide sustainable and informed decisions in order to reduce life cycle cost of a building (Aouad *et al.,* 1999). BIM model already contains LCA/LCC information, then the facilities managers just need to update the model with the new elements, and quickly run a new analysis (Santos, Costa, Silvestre, and Pyl, 2019).

The theoretical models and conceptual frameworks are fundamental for understanding factors that are going to affect BIM adoption and for the shaping of the implementation process. Nonetheless, there might be a need to assess their suitability and efficiency in certain contexts including but not limited to that of the Saudi Arabian construction industry that may require further consideration besides exigencies and uniqueness of specific cases (Alghamdi *et al.,* 2022). However, these models provide us with essential knowledge and engaging points where we can further improve implementations of BIM with the aim at increasing community's resilience and keeping its costs at the lowest level among other economical parameters.

2.3.2 BIM Motivating Factors to Stakeholders

BIM adoption means "the successful implementation whereby an organisation, following a readiness phase, crosses the 'Point of Adoption' into one of the BIM capability stages, namely, modelling, collaboration and integration" (Succar and Kassem 2015). Building life-cycle (BLC) consists of three main phases, design, construction, operation and maintenance (Karim, 2018; Haider and Kreps, 2004). Like different industry, the construction industry too has a keen interest in developing and adopting new technologies to improve project management practices in the design and construction phases of BLC (Al-Gahzari, 2014). Across all of the stages, stakeholders are critically embedded. The analysis of the stakeholders is a pivotal element for any construction project such as the one for which BIM is used for developing more sustainability and reducing costs during the lifecycle. Decision making during the adoption of BIM in current AEC projects is believed as a key element to improve both BIM performance and project outcome (Al Awad, 2015). In order to provide the most informed decision and strategic plan, two vital elements are required: a comprehensive set of decision-making criteria and a reasonable priority system (Chen, 2015).

Discussing the stakeholders' viewpoints, assignments, and obligations is the basic thing to do that right facilitation and teamwork of all the members will achieve (Akanbi *et al.,* 2018). The analysis of stakeholders would highlight the different groups of individuals, organisations or groups which concern or have considerable influence on BIM for sustainable construction projects implementation in Saudi Arabia (Alasmari, Martinez-Vazquez and Baniotopoulos, 2022a).

The main stakeholders country may comprise government bodies and regulatory branches, for instance, the ministries, municipalities and authorities responsible for approval of construction rules, building authorities, and provisions regarding sustainability. The management of the project and the client like government installations and real estate developers are another category of stakeholders which are also very important and put in a good volume (Alasmari, Martinez-Vazquez and Baniotopoulos, 2022b). The designers, architects, engineers, and other professional representatives are the leading actors in this process who reenact BIM primarily as the planning and designing tools for impending projects (Cao, 2016).

Another contribution is every construction contractor and subcontractor who, in charge of performing the construction works and cooperating with BIM models, and every facility manager and operator who operate and maintain buildings using BIM data for effective facility management, are also key stakeholders (Alasmari, Martinez-Vazquez and Baniotopoulos, 2023a). Vendors and tech companies offering BIM software and hardware, as well as scholars and universities that provide BIM education, training, and knowledge developments, are the other key players.

Associations and institution representing professional, supply, and demand side of the construction cycle and prioriying sustainable and effective practices, and consumers and tenants, the final users of repairable and comfortable buildings, should also be considered as a part of the stakeholder analysis (Alasmari, Martinez-Vazquez and Baniotopoulos, 2023b). Analysing the functions, interests, impacts and chances of get a promotion of all stakeholder's group with respect to BIM is recommended (Alasmari, Martinez-Vazquez and Baniotopoulos, 2023b). It must name certain individuals who may be interested in the change, their possible supporters, the opponents, and what they are interested in, worried about, and their specific needs.

BIM is applied in construction contracts because it creates a significant opportunity to reduce risks, including financial and schedule-related risks, while also decreasing the risk of errors and omissions (Jayasudha and Vidivelli, 2016; Mishra and Mishra, 2016; Renuka, Umarani and Kamal, 2014; Tadayon*,* Jaafar and Nasri, 2012). It enables addressing risks in the entire life cycle of the project (Gibbs *et al*., 2015). Capitalising on BIM by contractors significantly helps reduce risks over time (Mering *et al*., 2017; Sarhan *et al,* 2019; Alotaibi, Sutrisna and Chong, 2016). BIM can serve as a risk-mitigation tool for contractors during the design stage by providing a detailed building model. It can also help reduce the risk of incorrect installation of parts by subcontractors and it also decreases risks for clients (Mering *et al.*, 2017; Sarhan *et* *al,* 2019; Alotaibi, Sutrisna and Chong, 2016). Additionally, it improves stakeholder cohesiveness by improving communication (Sun, Man and Wang, 2015; Albogamy and Dawood, 2015; Badran, AlZubaidi and Venkatachalam, 2020; Tomek and Matějka, 2014; Wetzel and Thabet, 2015). In addition, it has a positive impact on environmental risks. It also allows the use of Integrated Project Delivery (IPD), which has a positive effect on risk reduction by bringing appropriate tools and processes (Yoon and Pishdad-Bozorgi, 2022). BIM also allows project stakeholders to manage legal and financial risks by ensuring that proper communication between the contracting parties is adopted (Mering *et al.,* 2017; Sarhan *et al.,* 2019; Alotaibi, Sutrisna and Chong, 2016). BIM also increases collaboration among the project stakeholders and improves team relationships (Jo, Ishak and Rashid, 2018; Gibbs *et al.*, 2015). It improves ease of access to project information while providing easier analysis of the project in its entire life cycle. ISO 19650 is considered the primary standard related to BIM implementation as it refers to the digitisation of different information in projects, increasing collaboration on the life cycle, as shown in Figure 17.

The stakeholders find it easier to make a trade-off between alternatives and improve workflow cycle time along with waste reduction (Mering *et al.,* 2017; Sarhan *et al*, 2019; Alotaibi, Sutrisna and Chong, 2016). These benefits are essential in reducing the lifecycle costs and scheduling growth as well as improving certainty and sustainability.

BIM incorporates risk management techniques. It also helps incorporate all stakeholders in the project including the supply chain, contractors, clients, and architects as well as ensuring that they undertake a sustainable design to lower operating costs (Mering *et al.,* 2017; Sarhan *et al,* 2019; Alotaibi, Sutrisna and Chong, 2016).

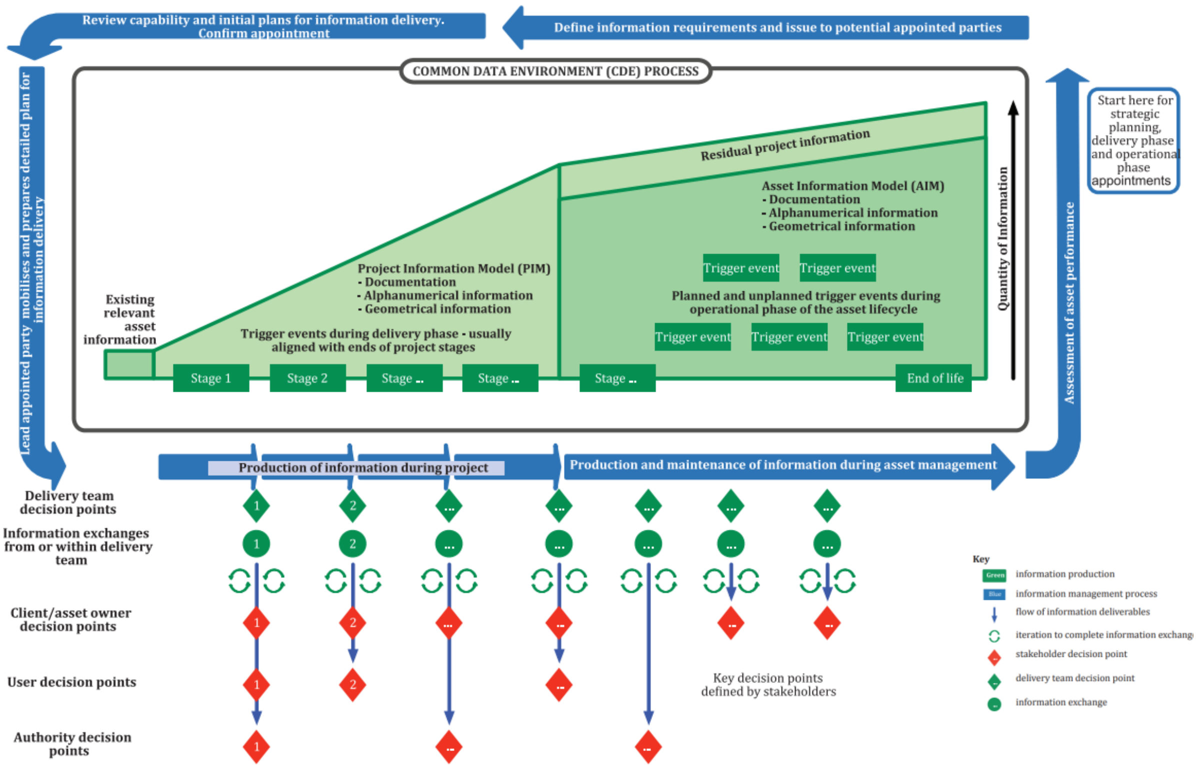


Figure 17: Process of management information on the life cycle of the project (ISO 19650, 2018)

Conversely, the rationale of the adoption of BIM at the organisational and project level is extensive, and among it efficiency gains, the effective collaboration; and better projects outcomes are part (Alasmari *et al.,* 2023c). Organisations appreciate BIM tool for its ability to simplify the procedures of planning, avoid mistakes and manage risks along the project timeline (Albogamy and Dawood, 2015). The project level cooperation which BIM provides, through enabling the stakeholders to coordinate, communicate and have a single Socrat databank, is among the main reasons for its popularity. Indeed, client pressures and the imperatives of regulatory authorities in certain jurisdictions may trigger the pace of BIM's uptake (Alhazmi *et al.,* 2021).

Critical success factors for smooth BIM implementation can be such things as authorisation by executive personnel, dissemination of objectives, and provision of resources. Involvement of the top leaders is key in leading organisational culture change and making it definitive with strategic responses (AlJaber *et al.,* 2023). Continuous training and worker skill development are awarded with BIM competencies which in turn promote BIM absorption habit by setting aside competent personals to use the system (Alotaibi *et al.,* 2016). On the flip side, setting strict BIM standards and protocols guarantee that there is uniformity and interoperability to the different projects thereby optimising the performance and participation amongst the project participants.

A significant value of this BIM is that it makes possible to see accurate visualisation of projects, to coordinate the entire designing and to provide right information when decisions have to be made. BIM makes it possible for designers, builders and others to visualise and simulate construction projects on a virtual platform which helps in better design optimisation and identifying any clash (Alshibani and Alshamrani, 2017). Enhanced teamwork and information exchange contribute not only to improves but also to eliminates errors, to less restarting, and to the more efficient project execution. These contributory factors also carry advantage of data driven decision making through which there occur more accurate resource allocations and cost-cutting over the life-span of the project (Areo Blog, 2020).

In the pre-construction stage, BIM expands the options of conceptualisation and feasibility analysis of projects (Gildam *et a.l,* 2011). Therefore, it allows for conducting in-depth site analysis, consequently leading to recognition of various environmental and resource-related problems (Azhar *et al.,* 2011b). BIM is especially accurate in documenting (Kjartansdottir et al., 2017) and enabling iterative (Khosrowshahi 2017) design reviews which are the basis for a sustainable design. Furthermore, it saves energy (Eastman, Hynes, and Croom, 2011) and facilitates the earlier resolution of design conflicts through the use of model visualisation (Latiffi, Khattab and Iqbal, 2016) which in turn, significantly reduces the duration of cost estimation (Khosrowshahi, 2017).

The initial stage of the whole process, construction, is grounded on BIM approach that entails a holistic assessment and evaluation of complex systems that would otherwise overburden resource planning and sequencing agent (Kjartansdottir *et al.,* 2017). It help in managing project resource storage and supply system (Eastman *et al.,* 2013) and support precision manufacturing of construction components according to the model design (Enshassi *et al.,* 2018). BIM can effectively serve the purpose of enhanced utilisation of the site thereby eliminating site congestion and providing health and safety measures (Deshpande and Whitman, 2014). Additionally, this technology has contributed positively to the safety measures of the site (Khosrowshahi, 2017).

The use of BIM in operation stage, through the record model supports and helps planning of the operations, maintenance, repair, and replacement activities (Kjartansdottir *et al.,* 2017). It provides higher levels of efficiency, enables faster and accurate asset management processes, and makes them rich in information (Husain *et al,* 2014). More importantly, BIM significantly contributes to the effective maintenance program by scheduling the work and providing instant information access during the maintenance operations (Enshassi *et al.,* 2018).

Issues that hold back the adoption of BIM technology are lagging software and hardware capacity, lack of interoperability, and data compatibility problems (Areo Blog, 2020). With more than a dozen of available BIM software programs and multiple formats which are not always interchangeable among project participants, data exchangeability is considered a major issue. Apart from that, inaccessibility of hardware can also undermine the BIM software's performance, which thereby, hinder its viability (Associated General Contractors of America, 2005).

The barriers within the organisations like change resistance and lack of qualification/training are to BIM adaption. Resistance to change might become perceptible due to an anxiety or refusal to switch over from already well-established routines or an intimidation caused by technology (Autodesk, 2020). However, conducting proper training and teaching employees is a way to deal with the problem, as staff will acquire skills to apply BIM using the capabilities of the last if need be (Azhar, 2011).

Elmualim and Gilder (2014) examined the hindrances to adoption of BIM in the USA, Canada, the UK, Ghana, South Africa, China, India and Australia. Their findings showed that the main barriers are deficiency of capital, BIM benefits not outweighing the implementation costs, unwillingness to start new workflows and BIM being too risky from a liability perspective.

Hosseini *et al.* (2016) described the barriers to the adoption of BIM in Australia. The barriers were sub-contractors not having sufficient knowledge about BIM, clients' lack of awareness about BIM benefits, high cost of BIM implementation, high cost of training and unwillingness to change current construction culture. Obstacles to BIM adoption in the construction industry of New Zealand are high initial cost, training issues and cultural resistance (Harrison and Thurnell, 2015).

Constructing legal and regulation-based barriers is added up as well, if only for the consideration of contractual constraints and intellectual property issues. While implementing of contractual platforms, partnership principles have to be considered that will deal with the particular demand of the projects that use BIM, such as dividing responsibility and data ownership (Azhar *et al.,* 2015). In addition to the task of dealing with the various rules and laws surrounding data privacy, and BIM implementation, the complexity increases even more (Badran *et al.,* 2020).

Monetary and budgetary obstacles that may arise include initial investment into software licenses, tutoring, and infrastructure upgrades or renewal. However, they must not forget the long-term benefits of BIM which, though, justify these expenses; this may make some organisations think about the costs which they, sometimes, perceive as unbearable in the resource-constrained environments (Bakx *et al.,* 2016). Furthermore, the lack of dependability on Breakeven of investment and the hassle that might come in the way of routine workflows could act as a deterrent to investing in BIM technologies.

2.3.3 Bibliometric Analysis of BIM Field

The bibliometric analysis of BIM forms a critical component of the literature review, facilitating the initial assessment of the field. This approach not only aids in data collection but also plays a pivotal role in uncovering knowledge gaps by elucidating areas that require further exploration. The methods used to define research and the entire approaches related to the subject of the thesis are various. In particular, one of the most important aspects of these methods is to establish critical determinants of critical review about the relationship between BIM and LCC. Furthermore, the primary benchmark of collecting data is to find reliable research papers to achieve an original contribution to knowledge.

The bibliometric analysis of BIM will be based on a research framework according to a set plan adopted to support the search strategy. Besides, the research process begins by studying current knowledge of the BIM community. This is done by selecting relevant academic publications from online databases and internet search engines. Knowledge from these publications will provide a detailed overview of the research field. Subsequently, data from current sources is analysed to identify existing research gaps. Consequently, the research data is analysed critically to contribute to knowledge in the research area. Figure 18 illustrates the research framework.

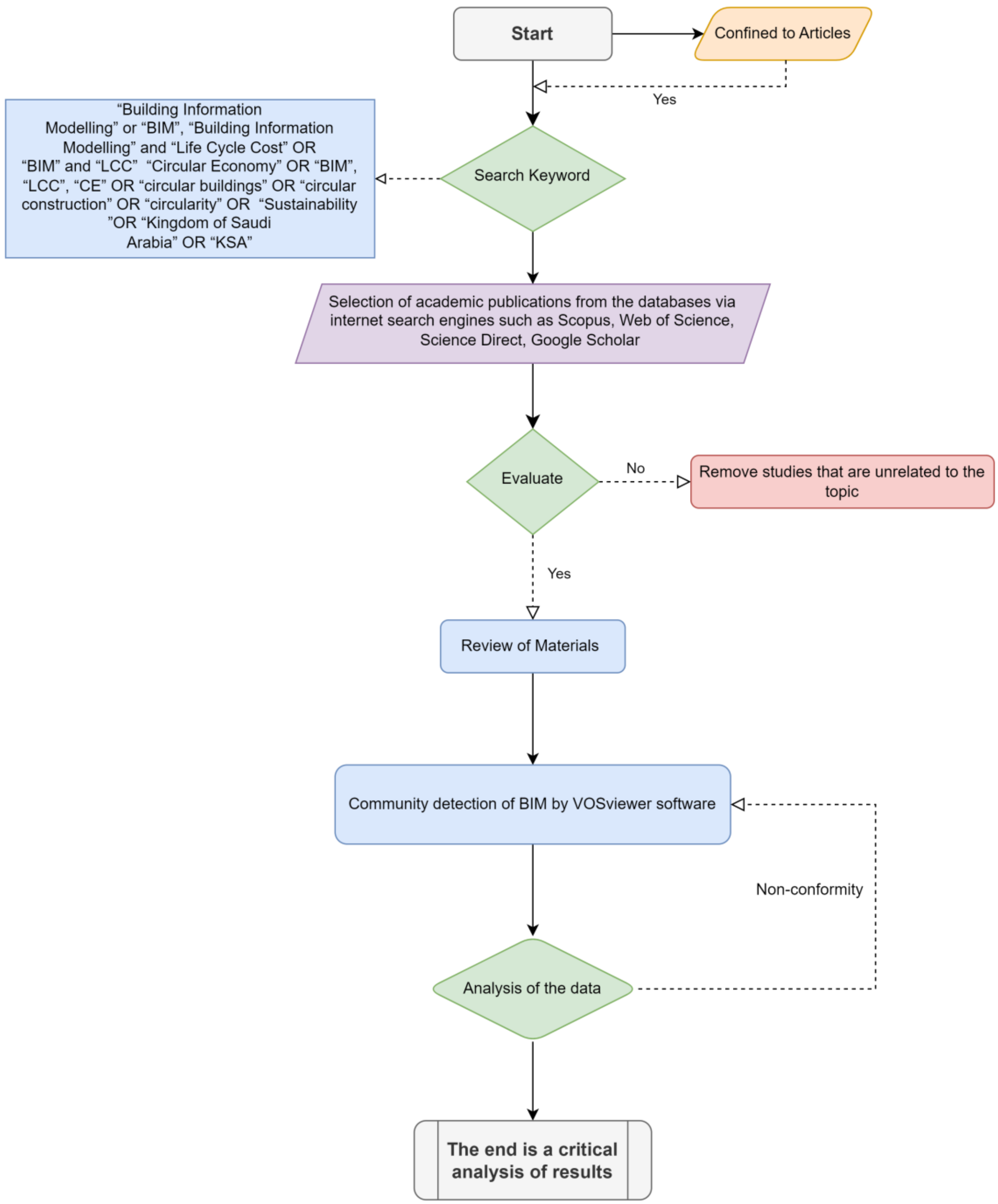


Figure 18: Flowchart of the process for BIM literature review and analysis

The main objective of this method was to provide a preliminary exploration of the BIM field for a comprehensive coverage of the literature review. Also, the initial research is based on a study of the BIM community in search engines to obtain a database of the BIM. In contrast, the period for the research published in the field of BIM was determined during the period from 2009-2024. In addition, specific words were used to obtain research related to the area of the thesis by using the search keywords of “Building Information Modelling” or “BIM”, “Building Information Modelling” and “Life Cycle Cost” OR “BIM” and “LCC” “Circular Economy” OR “BIM”, “LCC”, “CE” OR “circular buildings” OR “circular construction” OR “circularity” OR “Sustainability” OR “Kingdom of Saudi Arabia” OR “KSA”, to determine that the articles are related to the BIM field.

One of the most significant results to come out of this data is that a considerable amount of literature has been published in BIM in most countries in the world. However, there has been relatively little literature published on BIM in the KSA. Consequently, strong evidence of a knowledge gap was found when the results of the data analysis appeared; hence, more research with an entire approach is needed to cover this gap. The research process faced the challenge of matching keywords to obtain relevant sources from the BIM community.

2.3.4 Software Application of BIM

The usage of computer systems in the planning, building, and operating phase is subject to the creation of the level of software that will assist in the execution of construction sector activities. Also, BIM software introduced a comprehensive set of development resources and frameworks that can be employed in all stages of a project life cycle to build analyses and administer BIM models. The BIM software can store information in databases, which can be processed and used to make the best decisions in engineering.

Many companies that are designing BIM programs are currently competing to obtain the largest share of the construction market by offering their services through engineering programs. In this respect, information about these programmes and the resources used for them will be collected and evaluated with each other in order to obtain their usefulness in the LCC. See Table 4.

Table 4: BIM tools and applications

BIM Tools		Advantages	Company
1	Autodesk Revit	• Designing model in 2D and 3D. • Report and analysis. • An integrated approach to structural analysis. • The integration of energy analysis applications. • Quality analysis and management. • Cloud technology support. • A cost estimation application integrated with the system. • Project time schedule integration. • Quantity take-off. • Cost estimates and management.	Autodesk
2	Bentley Architecture	• Designing model in 2D and 3D. • An integrated approach to structural analysis. • The integration of energy analysis applications. • Cloud technology support. • Integration with cost estimating applications. • A cost estimation application integrated with the system. • Quantity take-off. • Cost estimates and management.	Bentley
3	Allplan Architecture	• Designing model in 2D and 3D. • Quality analysis and management.	Allplan - NEMETSCHEK
4	Structural Modeler V8i	• Designing model in 2D and 3D.	Bentley

		• An integrated approach to structural analysis. • The integration of energy analysis applications. • Cloud technology support. • A cost estimation application integrated with the system. • Project time schedule integration. • Quantity take-off. • Cost estimates and management.	
5	Tekla Structures, Engineering	• Structural analysis. • Report and analysis.	Tekla
6	AutoCAD	• Designing model in 2D and 3D. • Report and analysis.	Autodesk
7	ArchiCAD	• Designing model in 2D and 3D. • An integrated approach to structural analysis. • The integration of energy analysis applications. • Cloud technology support. • A cost estimation application integrated with the system. • Project time schedule integration. • Quantity take-off. • Cost estimates and management.	Graphisoft - NEMETSCHEK
8	Digital Project Designer	• Designing model in 2D and 3D. • Quality analysis and management. • Quantity take-off. • Cost estimates and management.	Gehry Technologies
9	ProSteel V8i	• Designing model in 2D and 3D. • Integration with structural analysis applications.	Bentley
10	Structural Analysis Professional	• Report and analysis.	Autodesk
11	STAAD.Pro V8i	• Designing model in 2D and 3D. • Integration with structural analysis applications. • Integration with energy analysis applications. • Quality analysis and management.	Bentley

Bellido-Montesinos *et al.* (2019) indicated that the most common connection of BIM software was between Revit and Cype, according to the analysis data of the program data used in the BIM Valladolid competition in Spain for the years 2014, 2015, and 2016. The study indicated that the analysis of the programs was used for several engineering specialisations (Structural Analysis, Architecture, Planning Execution, Energy Efficiency, Quantity and cost estimation, Facilities, and Coordination). To find out the most popular programs for use in the competition by speciality, see Figure 19.

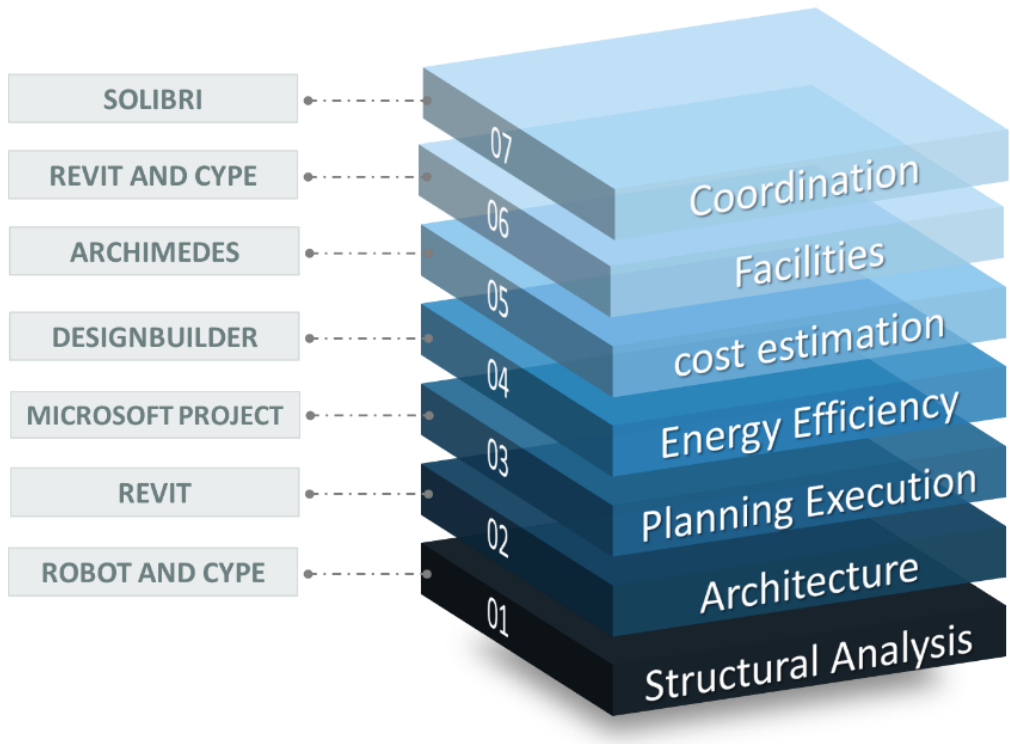


Figure 19: Software used in a contest, BIM Valladolid, by engineering field (Bellido-Montesinos *et al*., 2019)

Although there is currently minimal discourse regarding the most effective tools and software utilised in BIM, the fundamental advantages of BIM, such as enhanced productivity, are incredibly adaptable and thus appropriate for all construction projects, industries, and sectors. The extensive applicability of BIM highlights the comprehensive nature of its benefits. Despite the complexities and drawbacks associated with the implementation of BIM, the added value provided by BIM remains advantageous and stimulating for the construction industry.

2.4 Risk Management of BIM

Effective risk management is a crucial aspect of ensuring the prosperous conclusion of construction projects, and achieving a successful risk management process is a primary objective for the success of engineering projects. This involves identifying and assessing risks and implementing appropriate plans to mitigate them. The foremost steps of risk management include risk identification, risk assessment, planning, and implementation.

According to The International Organisation for Standards (2009), the definition of risk assessment is that "part of risk management which provides a structured process that identifies how objectives may be affected and analyses the risk in terms of consequences and their probabilities before deciding on whether further treatment is required." Accordingly, risks in construction projects negatively affect the extent to which project objectives are achieved in terms of time, cost, and quality and risk management is essential in any step of the project to mitigate losses and achieve goals.

The field of risk management based on building information modelling systems is a modern and incomplete field that needs more work to solve its technical limitations such as specialised risk analysis programs and not wholly relying on the experience of the human element only (Zou, Kiviniemi and Jones, 2017). Risk management is an important component of 5D by controlling costs and cash flows of the project LCC when linked with BIM (Mering *et al*., 2017). Integrating the central risk database with BIM will facilitate the identification and localisation of every risk. However, the absence of a unified database platform that can be integrated with BIM systems presents a significant challenge in analysing and identifying risks, given the current technological limitations (Zou et al., 2018). Therefore, it is necessary to begin to determine the types of risks affecting the project. Then, integration with BIM will support prediction and identify risks at the beginning of the project and detail these risks for assessing the severity and quality of their impact on the project.

2.4 Benefit of BIM for LCC

Building life cycle includes many responsibilities and engineering tasks and it is rare to find a specific program that can cover all the needs of the project life cycle. Therefore, the importance of BIM is to work on coordination between the exchanges of information among multiple engineering softwares. By utilising BIM for cost estimating and prioritising activities that offer the most value, valuable time can be saved for the approximate take-off production (Alasmari, Martinez-Vazquez and Baniotopoulos, 2023b). However, Azhar (2011) noted that it is possible to predict the performance of the building and its operation and improve and reduce its costs and manage the time optimally. Furthermore, the study reported that the average Return On Investment (ROI) for projects using BIM was 634%. This ROI takes into consideration the legal aspects and data ownership risks associated with the project.

According to RICS' (2016) guidance note UK, the ISO 15686-5 is an international standard that seeks to assert authority in adopting the LCC methodology. Further, the standard addresses all the issues of LCC implementation including its associated terminology. The standard makes a clear distinction between LCC and Whole Life Cost (WLC). LCC specifically examines the direct economic assessment of a building asset, while WLC is more comprehensive in nature including LCC considerations as well as external factors such as environmental costs and revenue aspects. The standard also recommends that LCC and WLC analyses should be used to optimise environmental costs, thereby enhancing sustainability. Figure 20 below illustrates the relationship between WLC and LCC.

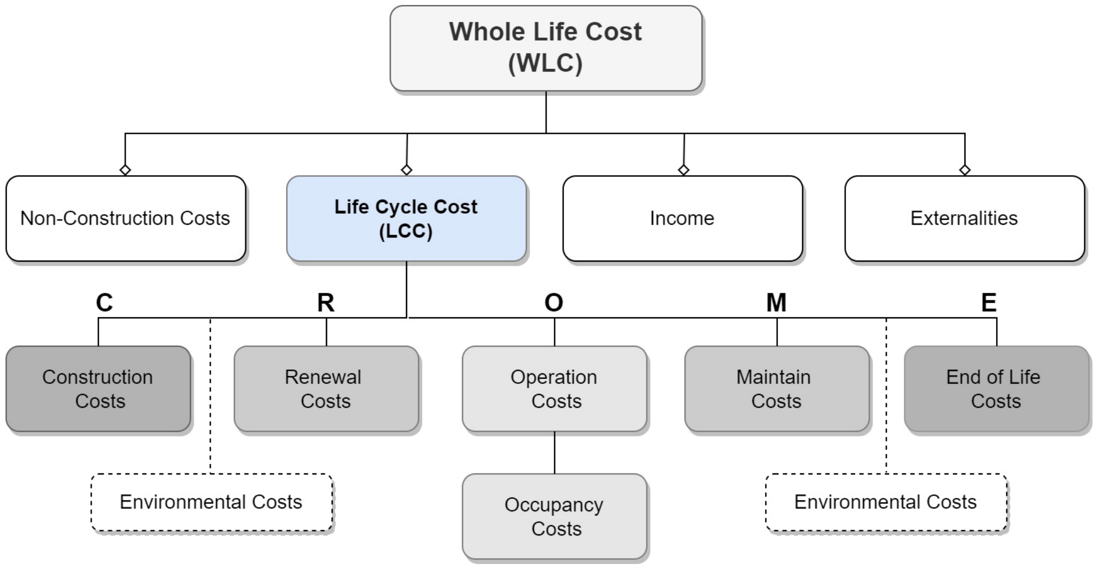


Figure 20: Relationship between whole life cost and life cycle cost (The Royal Institution of Chartered Surveyors (RICS), 2016)

BIM, including LCC, has been extensively studied to improve building performance. Santos *et al*. (2020) integrated Life Cycle Assessment (LCA) and LCC using BIM. BIM-based simulations with LCA and LCC data assessed building economic and environmental impacts. The findings showed improved LCA and LCC sustainability. The previous study found that BIM and data can improve efficiency. To improve sustainability in future projects, the technique can be used in predictive building performance analysis. This study has focused on European-built life cycle environmental and economic impacts.

This study cannot apply predictive analyses of building performance with sustainable standards to global building systems, which presents another challenge. In construction, virtual design tools affect LCC. LCC evaluates all costs and revenues during an asset's ownership life cycle (Kehily, 2016; Marzouk, Azab and Metawie, 2018; Alasmari, Martinez-Vazquez and Baniotopoulos, 2023a). LCC evaluates construction, asset management, operation, and end-of-life disposal costs. The benefits of LCC are well-documented, but LCC components are rarely implemented. LCC's sustainable benefits are limited by long requirements and non-standardised processes (Kehily and Underwood, 2017).

Akanbi *et al*. (2018) conducted a detailed WLC analysis of a building from design to assess material performance. BIM helped engineers choose recyclable building materials during design. Use of recyclable construction materials would reduce rebuilding costs and promote sustainability. BIM is an intelligent approach that improves LCC applications like building design and operation using various technologies and management tools (Di Biccari *et al*., 2019). BIM also facilitates stakeholder collaboration by sharing and updating project information. Therefore, BIM is suitable for optimising LCC effectiveness.

The longest WLC phase of a building is operation and maintenance, according to Chen and Tang (2019). In addition, operation and maintenance are the most expensive project phases. The main reason operation and maintenance costs have risen is poor maintenance planning. Thus, BIM systems must regulate building information flow and link design to operation and maintenance. Marzouk, Azab and Metawie (2018) noted that using cheaper materials makes the building sustainable throughout the project life cycle and building systems and materials affect every LCC component. Additionally, green building materials improve performance and sustainability. Juan and Hsing (2017) found that using BIM in residential projects will make future maintenance and renovation economically feasible, helping decision makers extend the building service life. Smith (2014) suggested that companies that use 5D BIM have competitive capabilities and budgets.

Lee *et al*. (2020) found that using 5D for BIM to simulate a building with design alternatives early on improves cost estimation, helping decision makers modify the design and choose the best option, saving LCC money. Undoubtedly, losing information during engineering project information exchange harms project life stages. Automatic information exchange between design, cost estimation, and scheduling programs will be addressed by BIM systems. View Figure 21 to understand the process. Thus, BIM is mostly used to improve project implementation, operation, and investment efficiency.

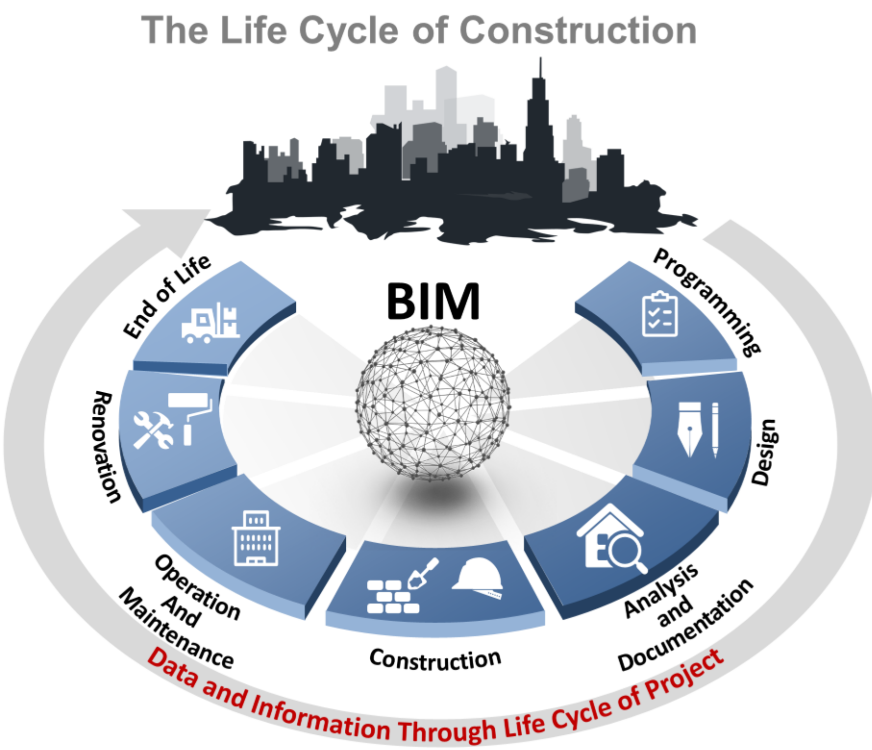


Figure 21: Information transfer during the project life cycle

There are a number of studies that have focused on the optimisation of LCC applications using the BIM technique. However, the efficiencies of different BIM models have been assessed on LCC applications. Kehily and Underwood (2017) examined the use of a 5D BIM technology in optimising an LCC calculation mode. The 5D BIM refers to a high-level framework of linking project data to an information model (Kehily and Underwood, 2017). The process involved integrating an LCC calculation model into the 5D BIM platform. The study's results demonstrate that the use of 5D BIM technology establishes a connection between cost plans and LCC calculations (Kehily and Underwood, 2017). The study demonstrates the efficiency of BIM technology in monitoring project costs in the LCC. However, it fails to explain how the technology can be optimised to enhance cost reduction.

On the other hand, some studies focus on the specific barriers of the LCC processes that can be eliminated through the effective implementation of BIM techniques. Kehily (2016) and Nwodo, Anumba and Asadi (2017) assessed the various challenges of the LCC processes that are addressed through BIM techniques. According to Kehily (2016) and Nwodo, Anumba and Asadi (2017), BIM resolves the perceived challenges of non-standardisation, document guidance, and inaccurate and inaccessible data. The overarching justification by both studies is that BIM's technological capabilities provide intelligent pathways for decision making (Kehily, 2016; Nwodo, Anumba and Asadi, 2017). The readiness of decision making goes a long way in enhancing the sustainability of the building construction sector. Some studies have shown that BIM technology can be used to manage both private and public assets effectively. Dawood (2016), Di Biccari *et al.* (2019) and Santos *et al.* (2020) suggest that benefits of BIM in the LCC, such as improvement of collaboration and communication, promote accountability and transparency in construction projects. Studies consistently demonstrate that BIM can be used to optimise the LCC processes.

In general, the literature suggests that BIM is effective in LCC applications with various approaches and models supporting this conclusion. However, few studies examine the current technology's influence on the benefits of BIM. Additionally, recent studies mainly focus on the economic aspects of LCC, while other sustainable aspects and the environmental impact of BIM on LCC need further exploration.

2.5 BIM of Promoting the Circular Economy in Construction

In the context of the Circular Economy (CE), building elements follow a continuous cycle of use, repurposing, repair, and recycling to sustain resource value over time. Circular buildings are envisioned as systems that efficiently consume and preserve materials. The CE is conceived as an industrial ecosystem that is restorative or regenerative by design, aiming to supplant the concept of 'end-of-life' with 'restoration'. It focuses on renewable energy usage, eschews harmful chemicals to facilitate reuse, and seeks to eradicate waste through advanced design of materials, products, systems, and business models (MacArthur, 2013). In parallel, circular construction in buildings is a method that emphasises energy efficiency and recycling potential during material and method selection.

This involves prioritising material longevity, durability, and energy-efficient design to reduce consumption throughout the building life (Rahla, Bragança and Mateus, 2021a). Material and component selection is crucial for effective CE implementation (Rahla, Mateus and Bragança, 2021b). Nine key criteria have been identified to promote CE adoption in construction, considering factors like recyclability, reusability, deconstruction, and durability.

Various circular systems are emerging, with methods to assess their circularity (Overend and Hartwell, 2020). Façades, a prominent building exterior component, often consist of materials like steel, aluminium or timber, offering high reuse potential (AlJaber *et al.,* 2023). The Morphological Design and Evaluation Model (MDEM) aids in conceptualising and evaluating circular façades (Bakx *et al*., 2016).

Despite advancements in design and materials, challenges persist in embracing the Circular Economy (CE) in construction. There is a lack of consensus and understanding, limited academic writings, and little focus on recycling construction waste (Munaro, Tavares and Bragança, 2020). CE design techniques face obstacles due to the absence of clear guidelines and tools for evaluation and value addition.

Transitioning from a linear to a circular economic model in construction waste management involves legal, technological, societal, attitudinal, and financial challenges (Purchase *et al*., 2021). These challenges vary based on project scope and regional factors. A study by Charef and Emmitt (2021) explored how BIM can support the CE transition through innovative applications. There are varied approaches for integrating circular construction principles during the phases of planning, design, and construction. Among these approaches is the Design for Adaptability and Disassembly (DfAD), which integrates the advantages of Design for Disassembly (DfD) and Design for Adaptability (DfA), enabling the easy disassembly and substitution or repair of building parts to accommodate changes in layout (Munaro, Tavares, and Bragança, 2022).

However, the adoption of CE practices in construction is often challenged by the traditional perspective of building for demolition instead of for deconstruction or adaptability. Additional obstacles include a widespread lack of familiarity with CE principles among urban planners and designers (Adams *et al.,* 2017; Rahla, Bragança, and Mateus, 2021), coupled with insufficient incentives from regulatory bodies (Adams *et al.,* 2017; Munaro, Tavares, and Bragança, 2020; Bilal *et al*., 2020; Hart *et al.,* 2019). Technical hurdles also exist, such as the discrepancy between the supply of and demand for reused materials and the disjointed nature of stakeholder collaboration within the construction industry (Hart *et al.,* 2019; Kanters, 2020). Nevertheless, researchers suggest these obstacles could be mitigated through the digitalisation of building materials and components.

Moreover, various tools have been designed to support the implementation of CE principles in the building sector. Many of these tools evaluate circularity levels by examining materials and components at the design phase (Hradil, Fülöp, and Ungureanu, 2019; Dams *et al.,* 2021) or by promoting cooperation across different segments of the construction supply chain (Leising, Quist, and Bocken, 2018). For instance, Akanbi *et al.* (2018) introduced a BIM-based Whole-life Performance Estimator (BWPE), which evaluates the performance of structural components during the design process and interfaces with Material Passports to facilitate the management of a building's performance and its subsequent restoration when necessary.

In a CE framework, building components are maintained through continuous cycles of utilisation, reuse, repair, and recycling to preserve their maximum intrinsic value over time. Moreover, the lifecycle of a circular building is envisaged as a closed-loop system, wherein components and materials are effectively managed to avoid quality degradation. It is imperative to select materials based on their durability and resilience to minimise quality loss. Additionally, careful consideration of materials selection, building design, and layout is crucial to reduce energy consumption throughout the building's lifecycle (Rahla, Bragança and Mateus, 2021).

Further, the selection of materials and components is vital for the successful implementation of CE principles (Rahla, Mateus and Bragança, 2021a). Rahla, Mateus, and Bragança (2021b) delineate nine critical material selection criteria to foster CE adoption in the construction sector. These criteria include recycled and recovered content, recyclability, reusability, ease of deconstruction, maintainability, durability, energy recoverability, upcycling potential, and biodegradability.

Regarding building components, various circular systems are under development, incorporating methodologies to assess their circularity (Overend and Hartwell, 2020). The building envelope predominantly consists of façades, typically constructed from materials such as steel, aluminum (Hartwell, Macmillan and Overend, 2021), or wood (Androsevic, Durmisevic and Brocato, 2019), which offer significant reuse potential compared to traditional masonry and concrete. The efficacy of these materials can be enhanced through the application of a Morphological Design and Evaluation Model (MDEM), which supports the design and evaluation of circular façades (Bakx *et al.,* 2016). Furthermore, Buyle *et al.* (2019) quantified the environmental benefits of circular design alternatives for internal wall assemblies, noting that demountable and reusable wall assemblies with metal substructures could equal or surpass the lifecycle impacts of conventional walls. Crucial to these advancements are removable interior linings and dismountable connections (O'Grady *et al.,* 2021).

Despite advancements in design strategies and materials, significant barriers remain in the adoption of CE principles in the construction sector. While building developers are increasingly aware of CE and regenerative design concepts, a coherent understanding and definition of these concepts are lacking. Munaro, Tavares, and Bragança (2020) identified a deficit in scholarly literature on the implementation of CE across the supply chain, which partially explains existing knowledge gaps but does not fully address the integration of these concepts into professional practice (Sala Benites, Osmond and Prasad, 2022). Consequently, CE initiatives are nascent, primarily focusing on enhancing the reuse and recycling of construction and demolition waste (CDW), yet often overlooking vital industry stakeholders, products, services, and systems (Munaro *et al.,* 2021). The application of CE design strategies in building projects is hindered by the absence of practical guidelines and design-support tools that would facilitate implementation, performance evaluation, and simulation of value addition over the entire lifecycle, especially at the end of service life (Askar, Bragança and Gervásio, 2022).

The transition from a linear to a circular economy in the construction and demolition waste sector faces challenges categorised into five primary domains: legal, technical, social, behavioral, and economic (Purchase *et al.*, 2021). Each category encompasses specific obstacles including policy compliance, permitting, technological constraints, quality assurance, knowledge dissemination, and cost implications. The magnitude of these challenges varies by project scale and geographic context. To expedite CE implementation in the building sector, several tools and innovations are proposed, with BIM recognised as a particularly versatile and influential tool.

Barriers to implementing CE strategies in the construction sector predominantly arise from a fundamental lack of understanding, experience, and skills in applying CE principles (Adams *et al.,* 2017; Akinade *et al.,* 2020). These challenges are compounded by insufficient economic incentives for designing buildings and products that facilitate deconstruction and reuse at their end-of-life (Tingley, Cooper and Cullen, 2017; Iacovidou and Purnell, 2016). Oluleye *et al.* (2023; 2022) elucidate that these impediments are significant deterrents to CE adoption. Tirado *et al.* (2022) suggested that selective deconstruction could be more successfully achieved with thorough planning and the engagement of stakeholders prepared to implement such strategies. However, Chini and Balachandran (2002) noted that less than 1% of buildings are designed to be demountable; most are constructed with the intention to be demolished rather than deconstructed or repurposed (Cruz, Grau and Bilec, 2021; Rios, Chong and Grau, 2015; Bragança, Alvarez and Cabeza, 2021). Technical barriers, such as building complexity, inadequate building data management, and poor knowledge of the quality and quantities of reclaimed materials, further inhibit CE strategies (Adams *et al.,* 2017; Tingley, Cooper and Cullen, 2017; Iacovidou and Purnell, 2016; Rahla, Bragança and Mateus, 2019; Charef and Emmitt, 2021).

CE approaches have been shown to reduce LCC of buildings (Jansen *et al.,* 2020). Slaughter (2001) asserted that the costs and time associated with the first renovation of flexible buildings could be reduced by 2% of the initial construction cost. Similarly, Manewa *et al.* (2016) argued that adaptable buildings significantly cut down LCC, particularly in terms of maintenance and operations. Despite these advantages, the adoption of CE strategies is often obstructed by the high costs involved and a pervasive lack of understanding among stakeholders about the financial benefits of circular design throughout the building's lifecycle (Cruz, Grau and Bilec, 2021). Charef and Emmitt (2021) proposed that digitalising building materials and components could mitigate some of these challenges, although they also highlighted a notable deficit in research promoting BIM for integrating CE principles across the building lifecycle. This gap was reinforced by Chong, Lee, and Wang (2017), who reviewed the implementation of BIM for sustainability and noted limited academic output on its application in building refurbishment and demolition processes.

Despite ongoing innovations in building materials and components, and the development of design strategies, substantial obstacles continue to impede the implementation of CE principles within the construction industry (Kozminska, 2019; Giorgi *et al.,* 2022). These challenges are primarily due to a lack of practical guidelines and design-support tools which are essential for facilitating CE adoption (Askar, Bragança and Gervásio, 2022; Kanters, 2020), difficulties associated with building data management (Göswein *et al.,* 2022), an absence of a holistic approach within the supply chain (Dunant *et al.,* 2017), limited trust or interest in integrating circularity (Mackenbach, Zeller and Osebold, 2020), and the high initial costs required (Guerra and Leite, 2021).

Research aimed at identifying these barriers has been robust. Göswein *et al.* (2022) undertook a series of interviews with consultants and architects well-versed in circular building design to elucidate both the obstacles and catalysts to CE transitions. Cruz Rios, Grau, and Bilec (2021) explored the specific challenges to designing circular buildings in the United States, aiming to understand the disparities between American and European approaches to circularity. Additionally, studies have pinpointed challenges related to the reuse of building materials, specifically focusing on structural steel (Kozminska, 2019; Rakhshan *et al.,* 2022; Tingley, Cooper and Cullen, 2017), thereby highlighting the sector-specific difficulties in adopting CE methodologies.

These applications include a digital blueprint for Sustainable End of Life (SEOL), a materials record system, a project data repository, data verification, circularity analysis, material reclamation processes, and a materials database, all of which have the potential to accelerate the CE transition in construction. BIM stands out as a versatile enabler (see Figure 22).

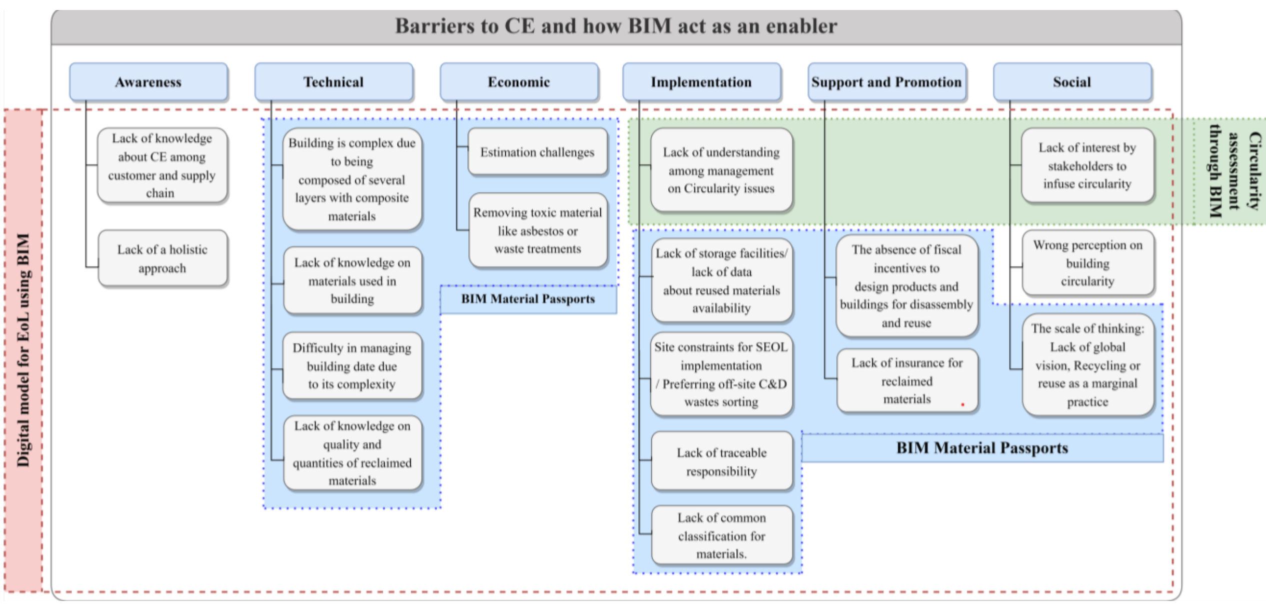


Figure 22: BIM as an enabler to CE barriers (Alasmari *et al.,* 2023c)

2.6 Systematic Review of BIM on LCC

This substantiates the rationale for embracing BIM. Utilising BIM in the field can mitigate the complexities involved in incorporating LCA and pertinent LCC data (Obrecht *et al*., 2020). LCC is characterised as a systematic approach to quantify the comprehensive costs associated with an asset throughout its entire lifespan (Sesana and Salvalai, 2013). This encompasses the spectrum of initial investment, upkeep expenses, operational costs, and the residual asset value at its life's conclusion. In the context of construction, the asset in question is the building under development.

Altaf *et al*. (2020) further elucidated that introducing dual modules—namely, the BIM and LCC modules—can minimise potential discrepancies in cost assessment. They also emphasised the benefits of incorporating BIM-LCCA during the planning phase, such as cutting operational and energy expenditures. The objective of this particular section of the systematic review is to offer a comprehensive analysis of existing practices concerning the deployment of BIM in relation to LCC. This scrutiny encompasses diverse methodologies, software tools, advantages, and challenges observed in studies focusing on BIM's role in LCC.

2.6.1 Methodology of Systematic Review

This review was carried out in accordance with the guidelines set forth in the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA), as advised by Page *et al*. (2021).

2.6.2 Search Strategy of Systematic Review

Digital repositories, specifically Web of Science, Google Scholar, Scopus, and Science Direct, were employed to systematically scour pertinent literature. The investigation encompasses papers published in English between the years 2012 and 2021.

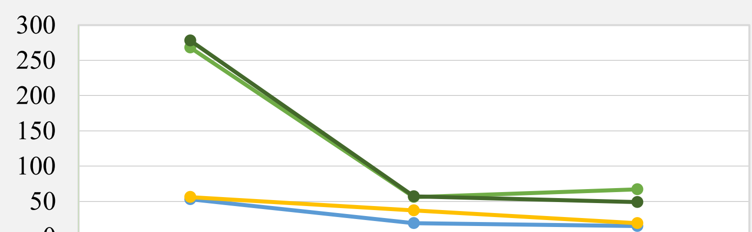
2.6.3 Key Terms Search

The search for pertinent articles employed a set of key terms, phrases, and their combinations, arranged using Boolean operators “And” and “Or”. These terms included “Building Information

Modelling”, “BIM”, “Life Cycle Cost”, and “LCC” as well as combinations like “Building Information Modelling and Life Cycle Cost” and “BIM and LCC”. Additionally, three specialised key phrases were utilised: “BIM on LCC”, “BIM adoption LCC”, and “BIM design on LCC”.

2.6.4 Search Outcomes

The search platforms—Web of Science, Google Scholar, Scopus, and Science Direct—yielded a total of 655 relevant articles for the term “BIM on LCC” during the 2012–2021-time frame. Specifically, Web of Science listed 268, Google Scholar had 53, Science Direct showed 56, and Scopus reported 278 articles using the same keyword and period. A subsequent search using “BIM adoption LCC” found 56 articles in Web of Science, 19 in Google Scholar, 37 in Science Direct, and 57 in Scopus. Finally, using “BIM design on LCC” led to the discovery of 67 articles in Web of Science, 15 in Google Scholar, 19 in Science Direct, and 49 in Scopus, as illustrated in Figure 23.



	BIM on LCC	BIM adoption LCC	BIM design on LCC
Web of Science	268	56	67
Google Scholar	53	19	15
Science Direct	56	37	19
Scopus	278	57	49

Figure 23: Screening and classification of the articles

The article selection proceeded through a set of inclusion and exclusion criteria. A total of 21 articles were initially scrutinised for relevance. One article was subsequently omitted for being irrelevant, leaving 20 articles for the final review. The PRISMA filtering process, which was guided by these criteria, is depicted in Figure 24.

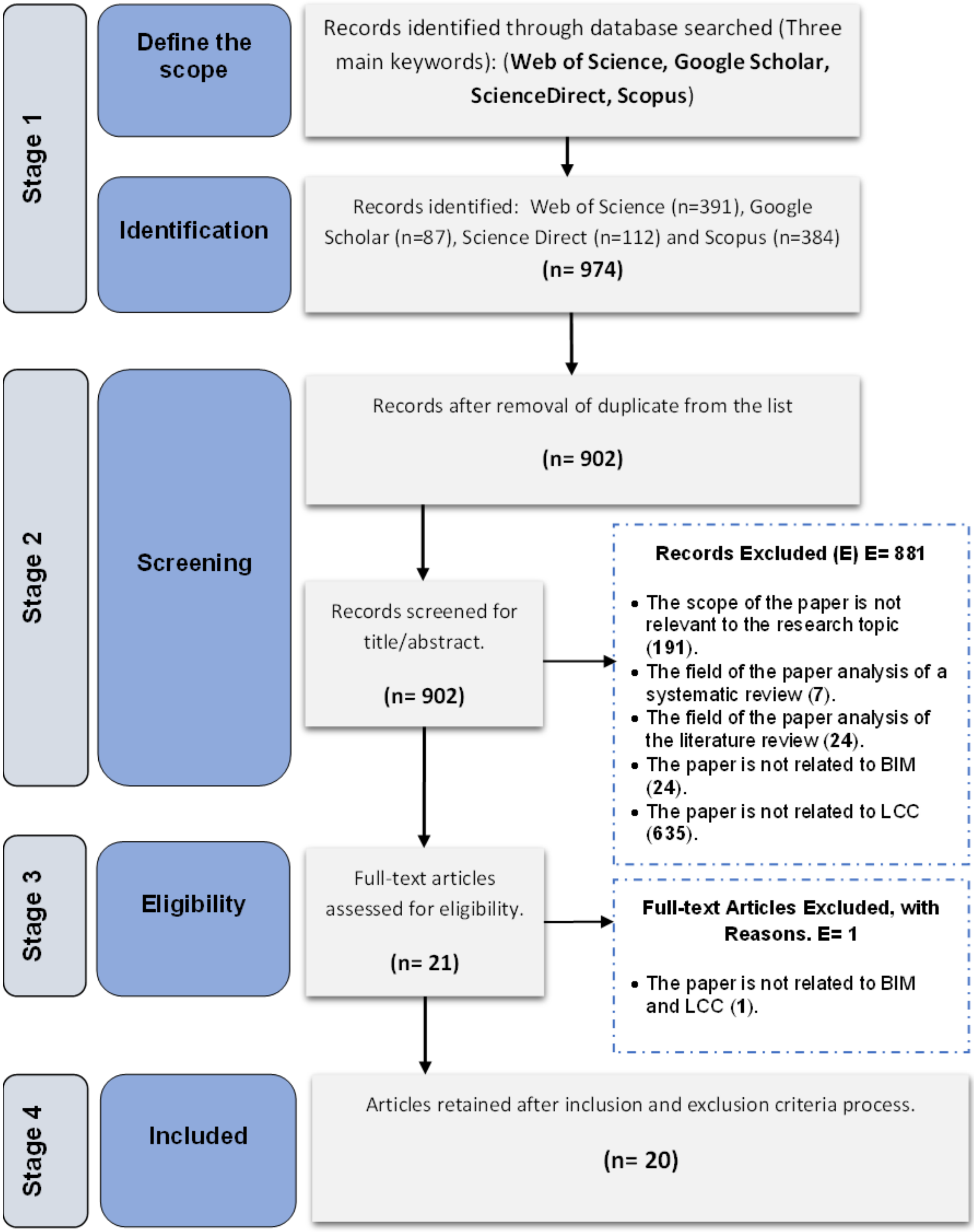


Figure 24: Details of flow-chart of the systematic review process (PRISMA)

The results show that a mere 2.05% of articles passed the database screening. The low approval rate primarily stems from the search engines' keyword-based aggregation of articles. Consequently, the search methodology played a crucial role in sorting the publications based on pre-established selection and elimination criteria. Figure 25 displays the categorisation of accepted and rejected papers.

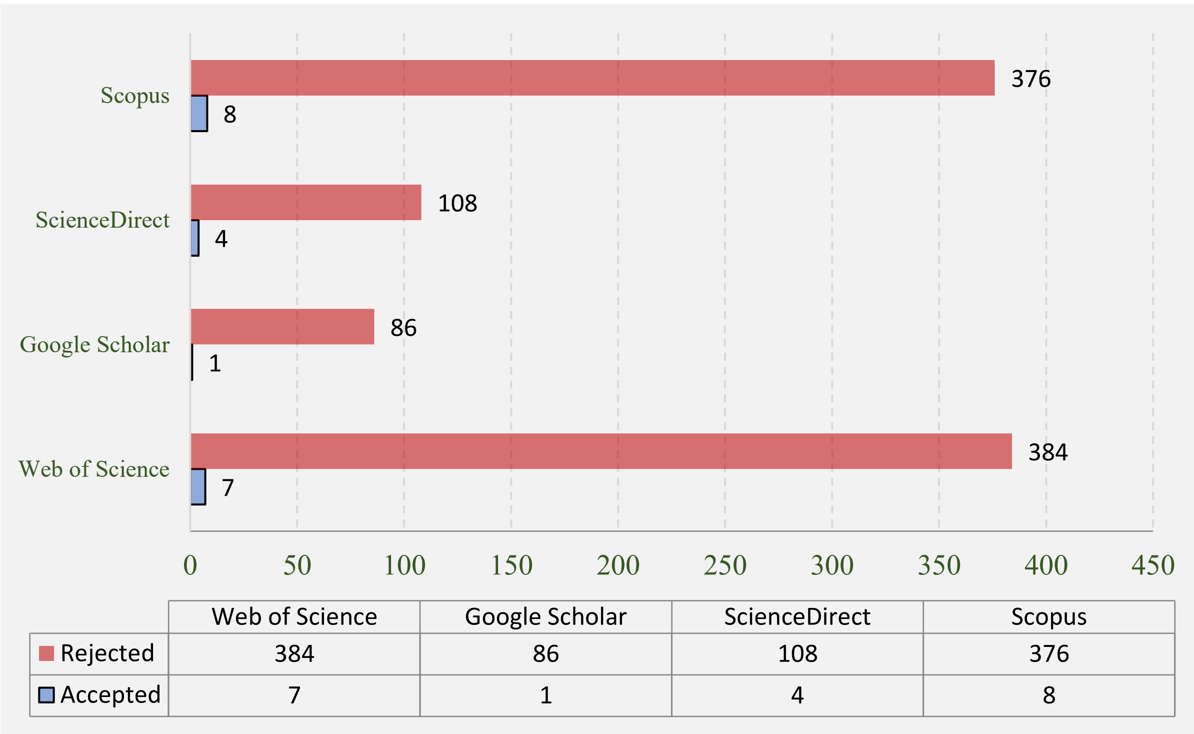


Figure 25: Number of accepted and rejected articles

After employing the search strategy, 20 articles were accepted. These articles encompassed review components such as benefits, drawbacks, methods, and software evaluations pertinent to BIM's impact on the LCC during the design phase. Table 5 offers an in-depth breakdown of the information in the chosen articles, categorised by each review facet (methodology, advantages, challenges, and software considerations).

Table 5: Details of selected articles (Alasmari, Martinez-Vazquez and Baniotopoulos, 2022b)

Reference		The Description
Marzouk, Azab and Metawie. (2018)	**Article Title**	BIM-based Approach for Optimising Life Cycle Costs of Sustainable Buildings **Article Focus:** To develop a cohesive BIM strategy that employs algorithmic optimisation and Monte Carlo Simulation to enhance the accuracy of LCC forecasting. ***(Case Study)***
	Methodology	1. Combining BIM with dual methodologies: stochastic Monte Carlo simulation and an optimisation framework. 2. Utilising Revit for BIM facilitates the extraction of various material specifications for simulation, including concrete masonry, coatings, plaster, and flooring, among others. 3. Life cycle cost assessment is conducted utilising the stochastic approach inherent in Monte Carlo simulations. 4. The simulation model leverages functional outputs derived from the optimisation framework, which incorporates Genetic Algorithms (GA). 5. The method reduces life cycle costs of building materials by pinpointing the most favorable conditions.
	Benefits	Merging BIM with Monte Carlo Simulation and Optimisation Modelling assists policymakers in choosing materials that are sustainable both economically and environmentally, enabling the forecasting of their LCC and the maximisation of potential LEED Credit Scores during assessment.
	Challenges	None
	BIM-Design Software Used	Autodesk Revit.
Santos *et al.* (2020)	**Article Title**	Development of a BIM-based Environmental and Economic Life Cycle Assessment tool **Article Focus:** Suggesting the BIMEELCA Tool as a methodology for the amalgamation of BIM with LCC. ***(Case Study)***
	Methodology	1. The BIMEELCA Instrument. 2. The tool automates the creation of unified metrics linking environmental impact categories with procurement costs within LCC assessments. 3. It enables users to access a display featuring details on components and materials included in the model, along with pertinent data for conducting evaluations.

		4. Selection is available for the environmental and economic appraisal of individual elements. 5. Efficient LCA/LCC Evaluation Process.
	Benefits	• Showcasing an operational BIMEELCA tool that allows for the input of essential data into BIM for conducting LCC analysis. • The process of the BIMEELCA tool includes the incorporation of spreadsheet information into the model, leading to an automated quantity take-off and resulting in a streamlined Optimised LCC analysis.
	Challenges	None
	BIM-Design Software Used	Autodesk Revit.
Liu, Meng and Tam. (2015)	**Article Title**	Building information modeling based building design optimisation for sustainability **Article Focus:** To develop a multi-objective optimisation framework based on BIM that assists designers in determining and choosing the optimal design strategy for their clients, balancing carbon dioxide emissions and cost computation. ***(Case Study)***
	Methodology	Steps were implemented to combine BIM modeling, simulation, thermal and lighting analysis, and database capabilities: 1. Implemented an optimisation model for building design rooted in BIM. 2. The BIM systems were used to adopt and advance the 3-D models. 3. The database has been compiled with essential data on location, climate, and materials. 4. The analysis employed Ecotect software, and for optimisation purposes, the research utilised MOPSO to identify the best design plan.
	Benefits	• The BIM framework enabled the integration of data on sustainability, including carbon emissions, from the early stages of the project. • With BIM, researchers could calculate maintenance expenses from the project inception. • BIM served as a versatile model facilitating the creation of designs that satisfy various sustainability criteria. • Designers can readily verify the logic and identify errors as the designs are graphically represented.
	Challenges	BIM lacks possess a native database, thus requiring researchers to depend on the insertion of new information

	BIM-Design Software Used	Ecoect software.
Kehily and Underwood (2017)	**Article Title**	Embedding life cycle costing in 5D BIM **Article Focus:** This study aims to assess the efficacy of incorporating LCC within a 5D BIM framework. ***(Case Study)***
	Methodology	• A method for implementing LCC computational frameworks within 5D BIM technology (CostX) as a supplemental process to 5D BIM. • CostX facilitates rapid and precise extraction of quantities from 2D drawings and BIM models. • LCC computations were subsequently integrated into the CostX Workbook.
	Benefits	• Emphasises the advantages of 5D BIM applications capable of handling fluctuating scenarios (like those found in probabilistic LCC analysis) more efficiently than BIM design programs (such as Revit or Archicad). • It is suggested that the outlined procedure offers a unified setting connecting the cost plans/Bills of Quantities (BOQs) from quantity surveying with LCC estimations.
	Challenges	• Lack of a standardised framework for the suggested LCC calculation method. • The advantages of LCC remain untapped owing to insufficient client demand.
	BIM-Design Software Used	Autodesk Revit.
Santos *et al.* (2019)	**Article Title**	BIM-based life cycle assessment and life cycle costing of an office building in Western Europe. **Article Focus:** Examining the fusion of BIM with LCC via a case study of an office building. ***(Case Study)***
	Methodology	Six-Step Methodology: 1. Unifying architectural and structural models into a cohesive model. 2. Employing the extracted inventory to scrutinise information from the BIM model. 3. Inspecting the extracted list for any repetitions. 4. Standardising the whole project to ensure LCC tools interpret the bills of quantities accurately. 5. Assembling a project dossier that encompasses environmental, economic, and mechanical data. 6. Cataloging every material and component within the project into an XLS spreadsheet.

		This enables a seamless and thorough LCC analysis. (Efficient LCA/LCC Analysis)
	Benefits	• Integration of data into the LCC computations can be done with ease. • There is an inherent adaptability when merging BIM tools with an external LCC database. • By choosing materials and products that align with the building remaining lifespan, the BIM-LCC framework advocates for the early adoption of sustainability-focused practices.
	Challenges	A comprehensive evaluation of a project is conducted with the assistance of users, including designers and LCC specialists
	BIM-Design Software Used	Athena software –Tally software
***Raposo, Rodrigues and Rodrigues.* (2019)**	**Article Title**	BIM-based LCA assessment of seismic strengthening solutions for reinforced concrete precast industrial buildings **Article Focus:** Examining cost and environmental implications via the implementation of BIM-integrated LCA/LCC assessment. ***(Case Study)***
	Methodology	1. Employing BIM practices by constructing virtual models of buildings. 2. The objective and range of each case, along with the inventory analysis and environmental impact evaluation, shaped the LCA study. 3. The LCC analysis of erecting and dismantling the new structure accounted for a 50-year timeframe, while the expenses related to seismic upgrades and the removal of precast components from the current building were projected over a 20-year span.
	Benefits	According to a LCA and LCC analysis, refurbishing the existing structure emerges as the preferable choice due to its markedly reduced environmental footprint and the potential to cut carbon emissions by a factor of 128.5, alongside yielding costs that are 3.79 times less than those associated with new construction.
	Challenges	Uncertainty existed in the LCC regarding the real expenses of installing and dismantling precast components and carrying out seismic reinforcements. Additionally, due to the absence of projections for a 50-year service life, inflation was not factored into the calculations.
	BIM-Design Software Used	Autodesk Revit.
Lee *et al.* (2020)	**Article Title**	BIM-based preliminary estimation method considering the life cycle cost for decision-making in the early design phase. **Article Focus:** To suggest an integrated BIM approach designed to facilitate decision-making with predictive capabilities for LCC.

		(Case Study)
	Methodology	Four Steps for LCC Estimation using BIM: 1. Retrieve essential project and BIM model details by connecting BIM model data with an initial estimate framework. 2. Create a database for performance costs and benchmark data to construct the initial estimation algorithm. 3. Utilise the information from the databases through system integration to link foundational database details. 4. Offer designers LCC estimates for various design options using BIM-based initial estimation, employing analogous cost and standard data (owing to the reliance on the mass model during the design's early phases).
	Benefits	• LCC can be delivered through BIM at the onset of the design phase using precise early estimations and varying strategies. • Such data can assist clients and designers in making well-informed choices.
	Challenges	• Calculating the cost for a building category does not present in the existing database presents difficulties. • It is essential to recognise that governmental standards can introduce limited classifications and scope beyond estimation criteria, complicating the LCC estimation process.
	BIM-Design Software Used	Autodesk Revit.
Le, Likhitruangsilp and Yabuki. (2020)	**Article Title**	A BIM-Integrated Relational Database Management System for Evaluating Building Life-Cycle Costs **Article Focus:** To create a unified BIM database system designed to employ LCCA effectively. ***(Case Study)***
	Methodology	The establishment of a BIM-integrated RDBMS featuring two interconnected components: 1. A Visualisation BIM Integration Module and a Relational Database Management Module. 2. Data can be accumulated, structured, preserved, and utilised with either methodology for the assembly of LCCA.
	Benefits	• The creation of a BIM-integrated RDBMS involves the synthesis of the database management system, BIM authoring tools, spreadsheet software, and visual programming interfaces to minimise computation duration. • This integration aims to decrease or eradicate data discrepancies and losses from human mistakes, thereby yielding more precise outcomes.

	Challenges	• Present BIM instruments lack the capacity to handle the data necessary for the LCCA procedure. • Due to unstructured data, diverse tools and formats often fail to align with one another. • Distinctly defining standards, computational methodologies, and interoperable technologies presents a significant challenge
	BIM-Design Software Used	Autodesk Revit.
Barbini *et al.* (2020)	**Article Title**	Integration of Life Cycle Data in a BIM Object Library to Support Green and Digital Public Procurements **Article Focus:** To assess a system and workflow with respect to the life cycle considerations of a construction project. ***(Review)***
	Methodology	Three Methods for Merging BIM-LCC: 1. Application of various programs like SimaPro, CostLab, Excel, etc., for performing LCC analyses. 2. Linking an LCC database to quantities produced by a BIM model. 3. Direct incorporation of LCC information into the BIM model.
	Benefits	• Optimisation of building performance can be achieved with respect to environmental and economic aspects. • Dealings have been finalised more swiftly. • There has been an uptick in productivity. • A higher degree of clarity has been realised. • Sustainability practices have improved.
	Challenges	None
	BIM-Design Software Used	None
Ansah *et al.* (2020)	**Article Title**	An integrated life cycle assessment of different façade systems for a typical residential building in Ghana **Article Focus:** To develop a comprehensive framework combining BIM, LCA, and LCC for conducting a comparative study of four distinct facade systems in Ghana. ***(Case Study)***
	Methodology	This initiative combines BIM, LCA, and LCC to evaluate the following facade systems against the conventional Concrete Block and Mortar Façade (CBMF) technique: (1) Shotcrete Insulated Composite Façade (Shotcrete ICF), (2) Galvanised Steel Insulated Composite Façade (G. Steel ICF), and (3)

		Stabilised Earth Block Façades (SEBF): 1. A BIM model of a case study structure utilising CBMF was crafted using Revit. 2. Three alternative facades were separately modeled using BIM. 3. Each facade model was subjected to an LCA in line with ISO 14000 standards. 4. Operational impacts were forecasted using Microsoft Excel for LCC estimation and the Integrated Environmental Solutions Virtual Environment (IES-VE) for energy modeling. 5. Economic assessments were also performed on the different life cycle stages for comparison.
	Benefits	The practicality of merging BIM with LCC facilitates comparative analyses aimed at minimising environmental impact through the selection of sustainable facade options.
	Challenges	None
	BIM-Design Software Used	Autodesk Revit.
Rad *et al.* (2021)	**Article Title**	BIM-based approach to conduct Life Cycle Cost Analysis of resilient buildings at the conceptual stage **Article Focus:** Development of a tool that integrates BIM with LCA/LCC processes. ***(Case Study)***
	Methodology	• A BIM-LCCA add-on has been created within Autodesk Revit, delivering separate outputs for distinct segments. • Information essential for LCC calculation can be exported to an external database from the BIM application.
	Benefits	Within the construction sector, the framework offers a chance to enhance the adaptability of seismic measurement scenarios throughout the design stage.
	Challenges	None
	BIM-Design Software Used	Autodesk Revit.
Zhuang *et al.* (2021)	**Article Title**	A performance data integrated BIM framework for building life-cycle energy efficiency and environmental optimisation design **Article Focus:** Creating a consolidated P-BIM framework that embeds LCC early in the design process to optimise the energy efficiency and environmental performance of buildings. ***(Case Study)***

	Methodology	P-BIM Methodology: 1. The system encompasses three tiers of carriers — the Inner Layer Carrier is Autodesk Revit, the Outer Layer Carrier is MySQL, and the Middle Layer Carrier is Rhino Inside. 2. Rhino's tool computes the preliminary construction costs by choosing from a range of pre-stored construction configurations. 3. The LCC index delivers comprehensive cost details, encompassing Initial Cost, Operational Cost, Replacement Cost, and Total System Cost.
	Benefits	• At the outset of the design phase, LCC evaluations can be conducted by augmenting the P-BIM framework with additional data dimensions related to costs, acoustics, and visual conditions. • Incorporating P-BIM throughout the project lifecycle allows architects to improve their understanding and management of their role throughout the project duration. • P-BIM has the potential to narrow the discrepancy between anticipated and actual performance arising from design and procurement divisions.
	Challenges	None
	BIM-Design Software Used	Autodesk Revit.
Lu *et al.* (2021)	**Article Title**	Integration of life cycle assessment and life cycle cost using building information modeling: A critical review. **Article Focus:** To examine pertinent scholarly articles concerning the amalgamation of LCA and LCC with BIM in a research context. ***(Review)***
	Methodology	Upon examining existing research, scholars identified three primary methodological approaches for incorporating LCC and LCA with BIM: 1. Gathering data (such as bills of quantities) via established BIM applications. (Most common approach—72.2%) 2. Employing auxiliary software platforms for exporting data from BIM models. 3. Generating pertinent data directly within the BIM model.
	Benefits	• Incorporating BIM-LCC/LCA at the initial design stages aids designers in assessing the project environmental footprint and costs over its life span. • BIM-integrated LCA and LCC encompass five life cycle stages: design, construction, operation, maintenance, and demolition.
	Challenges	• Operational data should be sourced from a diverse group of stakeholders.

		• When LCA and LCC are merged with BIM, it is possible to focus on just three critical phases: operation, design, and demolition.
	BIM-Design Software Used	None
Santos *et al.* (2019)	**Article Title**	Integration of LCA and LCC analysis within a BIM-based environment **Article Focus:** This project aims to investigate the capability of BIM to serve as a storehouse for LCA and LCC data, and to examine the utilisation of this information in performing a cost-benefit analysis relevant to the project. ***(Case Study)***
	Methodology	• Within a BIM framework, the researchers cataloged all necessary data for conducting LCA and LCC evaluations. • Subsequently, they established a BIM-LCA/LCC structure, to which IMD/MDV technology was applied
	Benefits	• BIM offers a robust framework conducive to creating appropriate models for the exchange of sustainability-related data across various software systems. • BIM serves as an instrumental resource for facilitating LCA and LCC analyses.
	Challenges	• BIM necessitates additional data beyond what is included in LCA and LCC for thorough analysis. • The limitations imposed by material constraints in current LCA-BIM models pose difficulties for existing BIM-based LCA tools. • The absence of semantic information within BIM may lead to inaccuracies in the data generated.
	BIM-Design Software Used	Autodesk Revit.
Sharif and Hammad (2019).	**Article Title**	Simulation-Based Multi-Objective Optimisation of institutional building renovation considering energy consumption, Life-Cycle Cost and Life-Cycle Assessment **Article Focus:** To determine optimal energy consumption and LCA scenarios for the renovation of institutional buildings. ***(Case Study)***
	Methodology	• The model comprises four primary stages. The initial phase focuses on gathering input data for the model, encompassing methods for defining data collection and creating the BIM model. • The second stage involves establishing a database and integrating allocation methods for each strategy. • The third stage entails the delineation of renovation strategies.

		• The final stage encompasses simulation-based optimisation of multiple objectives.
	Benefits	• BIM was identified as a valuable model for optimising building and renovation scenarios, leading to reduced LCC, Total Energy Consumption (TEC), and environmental impacts of buildings. • BIM can facilitate energy conservation in buildings, contributing to improved energy efficiency.
	Challenges	None
	BIM-Design Software Used	Autodesk Revit.
Zakaria, Ali and Zolkafli. (2020)	**Article Title**	The Implementation of Life Cycle Costing towards Private Client's Investment: The Case of Malaysian Construction Projects **Article Focus:** To examine the LCC situation in Malaysia. ***(Quantitative Case Study)***
	Methodology	Utilising a survey-based approach with a quantitative methodology and a structured questionnaire to assess: • The extent of consensus among real estate developers regarding the significance of implementing LCC practices within the construction sector. • The evaluation of advantages associated with LCC adoption. • The identification of obstacles hindering the implementation of LCC principles.
	Benefits	• Can assist the project owner in gaining insights into the projected LCC during the design phase. • Emphasises the evaluation of project value as a financial assessment method for project alternatives, aiding decision-making processes. • Enhancing awareness regarding the comprehensive cost aspects of the project.
	Challenges	Challenges in the seamless integration of design models with BIM in the context of implementing LCC methodologies.
	BIM-Design Software Used	None
Zimmermann, Bruhn and Birgisdóttir (2021)	**Article Title**	BIM-Based Life Cycle Assessment of Buildings—An Investigation of Industry Practice and Needs **Article Focus:** To explore the prerequisites for merging BIM and LCA through qualitative interviews with professionals from companies experienced in conducting LCA for their construction projects. ***(Qualitative Case Study)***
	Methodology	Five methods for integrating BIM and LCA are as follows: 1. Augmented BIM. 2. Quantitative Analysis from BIM.

		3. Geometry Importation. 4. Intermediate Viewing Platform. 5. Integration via LCA Plug-In.
	Benefits	None
	Challenges	• Insufficient management of building models in collaborative processes. • Workflow inconsistencies and errors, including modeling discrepancies. • Deficiencies in data quality and accessibility within the models. • Variations in the structural layouts of different models. • Aligning model data with LCA data through data interchange. • Utilising manual workflows for handling large models and their associated processes.
	BIM-Design Software Used	None
Juan and Hsing (2017).	**Article Title**	BIM-Based Approach to Simulate Building Adaptive Performance and Life Cycle Costs for an Open Building Design **Article Focus:** To investigate the benefits of an open building design and the prerequisites for extending a building lifespan in the future. ***(Case Study)***
	Methodology	• The research incorporated three design concepts tailored to achieve service lifespans of 30, 50, and 100 years, aligning with life cycle considerations and real-world instances. • For the 30-year design, a conventional building design approach was employed, while the 50-year design featured a semi-open design, and the 100-year project implemented an open design system. • BIM was employed to perform simulations pertaining to the renovation advantages associated with these distinct design proposals.
	Benefits	• BIM emerged as a crucial instrument for simulating forthcoming building renovations, utilisation, and maintenance. • BIM serves as a decision support system capable of optimising the expenses and advantages associated with renovation efforts. • BIM contributes to the enhancement of a building service life by providing sound estimates of benefits and costs. • It aids in achieving reduced LCC in comparison to conventional systems.

	Challenges	None
	BIM-Design Software Used	Autodesk Revit.
Saridaki, Psarra and Haugbølle. (2019)	**Article Title**	Implementing life-cycle costing: Data integration between design models and cost calculations **Article Focus:** This research endeavors to construct, evaluate, and consolidate insights gained from the integration of data across independent software applications connected to design models, cost estimations, and cost databases, with the objective of delivering comprehensive LCC evaluations. ***(Case Study)***
	Methodology	The scholars employed a thorough approach, commencing with a literature examination and subsequent interviews. The insights derived from both the literature review and interviews were subsequently harnessed to create tools aimed at establishing connections between design models and comprehensive building cost databases.
	Benefits	• BIM demonstrated its effectiveness in elevating productivity and fostering collaboration within the realm of sustainable construction. • BIM introduced a distinctive methodology for gathering data that contributes to the pursuit of building sustainability. • BIM promotes adaptability and innovation, facilitating the evolution of building practices.
	Challenges	• The absence of standardised BIM norms for models is a contributing factor to challenges in integrating and overseeing diverse stakeholders. • The existence of various data exchange formats contributes to issues related to standardisation in the BIM domain.
	BIM-Design Software Used	Autodesk Revit.
Shin and Cho (2015)	**Article Title**	BIM application to select appropriate design alternative with consideration of LCA and LCCA **Article Focus:** The improvement of LCCA and LCA can be achieved by formulating an approach grounded in 3D parametric BIM. ***(Case Study)***
	Methodology	• The researchers employed a sequential approach, commencing with a literature review. Subsequently, they performed data analysis on the initial LCA and LCCA data collected. In the third phase, BIM was employed to extract critical information pertaining to LCA and LCCA. Finally, a case study was executed, employing the BIM model on an actual building.

	Benefits	• BIM facilitated streamlined computations of LCA and LCCA. It significantly reduced the time required for conducting LCA and LCCA for the three alternatives, establishing BIM as the optimal solution for addressing these issues. • BIM serves as a proficient quality evaluator that seamlessly integrates with other software tools. • Pertinent information is readily accessible during the initial project stages through BIM.
	Challenges	• BIM did not furnish data pertaining to fuel consumption. This absence of data compromises the dependability and precision of the outcomes generated by BIM. • A deficiency of a comprehensive BIM library impeded engineers from swiftly accessing the essential information they needed.
	BIM-Design Software Used	ArchiCAD.

2.6.5 Outcome

The results are segmented into four subsections, focusing on the methodologies employed in BIM and LCC research, the software applications utilised in BIM integration, the advantages of applying BIM to LCC, and the obstacles faced in the adoption of BIM for LCC purposes.

2.7.5.1 Methodology in Studies of BIM and LCC

Different methods and strategies have been examined in research dedicated to merging BIM with LCC considerations. For example, Liu, Meng and Tam (2015) developed a BIM-centric multi-criteria optimisation model, integrating data from Ecotect for analytical purposes. Kehily and Underwood (2017) expanded 5D BIM by including LCC estimates via CostX software. Marzouk, Azab and Metawie (2018) employed BIM through Autodesk Revit, in conjunction with Genetic Algorithm Optimisation and Monte Carlo Simulation, for LCC prediction. Santos *et al*. (2019) utilised a six-phase methodology that involved the amalgamation of architectural and structural models, duplicate verification, and the inclusion of environmental, economic, and mechanical data for LCC evaluation.

Raposo, Rodrigues and Rodrigues (2019) evaluated both costs and ecological consequences using a blend of BIM, LCA, and LCC, with a focus on an industrial structure. Santos *et al*. (2020) introduced BIMEELCA, a tool based on BIM for concurrent environmental and economic life cycle assessments. Lee *et al*. (2020) showcased a method that merges BIM and LCC estimations during the initial design stages. Le, Likhitruangsilp and Yabuki (2020) created a Relational Database Management System that is BIM-compatible for LCC scrutiny. Barbini *et al*. (2020) stressed the importance of directly incorporating LCC data into BIM frameworks. Lastly, Ansah *et al*. (2020) fused BIM with LCC and LCA for analysing façade systems.

Rad *et al*. (2021) developed a plug-in for BIM-LCCA using Autodesk Revit for generating results. Zhuang *et al*. (2021) formulated a Performance-Integrated BIM (P-BIM) framework aimed at enhancing building energy efficiency and included LCC considerations. Lu *et al*. (2021) conducted a literature review and pinpointed three primary strategies for merging BIM with LCC and LCA. These varied techniques underscore the flexibility and ingenuity in amalgamating BIM and LCC evaluations in the field of construction.

2.7.5.2 Design Software Used in BIM Adoption

The predominant design software currently in use is Autodesk Revit. A majority of researchers (Juan and Hsing, 2017; Kehily and Underwood, 2017; Marzouk, Azab and Metawie, 2018; Raposo, Rodrigues and Rodrigues, 2019; Santos *et al*., 2019; Saridaki, Psarra and Haugbølle, 2019; Sharif and Hammad, 2019; Santos *et al*., 2020; Lee *et al*., 2020; Le, Likhitruangsilp and Yabuki, 2020; Ansah *et al*., 2020; Rad *et al*., 2021; Zhuang *et al*., 2021; Zimmermann, Bruhn and Birgisdóttir, 2021) have incorporated Autodesk Revit into their BIM systems for internal LCC analysis or through external platforms. Revit specialises in BIM and integrates the three core disciplines—Architecture, Engineering, and Construction—into a single modelling framework for optimised efficiency and cost management in construction projects. This indicates that the use of Revit as a BIM design tool is pervasive in the construction sector. Further details can be found in Table 6. Beyond the prior discussion on BIM-LCC advancements, the researcher now turns to the benefits identified by BIM practitioners.

Table 6: Overview of the software used for the integration

Author	Software of Model	Software of Data	LCC Analysis
Marzouk, Azab and Metawie (2018)	AUTODESK REVIT	Microsoft Excel	Monte Carlo. The optimisation model utilises Genetic Algorithms (GA).
Santos *et al*. (2020)	AUTODESK REVIT	Excel format, Revit GUI	BIMEELCA tool. Streamlined LCA/LCC analysis based.
Liu, Meng and Tam (2015)	Autodesk Ecotect	Multiple Objective Particle Swarm Optimisation (MOPSO)	Pareto-optimal front.
Kehily and Underwood (2017)	AUTODESK REVIT	Exactal CostX with 5D BIM platform	CostX 5D BIM software.
Santos *et al*. (2019)	REVIT, tally, Athena Impact Estimator for Buildings	LCA database (GaBi), Microsoft Excel	BIMEELCA tool.
Raposo, Rodrigues and Rodrigues (2019)	AUTODESK REVIT	Tally database	Tally LCA Software.
Lee *et al*. (2020)	AUTODESK REVIT	Oracle SQL Developer	JAVA-based eclipse JSP. Web-based user interface (UI).
Le, Likhitruangsilp and Yabuki (2020)	AUTODESK REVIT	Microsoft Excel	Relational database management system (RDBMS).
Ansah *et al*. (2020)	AUTODESK REVIT	Microsoft Excel	Integrated Environmental Solutions Virtual Environment (IES-VE).
Rad *et al*. (2021)	AUTODESK REVIT	RSMeans cost database, Microsoft Access, Microsoft Excel, Platform Revit API	Green Building Studio (GBS). The developed BIM-LCCA plug-in.
Zhuang *et al*. (2021)	AUTODESK REVIT	Platform Revit API, MySQL (V5.7), Rhino.Inside (V0.0.7668).	A performance integrated BIM (P-BIM). LadybugTools. EnergyPlus. Octopus tool.
Santos *et al*. (2019)	AUTODESK REVIT	Ifc Doc tool, IDM/MVD	BIM-LCA/LCC analysis.
Sharif and Hammad (2019)	AUTODESK REVIT	Take-Off (MTO) table	Simulation-Based Multi-Objective Optimisation (SBMO) model. Pareto front.
Juan and Hsing (2017)	AUTODESK REVIT	Microsoft Excel	Net Present Value "NPV". The FDS+EVAC tool. Computational Fluid Dynamics (CFD) Simulation of Indoor Wind. The daylight analysis software.
Saridaki, Psarra and Haugbølle (2019)	AUTODESK REVIT	Molio Price Database, MS Excel-based tool	Sigma Estimates. 5D BIM cost software. Dynamo model.
Shin and Cho (2015)	GRAPHISOFT Archicad	Microsoft Excel	Eco Designer software. Excel worksheet-based framework.

2.7.5.3 Benefits from the Application of BIM and LCC

The incorporation of BIM into LCC assessments presents various advantages. Liu, Meng and Tam (2015) underscored its utility in early maintenance cost predictions and achieving sustainability goals. Kehily and Underwood (2017) stressed the analytical capabilities of 5D BIM for thorough LCC evaluations. Marzouk, Azab and Metawie (2018) observed that when BIM is paired with Monte Carlo Simulation and Optimisation Models, it facilitates the choice of environmentally-friendly materials and LCC forecasting.

Santos *et al*. (2019) touched on the adaptability of merging external LCC data repositories with BIM, encouraging early adoption of sustainable practices in projects. Santos *et al*. (2020) presented the BIMEELCA tool, which eases the incorporation of spreadsheet data and facilitates efficient LCC evaluations. Lee *et al*. (2020) highlighted the efficacy of BIM in delivering precise initial LCC projections, aiding early-stage decision making.

Barbini *et al*. (2020) and Ansah *et al*. (2020) emphasised the benefits of BIM-LCC integration in improving environmental and economic outcomes, cutting down transaction durations, and bolstering sustainability. Zhuang *et al*. (2021) and Lu *et al*. (2021) stressed the advantages of BIM integration in increasing oversight, minimising discrepancies between anticipated and real-world performance, and offering rapid, dependable life cycle information in the preliminary design phase.

2.7.5.4 Challenges in the Study of BIM and LCC

Scholars have emphasised numerous obstacles in researching the integration of BIM with LCC. Kehily and Underwood (2017) highlighted the lack of standardised frameworks for LCC calculations and a low client interest in incorporating LCC into projects. This is likely attributed to the specialised data required for LCC analysis, which is viewed as a common hurdle among various stakeholders including designers and LCC specialists (Santos *et al*., 2019).

Lee *et al*. (2020) posited that the availability of data in the project database is one of the challenges. They explained that the selection of a building type is difficult to find in the constructed database. The estimation criteria based on government's standards often lead to a limitation of the classification and the respective scope. This induces difficulties in the LCC estimation.

In addition, Le, Likhitruangsilp and Yabuki (2020) emphasised that challenges exist in the capacity of BIM software to conduct LCC analyses. Issues cited include non-standardised data formats, limited tool interoperability, fragmented standards, computational approaches, and compatible technologies. Zakaria, Ali and Zolkafli (2020) concurred, stating that fully integrating LCC into BIM design models presents difficulties.

Zimmermann, Bruhn and Birgisdóttir (2021) identified seven impediments to the complete integration of BIM into LCC within the industry. These include inadequate management of building models for collaborative efforts, workflow errors, insufficient data quality and availability in models, mistakes in the modelling phase, inconsistencies in model structures, issues in data interchange and aligning model data with LCA data, and finally, the manual nature of workflows and the size of the models involved. Lu *et al*. (2021) also touched on complexities in project workflows, stating that the challenge in merging BIM and LCC lies in collecting operational information from diverse stakeholders. This is problematic as each stakeholder employs their own tools and processes, limiting the integration of BIM and LCC to design, operation, and demolition stages.

2.6.6 Discussion

Present methods for integrating BIM and LCC involve the use of internal databases, external databases or the development of new tools. Santos *et al*. (2019), Raposo, Rodrigues and Rodrigues (2019), Lee *et al*. (2020), Le, Likhitruangsilp and Yabuki (2020), and Ansah *et al*. (2020) opted for an internal BIM database for LCC integration. An external database was employed by Kehily and Underwood (2017), Marzouk, Azab and Metawie (2018), and Lu *et al*. (2021). Three researchers (Santos *et al*., 2020; Rad *et al*., 2021; Zhuang *et al*., 2021) crafted new tools to incorporate LCC into BIM. Autodesk Revit has been widely utilised as the BIM design software by fourteen authors (Juan and Hsing, 2017; Kehily and Underwood, 2017; Marzouk, Azab and Metawie, 2018; Raposo, Rodrigues and Rodrigues, 2019; Santos *et al*., 2019; Saridaki, Psarra and Haugbølle, 2019; Sharif and Hammad, 2019; Santos *et al*., 2020; Lee *et al*., 2020; Le, Likhitruangsilp and Yabuki, 2020; Ansah *et al*., 2020; Rad *et al*., 2021; Zhuang *et al*., 2021; Zimmermann, Bruhn and Birgisdóttir, 2021) in studies focusing on BIM's role in LCC.

LCC serves as a tool for gauging the extent of sustainable development in construction (Marzouk, Azab and Metawie, 2018). The integration of BIM into LCC empowers decision makers to opt for eco-friendly building materials (Kehily and Underwood, 2017; Santos *et al*., 2019; Barbini *et al*., 2020; Ansah *et al*., 2021), aiding in the reduction of unsustainable projects and thereby mitigating climate change. Traditional project designs, with their rigid processes, constrain opportunities for sustainability (Zhuang *et al*., 2021). Benefits of adopting BIM-LCC also include cost and value optimisation across projects, as noted by Lee *et al*. (2020) and Le, Likhitruangsilp and Yabuki, (2020). Furthermore, this approach enhances both environmental and economic performance, shortens transaction times, and boosts productivity and transparency (Barbini *et al*., 2020). Early-stage adoption of BIM-LCC enables immediate access to data on environmental impact and costs, providing designers with greater project control (Zhuang *et al*., 2021; Lu *et al*., 2021). This is crucial as early-stage decisions tend to have a lasting impact on the project entire lifecycle (Lee *et al*., 2020).

Prominent challenges in integrating BIM with LCC, as identified by researchers, include inadequate or incompatible data within project databases (Kehily and Underwood, 2017; Santos *et al*., 2019; Lee *et al*., 2020; Zimmermann, Bruhn and Birgisdóttir, 2021). Questions also arise about the efficacy of BIM software in carrying out LCC-specific tasks (Le, Likhitruangsilp and Yabuki, 2020; Zakaria, Ali and Zolkafli, 2020). Lu *et al*. (2021) emphasised that stakeholders accustomed to conventional construction methodologies contribute to the issue by providing inconsistent or non-standardised data as each stakeholder employs their own distinct tools and workflows.

In summary, sustainability serves as a crucial metric for construction endeavours, advocating for eco-friendly development with minimal contributions to greenhouse gas emissions. The amalgamation of BIM and LCC enables decision makers to select sustainable building materials, thereby enhancing the sustainability of constructed assets, whether buildings, facilities, or infrastructure. The most pervasive obstacle lies in the integration of data between BIM and LCC within the project database. The current paper offers insights into a systematic review on the incorporation of BIM into LCC, focusing on four key aspects: Methodology, Design Software, Benefits, and Challenges. This aims to enrich the discourse on prevailing trends in the adoption of BIM for LCC purposes.

2.7 Adoption of BIM on LCC in Saudi Arabia

Building Information Modelling (BIM) and Life Cycle Cost (LCC) have gained significant attention in Saudi Arabia's construction industry in recent years. The country recognises the potential of these methodologies to enhance project efficiency, sustainability, and cost-effectiveness. In Saudi Arabia, BIM adoption has been driven by government initiatives and regulatory frameworks, such as:

- Saudi Vision 2030 emphasises the importance of adopting advanced technologies in various sectors including construction. BIM plays a crucial role in achieving the goals of Vision 2030 by improving project coordination, reducing waste, and enhancing productivity (Alaboud and Alshahrani, 2023).
- The National Transformation Program (NTP) focuses on diversifying the Saudi economy and it includes initiatives to enhance the construction industry's efficiency. BIM implementation is one of the key strategies to achieve this goal (Alaboud and Alshahrani, 2023).
- Saudi Standards, Metrology and Quality Organisation (SASO) has introduced guidelines and standards for BIM implementation in Saudi Arabia. These guidelines provide a framework for the use of BIM across different construction projects in the country (Alaboud and Alshahrani, 2023).

In the prior studies, the application of BIM through LCC approach has gained considerable attention in Saudi Arabia. For instance, Rashed *et al*. (2019) empirical work affirmed that the BIM approach can save 17% LCC and recognised it as the most cost-effective method in construction. In the same vein, Alaboud and Alshahrani (2023) critical reviewed the dynamic association between BIM and LCC and affirmed that BIM and sustainability benefits are expected to be the most important variable in the Middle East construction sector. Likewise, Alshibani and Alshamrani (2017) contended that BIM-based model validation saves energy costs of residential buildings in Saudi Arabia. However, the review study of Alghamdi, Beach and Rezgui (2022) concluded that there is a lack of BIM use in Saudi Arabia for both public and private projects.

2.8 Findings of the Literature Review

The following literature review examines the utilisation of BIM in relation to the LCC analysis of sustainable buildings. BIM has emerged as a powerful tool for integrating various aspects of the building process, enabling more efficient planning, design, construction, and maintenance. This review aims to explore existing research, case studies, and industry practices to determine how BIM can contribute to the evaluation and optimisation of LCC in sustainable building projects.

- With the fundamental concepts of BIM and its role in sustainable building design and construction, the review explores how BIM facilitates collaboration, data integration, and visualisation, leading to improved decision making and resource efficiency. Additionally, it highlights the potential benefits of using BIM for sustainable design, including energy performance analysis, material selection, and waste reduction (Alaboud and Alshahrani, 2023).
- Here, the focus shifts to the LCC analysis, which considers costs incurred over a building entire life cycle, including construction, operation, maintenance, and disposal. The section provides an overview of LCC concepts, methodologies, and factors influencing cost analysis. It emphasises the significance of incorporating sustainability aspects into LCC assessments, such as energy consumption, environmental impacts, and social considerations.
- The integration of BIM and LCC methodologies. It highlights research and case studies

that demonstrate how BIM can enhance LCC analysis by providing accurate and comprehensive data throughout a building life cycle stages. Topics covered include BIM-enabled energy simulations, material selection optimisation, maintenance planning, and facility management.

- The benefits and challenges associated with the use of BIM on the LCC of sustainable buildings are crucial. The section discusses the potential advantages, such as improved accuracy, cost reduction, and enhanced project coordination. It also addresses challenges, including data interoperability, skill requirements, and the need for standardised workflows. Strategies for overcoming these challenges are explored to maximise the benefits of BIM in LCC analysis.
- The current industry adoption of BIM for LCC analysis in sustainable building projects. This examines real-world case studies, pilot projects, and industry initiatives that showcase successful integration. Best practices and lessons learned are identified, highlighting effective implementation strategies and key considerations for maximising the potential of BIM in LCC evaluations.
- By conducting a comparative analysis with existing global studies, this research highlights the distinctive outcomes and potential of BIM in Saudi Arabia, underscoring how local adaptation and integration can lead to different results and recommendations. This comparative insight is critical for policymakers and practitioners in the KSA and similar economies, offering a tailored approach to BIM integration not covered in the open literature.

In conclusion, the literature review demonstrates the potential of BIM as a valuable tool for optimising LCC analysis in sustainable building projects. It highlights the benefits of integrating

BIM and LCC methodologies, emphasising the need for interdisciplinary collaboration and standardised workflows. By leveraging the power of BIM, stakeholders can make informed decisions, improve resource efficiency, and contribute to the development of sustainable built environments. Future research directions are suggested to further explore the application of BIM in LCC analysis and address the remaining challenges.

2.9 Literature Gap

In regard to literature that had been compiled on BIM adoption, LCC analysis, and sustainability practices in construction, the construction industry in Saudi Arabia, the [construction industry in Saudi Arabia] has a rather unique environment, yet this is not thoroughly looked into in the available body of knowledge. In a sense, that may not be enough to deeply understand the mentioned intricacies of regulatory framework, market structure, cultural customs and institutional constraints of the country.

In addition to the fact that the construction industry is significantly affected by the local aspects such as regulations, policies, conditions in the market and individual actors' patterns of behavior. Although BIM, LCC and sustainability principles are mainly feasible to all contexts, it needs to be adapted and adhered to the unique setting of the construction sector in Saudi Arabia This study seeks to fill this gap with a specific local base and developing the frameworks and approaches appropriate for the context through the research process.

What makes this research staged differently is that it is based on holistic approach which includes systematic literature review, empirical studies, advanced BIM simulations, and stakeholders involvement. Although previous studies are fashioned around BIM adoption, LCC analysis, or sustainability as they relate in the construction industry, this unique mixed-method approach offers a more holistic view of the challenges, opportunities, and strategies that help

BIM firms optimise LCC and sustainability for residential construction in Saudi Arabia.

Research designed to comprehensively analyse the local specifics, challenges and opportunities is purposed to create methodologically sound guidelines and strategies which then may be applied by actors involved in residential construction projects in Saudi Arabia that include the government, contractors, developers and any other relevant entities to help achieve cost-effectiveness and high sustainability through the use of BIM. The results and suggestions of this study can end up owning the transformation of the construction industry in the Saudi Kingdom that its efficiency, costs, and environmentalities will be very improved as a result.

There is a need to recognise the past research and studies as they have been a crucial part of the development of theories about BIM adoption, LCC and sustainability in construction. Nevertheless, to preserve the general theory of the above knowledge, the given research will be focused on the Saudi Arabian construction industry providing a complete and site-specific investigation with the incorporation of the country context. This research work can be able to bring about community and thinking beyond the use of existing knowledge to get localised insights and empirical data; thereby will provide a more nuanced and actionable understanding with regards to the possibilities and provoking challenges in employing BIM for optimising LCC and sustainability in Saudi Arabia’s residential construction projects.

Offering a varied perspective, the research informs the global knowledge-base by addressing a specific knowledge-gap and conducting a localised review of the practices in the Saudi Arabian construction industry which can have a practical impact. The amalgammation of theoretical thoughts, empirical data, and advanced simulations put forth a special perspective that helps us understand and solve the intricate link between BIM adoption, life cycle cost optimisation and sustainability as a practice in Saudi Arabia's construction sector.

2.10 Theoretical Background

The theoretical background of this research is based on the Technology Acceptance Model (TAM), Life Cycle Cost Analysis (LCCA) framework, and Building Performance Simulations.

- Technology Acceptance Model (TAM): The Technology Acceptance Model provides a theoretical foundation for understanding the adoption and use of BIM technology in the context of sustainable building projects. TAM posits that the intention to use a technology is influenced by two key factors: perceived usefulness and perceived ease of use. In the context of BIM and LCC, this framework suggests that stakeholders' perception of the usefulness and ease of use of BIM will affect their willingness to adopt and utilise BIM for LCC analysis in sustainable buildings (Hilal, Maqsood and Abdekhodaee, 2019).
- Life Cycle Cost Analysis (LCCA) Framework: The Life Cycle Cost Analysis framework provides a systematic approach for evaluating the costs associated with a building project over its entire life cycle. This framework emphasises the importance of considering costs beyond initial construction including operation, maintenance, and disposal. Integrating BIM within the LCCA framework allows for enhanced data management, analysis, and decision making throughout the life cycle stages, enabling more accurate and comprehensive cost evaluations (Pan *et al*., 2021; França *et al.,* 2021).
- Building Performance Simulation: Building performance simulation models simulate the behaviour and performance of a building throughout its life cycle. BIM provides the necessary data for energy analysis, thermal performance, daylighting, and other performance simulations (Habibi, 2017; Utkucu and Sözer, 2020). By incorporating

these simulations within the LCC framework, stakeholders can assess the long-term energy efficiency, operational costs, and environmental impacts of sustainable buildings, supporting decision-making processes (Hajare and Elwakil, 2020).

The theoretical framework outlined above integrates key concepts and models from technology acceptance, life cycle cost analysis, and building performance simulation. This framework provides a comprehensive understanding of how BIM can be effectively used to analyse and optimise the life cycle cost of sustainable buildings. It emphasises the importance of stakeholder perceptions, collaboration, data integration, and consideration of sustainability aspects throughout the building life cycle.

2.11 Hypotheses Development: Role of Enablers and Constraints towards the Adoption of BIM

The presence of enablers positively influences the adoption and implementation of BIM in construction projects. This hypothesis suggests that factors such as organisational support, technological infrastructure, training and education programmes, and industry standards act as enablers that facilitate the successful adoption and implementation of BIM in construction projects (Alaboud and Alshahrani, 2023). Organisations with strong enablers are more likely to embrace BIM and effectively integrate it into their project workflows. On the other hand, constraints negatively impact the adoption and implementation of BIM in construction projects. This posits that barriers and challenges, such as financial constraints, resistance to change, limited interoperability, and inadequate knowledge and skills, hinder the adoption and implementation of BIM in construction projects (Kehily, 2016; Nwodo, Anumba and Asadi, 2017). Organisations facing significant constraints are likely to face difficulties in fully embracing and utilising BIM to its full potential. Based on the above arguments the following hypotheses have been developed. See Figure 26.

H1: Enablers positively affect the adoption of BIM in the Saudi Construction industry.

H2: Constraints negatively affect the adoption of BIM in the Saudi Construction industry.

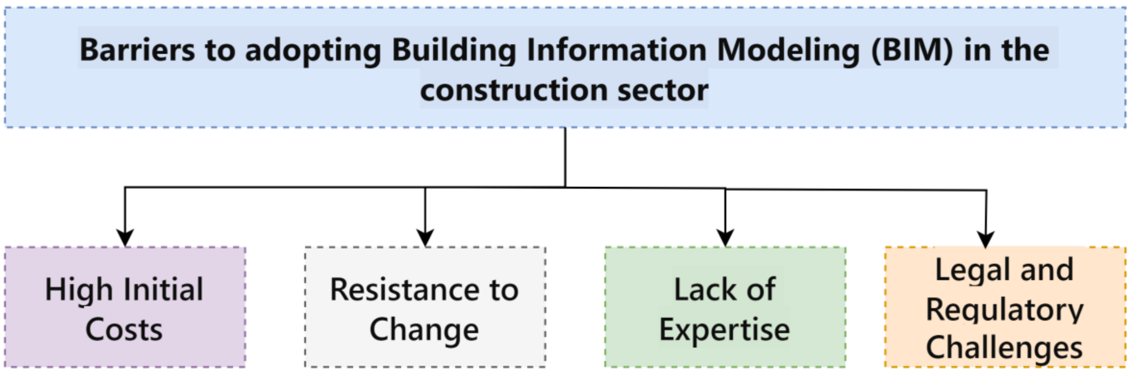


Figure 26: Obstacles to Implementing BIM in the Construction Industry

2.12 Summary of Chapter

This chapter highlights the use of BIM in relation to the LCC analysis of sustainable buildings, particularly in Saudi Arabia. It explores the integration of BIM and LCC methodologies, highlighting the potential benefits, such as improved accuracy and cost reduction, as well as the challenges including data interoperability and skill requirements. The review emphasises the importance of interdisciplinary collaboration, standardised workflows, and stakeholder perceptions in maximising the potential of BIM for LCC evaluations. It also discusses the industry adoption of BIM for LCC analysis, showcasing case studies and best practices. Overall, the literature review demonstrates how BIM can enhance LCC analysis in sustainable building projects and contribute to informed decision making and resource efficiency. From the knowledge gained through this chapter, the researcher is able to draw a research methodology, which will be discussed in the next chapter.

Chapter 3

Research Methodology

3 Chapter Three: Research Methodology

3.1 Introduction

This chapter focuses on designing an effective strategy for collecting and analysing data to achieve the research objectives. It demonstrates the impact of research principles on the design process. Various approaches were utilised to select appropriate methods for conducting the research. The chapter outlines the research strategy, target population, participant sampling, ethical considerations, and how these issues were addressed. See Figure 27.

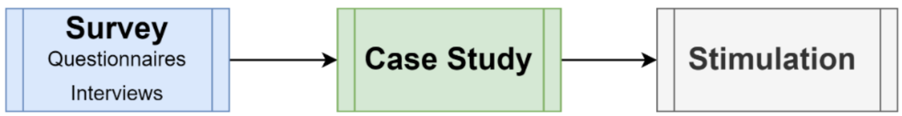


Figure 27: Data collection strategy

3.2 Research Methodology

Research methodology is a fundamental component of any research, encompassing the necessary methods and techniques for conducting academic investigations. According to Fellows and Liu (2009), research methodology involves the application of logical processes in scientific inquiries. Aletaiby (2018) defined it as an analytical procedure rooted in philosophical principles, guiding the research design to ensure the validity and reliability of its objectives. Kothari (2004) emphasised that research methodology provides a systematic approach to problem-solving in research.

Various research methodology designs can be found in the literature. A nested model, consisting of three layers, was proposed by Aouad *et al*. (1999) to establish the research methodology. The first layer encompasses the research philosophy, the second layer involves research approach or strategies of inquiry, and the final layer pertains to research techniques or data collection methods. Figure 28 illustrates the nested model of the research methodology.

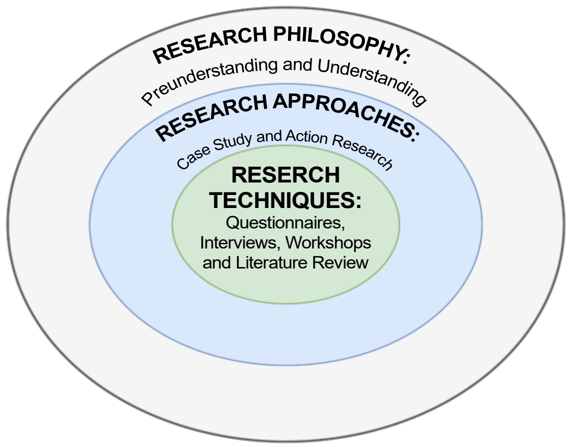


Figure 28: Nested research methodology adopted (Aouad *et al.*, 1999)

Clark and Creswell (2014) presented an alternative research methodology model or framework, which consists of three interconnected steps. The first step involves philosophical worldviews, the second step encompasses research design, and the final step pertains to research methods. Figure 29 illustrates the interlinked steps of this research methodology model.

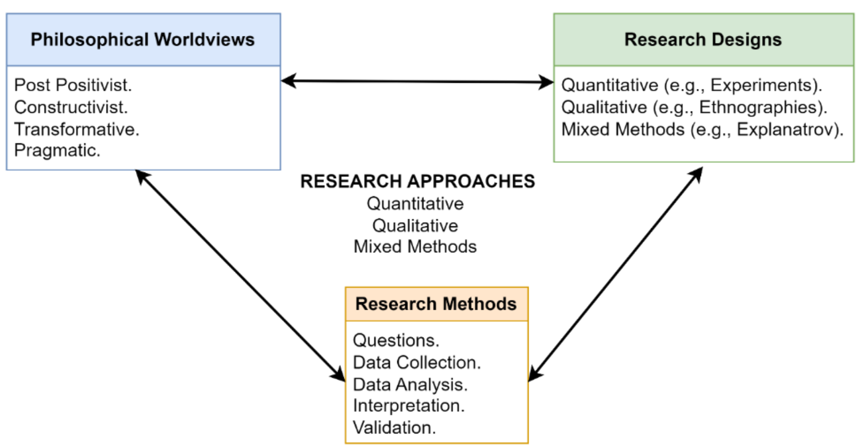


Figure 29: Framework for research methodology source (Clark and Creswell, 2014)

Saunders, Lewis and Thornhill (2009) introduced a more comprehensive research methodology model, often known as the research onion or onion model. The research onion model consists of six layers: philosophy, research approach, methodological choice, strategy, time horison, and techniques and procedures. Although the research onion seems more complicated, it provides clear direction regarding the establishment of the research properly. Figure 30 illustrates the research onion.

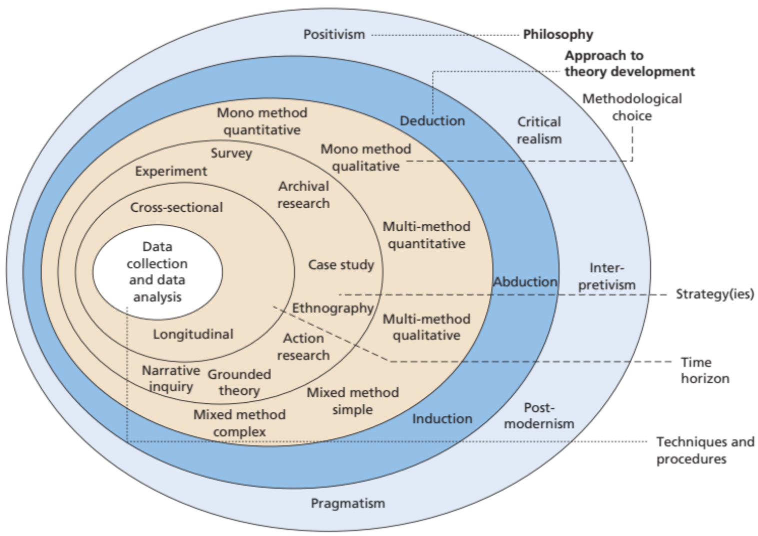


Figure 30: Research onion (Saunders, Lewis and Thornhill, 2019)

Additionally, Saunders, Lewis and Thornhill (2015) highlighted the interconnected relationship between researcher beliefs and assumptions, research philosophies, and research design. They considered research methodology as a reflexive process. Figure 31 demonstrates the research methodology as a reflexive process.

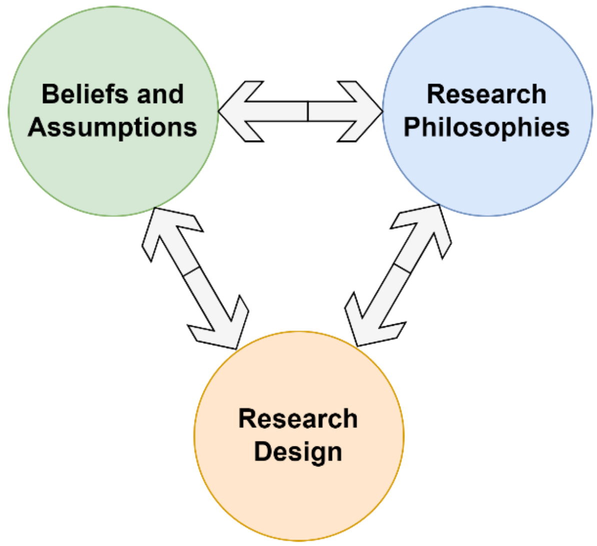


Figure 31: Reflexive research methodology (Saunders, Lewis and Thornhill, 2015)

Based on the above discussions, this thesis follows the research methodology directions proposed by Saunders, Lewis and Thornhill (2015). This is because they provide a systematic order of processes and give the researcher clear guidelines to become more familiar with upcoming stages, thus, paving the way to achieve the research aims.

3.3 Research Philosophy and Assumptions

The first step considered when designing the research method is the research philosophy. Singh (2006) stated that research philosophy is a disciplined, orderly, and analytical study of the universe, i.e. of literally everything, all reality. In other words, the term "philosophy" requires an intelligible and coherent account of life experience. Easterby-Smith, Thorpe and Jackson (2012) highlighted the importance of research philosophy in behavioural studies. Firstly, the research philosophy can assist the researcher in recognising which research design would work appropriately. Secondly, it helps to clarify the research designs. Lastly, it assists the researcher in creating a research design. Saunders, Lewis and Thornhill (2015) discussed five major philosophies: positivism, critical realism, interpretivism, postmodernism, and pragmatism. Moreover, Saunders, Lewis and Thornhill (2015) highlighted three significant ways of thinking about research philosophy: ontology, epistemology, and axiology.

3.4 Ontological Assumptions

Ontology refers to assumptions about the nature of reality. It shapes how researchers view the world and develop research objectives (Saunders, Lewis and Thornhill, 2015). From a business and management perspective, reality includes individuals, organisations, and management. The ontological assumption can be viewed in two aspects: objectivism and subjectivism (Saunders, Lewis and Thornhill, 2009). Objectivism portrays those social entities existing in reality externally to social actors. The subjectivism aspect reveals that social actors' perceptions are responsible for creating social phenomena. In the positivism approach, objectivism assumes that organisations and other social entities exist in reality and are considered physical objects. During the research process, the researcher remains detached and neutral. More precisely, the researcher holds an external position during data collection. Furthermore, the positivism approach assumes a single true reality or universalism.

On the other hand, critical realists observe reality as if it is independent and external. Furthermore, a layered and structured ontology is crucial. The critical realist understands the world only if they understand the social structures. So, their primary focus is on explaining the underlying causes and mechanisms. The interpretivism philosophy observes social worlds and contexts in a newer and richer sense. The business entity is socially connected through language and culture. In the interpretivism approach, the reality is complex and meaning is constructed through interpretations. Thus, the ontological stance is explicitly subjective. Next, with postmodernism, the ontological stance emphasises the chaotic primacy of flux, fluidity, movement, and change. This philosophy believes that the nature of reality is nominal and the world is socially constructed. This approach is not abstract; instead, decisions are taken collectively. Finally, the philosophy of pragmatism argues that the nature of reality is complex, rich, and external. Reality is the practical consequence of ideas, the flux of processes, experience, and practices.

3.4.1 Epistemological Assumptions

The term “epistemology” refers to what should be regarded as acceptable knowledge. It is mainly concerned with “how we come to know what we know” (Clark and Creswell, 2014). It focuses on how a researcher can acquire the truth of the matter under investigation and what constitutes valid knowledge (Saunders, Lewis and Thornhill, 2015). According to Saunders, Lewis and Thornhill (2015), the epistemological assumption of positivism is that reality can be observed, studied, and even sculpted. Positivism works with observable social reality and the outcomes can be generalised. Furthermore, the existing theories are adopted to generate hypotheses. These hypotheses have been tested, leading to further development of theory. Another essential part of positivist philosophy is that the research is value-free (Saunders, Lewis and Thornhill, 2009). Additionally, the positivist research methodology is highly structured, which makes it amenable to statistical analysis (Kothari, 2004).

On the other hand, critical realism focuses on explaining what researchers see and experience in terms of underlying structures of reality that shape observable events. The critical realism philosophy is also known as direct realism. This research philosophy mainly concerns the historical analysis of systems; critical realists embrace epistemological relativism. It recognises that information and knowledge are historically located. Also, causality in information cannot be reduced through quantitative and statistical analysis (Saunders, Lewis and Thornhill, 2015). Next, the interpretivist research philosophy focuses on reality as something which can be interpreted and that theories can be proposed to define new knowledge according to that interpretation (Aletaiby, 2018). It assumes that people are more likely to influence events and act unpredictably (Clark and Creswell, 2014). Acceptable knowledge under the interpretive approach is based on interpretations, stories, and narratives (Saunders, Lewis and Thornhill, 2015).

Postmodernism emphasises the role of language as a source of knowledge. This approach seeks to question and expose the power of language that sustains dominant realities. Postmodernism challenges organisational theories and concepts and demonstrates what facts and perspectives remain silent. The approach mainly focuses on the ongoing administrative processes rather than management, performance, and resources (Saunders, Lewis and Thornhill, 2015).

Finally, Pragmatism focuses on research problems and contributes practical solutions that inform future practices. The research design and strategy would be the research problem and questions (Saunders, Lewis and Thornhill, 2015). This philosophy emphasises multiple methods to solve research problems and the outcomes are reflected in themes.

3.4.2 Axiological Assumptions

According to Saunders, Lewis and Thornhill (2009), axiology refers to ethics and values within the research process. Clark and Creswell (2014) added that axiology is a value ascertained by human interests, beliefs, and experiences. People's opinions are based on backgrounds, experiences, and beliefs that constitute truth. Therefore, axiology assumes that human judgements are either value-free and unbiased or value-laden and biased (Aletaiby, 2018).

In positivism, the researcher remains neutral, independent, and detached from research. The researcher maintains an objective stance (Saunders, Lewis and Thornhill, 2015). This philosophy tends towards deductive methods and quantitative, seeks to be value-free and unbiased through its objective testing of hypotheses by statistical means (Aletaiby, 2018). By contrast, in critical realism, the researcher remains attached to the research objectives and tries to maintain the objective as much as possible (Saunders, Lewis and Thornhill, 2015). This philosophy tends towards retrodictive and qualitative analysis and research outcomes are value-laden and biased. In interpretivism, on the other hand, researchers perform an active role in the research and their interpretations are essential. Therefore, the research outcomes are value-bound and biased.

In postmodernism, the study and the researcher are embedded in a power relationship. This philosophy tends towards qualitative and value-laden research through various data types. Finally, in pragmatism, the investigation is initiated and sustained by the researcher's beliefs and doubts. Under the axiological assumptions, this philosophy typically applies mixed methods, and outcomes are value-driven. Table 7 gives a more comprehensive overview of research philosophies and assumptions.

Table 7: Comparison among different research philosophies and assumptions

Philosophy	Ontology	Epistemology	Axiology	Methods
Positivism	▪ The nature of reality is real, independent, and external. ▪ The world is based on one true reality or universalism.	▪ Knowledge is based on the scientific method, measurable and observable facts. ▪ Prediction and causal explanation as a contribution.	▪ Value-free and unbiased. ▪ The researcher maintains an objective stance.	Deductive and quantitative
Critical realism	▪ The nature of reality is stratified or layered. ▪ The world is based on causal mechanisms.	▪ Knowledge is based on real historical events. ▪ Historical causal explanation as a contribution	▪ Value-laden and biased. ▪ The researcher tries to remain as objective as possible.	Reproductive and in-depth historically analysis
Interpretivism	▪ The nature of reality is complex and	▪ Knowledge is based on narratives,	▪ Value-bound and biased.	Inductive and qualitative

	socially constructed through culture & language. ▪ The world is based on interpretations, experiences, and practices.	interpretations, perceptions, and stories. ▪ Worldview and new understanding viewed as a contribution.	▪ The researcher is part of the research and has a subjective role.	
Postmodernism	▪ The nature of reality is nominal & complex, and socially constructed. ▪ The world is based on experiences and practices.	▪ Knowledge is based on ideologies, voices, and interpretations. ▪ Challenge of dominant view and exposure of power relations viewed as a contribution.	▪ Value-constituted and biased. ▪ The researcher is part of research and radically reflexive.	Deconstructive and qualitative
Pragmatism	▪ The nature of reality is complex & external and practical outcomes of ideas. ▪ The world is based on experiences, flux of processes, and practices.	▪ Knowledge is based on practical meaning and true theories. ▪ Problem-solving and informed future practices viewed as a contribution.	▪ Value-driven and biased. ▪ The researcher is part of research and radically reflexive.	Focus on problem–solution relationships and mixed methods.

3.5 Research Approach

The selection of the research approach is based on a study's objectives. Generally, the two research approaches are inductive and deductive (Bryman, 2016; Saunders, Lewis and Thornhill, 2009). Later, Saunders, Lewis and Thornhill (2015; 2019) proposed an abductive research approach to add to inductive and deductive.

3.5.1 Inductive Research Approach

The inductive approach represents the association between phenomenon and theory building. This approach mainly focuses on theory development based on observations/findings (Bryman, 2016) and is referred to as the bottom-up approach. On the other hand, the deductive approach represents the relationship between theory and social research. In other words, the deduction is theory-driven and seeks to refine or confirm existing theory through hypothesis testing (Saunders, Lewis and Thornhill, 2019). This is referred to as a top-down approach. The abductive research approach is a combination of inductive and deductive approaches. Saunders, Lewis and Thornhill (2015) argued that instead of moving from data to theory (inductive) or theory to data (deductive), combining both approaches gives plausible advantages. However, the combination of inductive and deductive approaches within the same research is not straightforward, but it is often advantageous (Aletaiby, 2018; Saunders, Lewis and Thornhill, 2015).

3.5.2 Deductive Research Approach

The deductive approach adopted for this thesis research as it is well known in the research domain and theoretical considerations that translate into hypotheses to update the theory can be subjected to empirical scrutiny. According to Balaikie (2010), the application of the deductive approach has six sequential steps.

- Generate a set of hypotheses to form a theory.
- Based on prior literature; identification of theory(ies).
- Examine the logic of the arguments and compare them with the theory(ies).
- Test the hypotheses by collecting data and analysis.
- If the findings are inconsistent, reject the theory or modify and restart the process.
- If the findings are consistent, then the theory is corroborated.

3.6 Mixed Method (Pragmatic) Approach

Some researchers argue that the traditional approaches of qualitative or quantitative research methods may not always be suitable for a given study (Onwuegbuzie and Leech, 2005). In certain cases, it may be necessary to combine aspects of both approaches to effectively achieve the research objectives. This gives rise to the concept of mixed methods, which considers positivism and interpretivism as complementary rather than opposing views (Feilzer, 2010; Creswell, 2012; Amos and Pearse, 2008). Creswell refers to this fresh approach as multimethodology, emphasising the importance of gathering relevant philosophies, methods, and tools to address the research problem (Creswell, 2012). A mixed design approach, utilising multiple methods and potentially yielding both quantitative and qualitative data, can be employed in research (Hewson, 2008). Quantitative methods are particularly valuable for collecting and analysing data, often involving statistical analysis and surveys (Bell, 2009).

The use of qualitative methods complements quantitative research by addressing the limitations of focusing solely on numbers, statistics, and percentages. Qualitative investigations prioritise understanding of individual perspectives of the world instead of quantifying data (Bell, 2009). Analysing qualitative information aims to determine relationships, categories, and assumptions that inform participants' worldview (Basit, 2003).

While positivism aligns with quantitative research and interpretivism aligns with qualitative research, the pragmatic stance supports mixed methodology where both quantitative and qualitative methods can be employed in a single study to investigate different aspects of a phenomenon.

The mixed-method approach has garnered praise from researchers. Johnson and Turner (2003) proposed a "fundamental principle of mixed methods research", emphasising the need for complementary strengths and non-overlapping weaknesses in the combination of methods. This approach allows for answering questions that other methodologies cannot and presents a broader range of perspectives (Johnson and Turner, 2003). By combining quantitative and qualitative approaches, researchers can harness the strengths of both methods (Creswell, 2012; Feilzer, 2010; Jackson and Niblo, 2003).

In the context of the construction industry, which relies on inter-disciplinary collaboration and processes, mixed methods research is particularly applicable (Chynoweth, 2009). For a built environment like BIM, the application of mixed methods to capture the perspectives of participants can benefit in understanding the research (Fellows and Liu, 2008). Construction organisations can implement BIM processes and technology by allowing collaborative and proactive approaches among stakeholders (GhaffarianHoseini *et al.*, 2017). Figure 32 shows the mixed methods research approach.

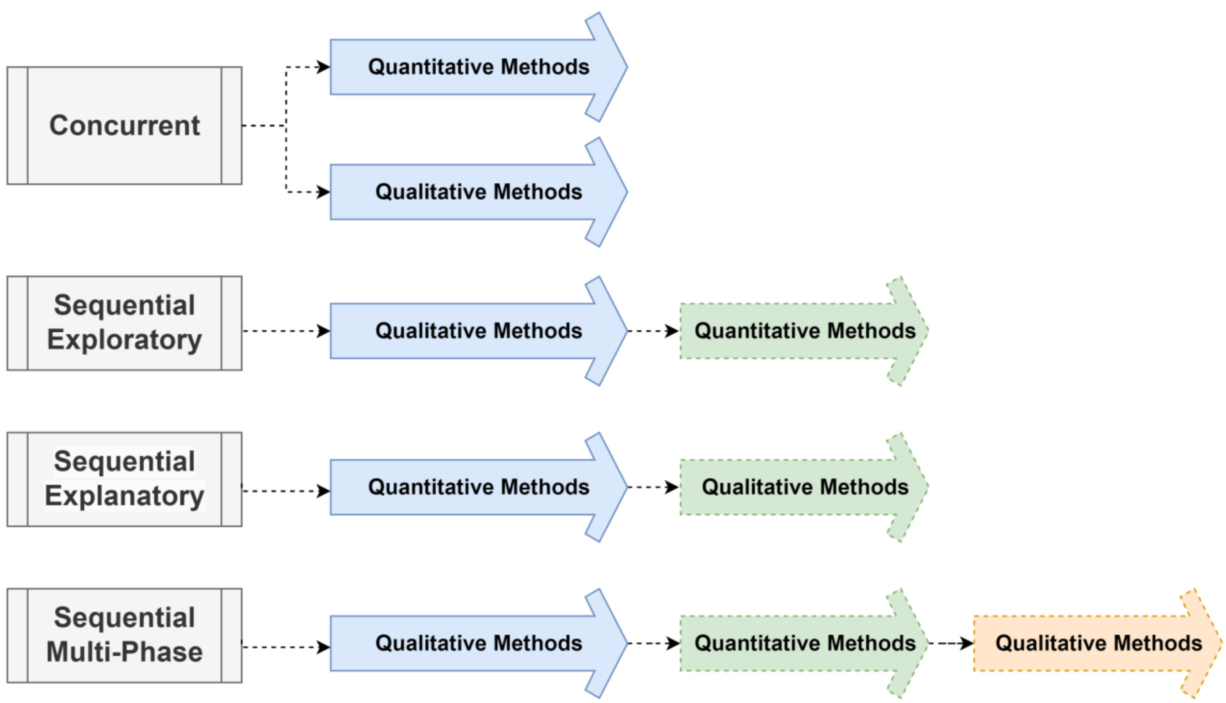


Figure 32: Mixed method research design

3.7 Research design

The research design incorporates a mixed-method methodology, including qualitative and quantitative strands, using case studies and simulations to achieve its research objectives. Due to the lack of data on the topic within the Saudi Arabian milieu, the study adopts an exploratory approach. To obtain comprehensive insights, semi-structured interviews will collect qualitative data, allowing for in-depth discussions informed by participants' responses. In Table 9, the thesis outlines how research objectives are aligned with the methodological framework.

Table 8: Research Matrix

N	Methodology	Data Source	Analytical Approach	Justification	Impact on LCC Robustness
1.	Systematic Literature Review	Peer-reviewed journals, industry reports, case studies	Content analysis, thematic synthesis	To identify established LCC models and gaps in current practices.	Provides a foundational understanding of LCC calculations and benchmarks against industry standards.
2.	Quantitative Surveys	Survey of industry professionals (engineers)	Statistical analysis, regression models	To quantify the prevalence of BIM tools that influence LCC and identify factors affecting LCC accuracy.	Enhances the empirical validity of LCC models by integrating contemporary practice metrics.
3.	Qualitative Interviews	Interviews with BIM experts	Thematic analysis, narrative synthesis	To gain in-depth insights into practical challenges and strategies in LCC estimation.	Offers contextual depth, uncovering nuanced factors that influence LCC calculations.
4.	Case Studies	Document analysis of completed projects using and nouning BIM	Comparative analysis, scenario evaluation	To assess the accuracy and effectiveness of LCC models in real-world applications.	Validates LCC models through direct comparison of predicted vs. actual costs, enhancing methodological robustness.
5.	Simulation and Optimisation	Simulated BIM models of projected construction projects	Sensitivity analysis, what-if scenarios	To test the resilience of LCC calculations under varying economic and project conditions.	Strengthens the reliability of LCC models by testing them under controlled, variable scenarios.

3.8 Research Design for Quantitative Study

According to Sekaran and Bougie (2016), a research design is a “blueprint or plan for collecting, measuring, and analysing data, created to answer research questions.” It is a general plan of action on how the researcher will answer research questions. A research design consists of methodological choice, research strategies, unit of analysis, time horison, and data collection and analysis procedures and techniques (Saunders, Lewis and Thornhill, 2019; Sekaran and Bougie, 2016). Additionally, the research design also incorporates ethical issues.

3.8.1 Methodological Choice

The first layer of the Research Onion by Saunders, Lewis and Thornhill (2019) explains the methodological choice or research choice in research design. In the mixed method study design, the first study is quantitative. Quantitative research design is generally linked with positivism. Specifically, the data collection techniques are predetermined and highly structured. Saunders, Lewis and Thornhill (2015) argued that there is an exclusive association between positivism, deduction, and quantitative research. Saunders, Lewis and Thornhill (2015) highlighted some of the essential characteristics of quantitative research.

- Generally, the researcher is independent of the research object.
- The study analyses the association between variables or constructs.
- The probability sampling technique is frequently used to ensure generalisability.
- Research methods are highly structured and rigorous.
- Data is collected in numerical form and standardised.
- Statistical analyses are performed on numeric data to derive meanings.

In conclusion, quantitative research was adopted as part of the methodology for this study.

3.8.2 Research Strategy

In research design, the next important element is research strategy(ies). Saunders, Lewis and Thornhill (2015) defined research strategy as "a plan of how a researcher will go about answering his/her research questions." Sekaran and Bougie (2016) stated that research strategy helps accomplish research objectives and answer the research questions. In other words, the choice of the research strategy is guided by research objectives and questions, coherent with research philosophy, research approach, purpose, access to the data source, and time constraints. Aletaiby (2018) highlighted three essential conditions for selecting the appropriate research strategy.

- The type of research question posed.
- The extent of control a researcher has over actual behaviour.
- The degree of focus on contemporary as opposed to historical events.

This study is based on a positivistic philosophical stance and involves a value-free and unbiased approach with a deductive approach. This research adopted a survey approach as the most suitable strategy for achieving the research objectives. Survey research refers to a system for collecting information about or from people to explain, describe, or compare their behaviour, attitudes, and knowledge (Sekaran and Bougie, 2016). In business research, the survey strategy is prevalent because it permits the researcher to gather qualitative and quantitative data on various types of research questions. Additionally, surveys can suggest possible reasons for particular relationships between variables and can produce models of these relationships. Furthermore, the researcher has more control over the research process, and when probability sampling is used, the findings are statistically representative of the whole population at a lower cost (Saunders, Lewis and Thornhill, 2019). Indeed, the survey strategy tends to be adopted in exploratory and descriptive research.

3.8.3 Unit of Analysis

In research design, a unit of analysis is considered an essential element. It refers to the level of aggregation of data collection during subsequent data analysis (Sekaran and Bougie, 2016). According to Saunders, Lewis and Thornhill (2015), the unit of analysis could be a group, an individual, an organisation, an industry, a country, a programme, or another issue. In other words, it refers to an object, event, individual, group, organisation or society. It is the 'who' and 'what' the researcher wants to explore, describe, explain or understand. The research questions determine the appropriateness of the unit of analysis. In the quantitative domain, the aim of this research is to investigate the awareness of engineers regarding BIM in the Kingdom of Saudi Arabia. Thus, the unit of analysis is based on individual levels.

3.8.4 Time Horison

According to Saunders, Lewis and Thornhill (2019), the time horison refers to the time frame adopted in most research studies to understand the research project. Generally, the time horison is considered part of the research design and can be classified into two types: cross-sectional and longitudinal. In cross-sectional, the researcher studies a particular phenomenon at a specific time. Sekaran and Bougie (2016) stated that in cross-sectional studies, the data are gathered at one point in time to answer the research question. Cross-sectional studies are also known as one-shot studies. In academic research, most research projects are necessarily time constrained. Generally, cross-sectional studies often employ the survey strategy (Saunders, Lewis and Thornhill, 2019).

Alternatively, in longitudinal studies, the data are collected at two or more points in time to answer the research question. The strong point of longitudinal research is studying the development and change over time. Conclusively, due to time constraints, the researcher cannot seek to evaluate changes or developments of a specific phenomenon over time. So, a cross-sectional aspect is more appropriate in this study. Therefore, this study focuses on a particular phenomenon at a specific time.

3.9 Research Design for Qualitative Study

3.9.1 Case Study

As Saunders*,* Lewis and Thornhill (2019) emphasised, the design of a case study research needs careful consideration of numerous critical issues. To begin, it is critical to establish the purpose of the case study, whether it is evaluative, explanatory, exploratory, or descriptive. This goal establishes the framework for the research and gives a defined path for the investigation. Second, the approach used in the case study design is important. The approach, whether deductive, inductive, or abductive, influences the theoretical framework and analytical procedure used in the research. Each approach provides distinct advantages and contributes to the overall rigour and depth of the research.

Furthermore, choosing a suitable case study technique is critical. The choice of an orthodox or emergent strategy influences study design and data collection methodologies. An orthodox strategy adheres to predetermined protocols and theories, whereas an emergent strategy allows for flexibility and adaptation when new insights arise during the research process. The study can capture the dynamic aspect of the instances under inquiry by embracing an emergent strategy. In addition, the selection of the case or instances under consideration is critical. The study can include a wide range of views and contextual elements by carefully selecting various examples from the Kingdom of Saudi Arabia. This method ensures a thorough examination of the phenomena of interest, providing significant insights into the distinct traits and dynamics of each instance. Finally, the analysis of the case study or studies must be taken into account. The decision to investigate the instances holistically, as whole units, rather of focusing on distinct analytical units within each case, allows for a thorough knowledge of the general context and interrelationships within the chosen cases. This method enables a more sophisticated interpretation and assessment of the research findings. The study improves credibility, depth, and relevance by considering and addressing these crucial issues in the case study research design. It enables a thorough examination of the research topic, aids in the formulation of relevant assessments, and contributes to the growth of knowledge in the specific subject.

The case study approach is used in the research design for this qualitative study, with a specific focus on the explanatory or evaluative goal. This study's primary purpose is to provide light on the complex dynamics and causes influencing diverse real-life events in the Kingdom of Saudi Arabia. The researcher hopes to bridge the gap between theory and practice by using an abductive technique to produce plausible explanations or evaluations for the phenomena under consideration. The case study technique used for this study is emergent in order to capture the multidimensional nature of the research problem. This technique allows for a flexible and adaptive research design, enabling the study of many points of view as well as the identification of unknown variables that may develop during the research process. We may thoroughly explore the selected cases, which include residential buildings, football stadiums, international culture centres, and hospital renovations, by applying an emergent case study technique. The planned and intentional selection of the various cases is within the Kingdom of Saudi Arabia. The researcher can obtain a full understanding of the contextual factors that influence the phenomena under research by investigating a varied variety of cases. Each instance illustrates a distinct situation within the Kingdom of Saudi Arabia, providing useful insights into the interplay of cultural, social, economic, and political issues.

3.10 Research Design for Simulation Study

Simulation studies are useful for investigating complicated systems, evaluating various scenarios, and providing insights that would be difficult or impractical to investigate in real-world contexts. The goal of this research project is to use simulation to examine the effects of numerous factors on the performance of a certain system. This study hopes to obtain a comprehensive understanding of the system dynamics, identify crucial factors, and analyse the impact of various interventions by applying a properly developed study strategy. The research strategy includes a simulation-based method, which allows modelling and simulating the system under investigation. The researcher hopes to add to the field's knowledge base, enlighten decision-making processes, and suggest effective techniques for optimising system performance through this research.

Computer simulation is becoming increasingly popular as a study tool in organisational studies due to its unique capacity to embrace the intrinsic complexity of organisational systems. Unlike other methodologies that rely on preset cause-and-effect assumptions, simulation allows one to analyse "what if" situations and the potential repercussions of various activities. Simulation allows for the forward-looking study of complex systems by modelling future trajectories, providing significant insights into system dynamics, and anticipated future changes. There are three main schools of practice in simulation.

- Discrete event simulation
- System dynamics

- Agent-based simulation

Traditionally, simulation researchers have specialised in one approach and may not be well-versed in all three realms. The growing nature of complex organisational systems, on the other hand, needs a shift towards a more integrated approach. As these systems become more complicated, it becomes clear that capturing their real complexity necessitates elements from all three research disciplines.

3.10.1 Discrete Event Simulation

Discrete event simulation is the application of simulations in organisational environments that have discrete, dynamic, and stochastic properties. The system's state variables change only a finite number of times at certain points in time in a discrete system, resulting in a piecewise continuous representation of the system's quantitative values. When the system's behaviour is influenced by random factors, stochasticity enters the picture. Dynamic modelling incorporates time as an important component in the model, impacting the system's behaviour and evolution across time (Happach and Tilebein, 2015).

Law and Kelton's (1982) discrete event simulation approach includes several critical components. To begin with, it involves entities, which are objects that represent the system's components. The system state is made up of state variables connected with certain entities and it serves as a snapshot of the system at any given time. The simulation clock describes the passage of simulation time, ensuring that events take place in the correct order. The event list defines future events, making management and scheduling easier. Statistical counters are used to collect, record, and analyse data during the simulation run, allowing system performance to be evaluated. An initialisation method prepares the model for testing by guaranteeing proper setup. The event list is managed by a timing procedure, which controls the timing and sequencing of occurrences. Event routines define the activities associated with generating the event, such as creating new events or changing state variables. The report generator aggregates and displays the findings of the statistical counters. Finally, as the central coordinator, the main program integrates and orchestrates the operations of all the simulation system pieces. These aspects constitute the cornerstone of the discrete event simulation approach, allowing researchers to effectively model and analyse complex systems (Dooley, 2002).

3.10.2 System Dynamics

System dynamics is a kind of simulation that attempts to comprehend the behaviour of complex systems over time. Invented by Jay W. Forrester in the 1950s, it has since been a widely utilised approach in a variety of sectors including management, economics, engineering, and social sciences. The primary focus of system dynamics is on capturing feedback loops, delays, and nonlinear interactions that influence a system's dynamics. A system is represented in system dynamics by interrelated components, which frequently appear in the form of causal loop diagrams. These components interact and influence one another, providing a dynamic framework that governs the system's behaviour. System dynamics simulation models capture the flows of information, materials, and resources inside the system, allowing researchers to simulate alternative situations and study the system's long-term behaviour (McKelvey, 1997; Happach and Tilebein, 2015).

The significance of system dynamics arises from its capacity to describe the intricate interdependencies and nonlinear behaviours that are prevalent in many real-world systems. Instead of focusing primarily on individual components, it allows researchers to acquire insights into the behaviour of the system as a whole. System dynamics makes it easier to identify important leverage points and policy interventions that can have a major impact on system behaviour. It also aids in comprehending the unintended repercussions of policy decisions as well as the time delays associated with system responses (Sterman, Repenning and Kofman, 1997).

When investigating complex systems with feedback loops, delays, and nonlinearity, system dynamics is especially valuable. It excels in analysing dynamic and interconnected systems like supply networks, ecological systems, economic systems, and social systems. Furthermore, system dynamics can be useful in instances when data availability is restricted or ambiguous as it allows researchers to investigate several hypothetical scenarios and comprehend the potential consequences (Dooley, 2002).

3.10.3 Agent-based Simulation

Agent-based simulation is a type of simulation that focuses on modelling and analysing large systems through the representation of individual entities (agents) and their interactions. Each agent in an agent-based simulation and has its own set of traits, behaviours, and decision-making rules, allowing for the emergence of system-level behaviours and patterns through the agents' interactions. When examining systems with interactions, dependencies, and nonlinearities among individuals or entities, agent-based simulations are especially useful. This method is excellent for investigating social dynamics such as crowd behaviour, opinion formation, and disease propagation. It can also be used to analyse economic systems, transportation networks, ecological systems, and a variety of other complex systems with individual decision making and interactions (Dooley, 2002). Agent-based simulation is very useful when empirical data is scarce or difficult to acquire. Based on expert knowledge, theories, or observable behaviours, researchers can describe the traits, laws, and interactions of agents. Researchers can investigate the ramifications and outcomes of various events in a controlled setting by modelling alternative agent behaviours and decision-making techniques (Happach and Tilebein, 2015). The following table highlights the conditions and characteristics required for each approach. See Table 8.

Table 9: Simulation approaches

Simulation approach	Terms of usage	The main characteristics
Discrete event	Variables and events that cause those variables to change are described as a system.	Sequentially and probabilistically triggering events.
System dynamics	System described by variables that cause change in each other over time.	The main variables of the system and their interrelations are precisely formulated as differential equations.
Agent-based	A system defined by agents interacting with each other and their surroundings.	Agents possessing schemas engage in interaction and learning processes

3.11 Pilot Study

As indicated by IN (2017), a small group of participants participated in a pilot study for the questionnaire and interview sessions, and the pilot study will assist in testing the research protocols and data collection instruments prior to the actual research. In addition, it is possible to conduct a pilot study for questionnaires and interviews to test the effectiveness of the instruments and gather preliminary data (Hassan *et al,* 2006). For questionnaire and interview sessions, a pilot study can assist in identifying potential issues, improving data quality, and increasing confidence, resulting in more reliable and valid results (Malmqvist *et al,* 2019). A pilot study is a small study sponsored by a research organisation that tests the feasibility of enrolling, designing the study, and collecting data before starting a larger research project.

3.12 Validity and Reliability

A preliminary test will be performed to verify the credibility of the survey tool, allowing each question and the overall survey to be assessed. As part of this research, the content's apparent relevance and thoroughness will be considered. Furthermore, Cronbach's Alpha, a measure of participant understanding of the questions, will determine the survey's consistency. According to Peterson (1994), Cronbach's Alpha measures how consistent the items are among each other. An alpha greater than 0.7 indicates satisfactory reliability, while one below 0.6 indicates insufficient reliability.

3.13 Research Ethics

Ethics has become a keystone in conducting effective and meaningful research. According to Saunders, Lewis and Thornhill (2019), research ethics refers to the "standards of behaviour that guide researcher conduct in relation to the rights of study subjects or are affected by it." In any research study, the researcher is primarily responsible for complying with research ethics. If this is not done, it is considered a scholarly crime that brings disrepute to the research community. Saunders, Lewis and Thornhill (2015) indicated general categories of ethical issues recognised as codes of ethics. In general, the ethical considerations are that the researcher should maintain integrity and fairness during the research process. Moreover, the researcher should give respect to respondents and maintain their privacy during and after the research process. It is the researcher's ethical responsibility to maintain data confidentiality and autonomy. Additionally, respondents do not need to give responses, their participation in the research process is entirely voluntary, and they have the right to withdraw at any time. Figure

33 shows the research ethics during different stages of research.

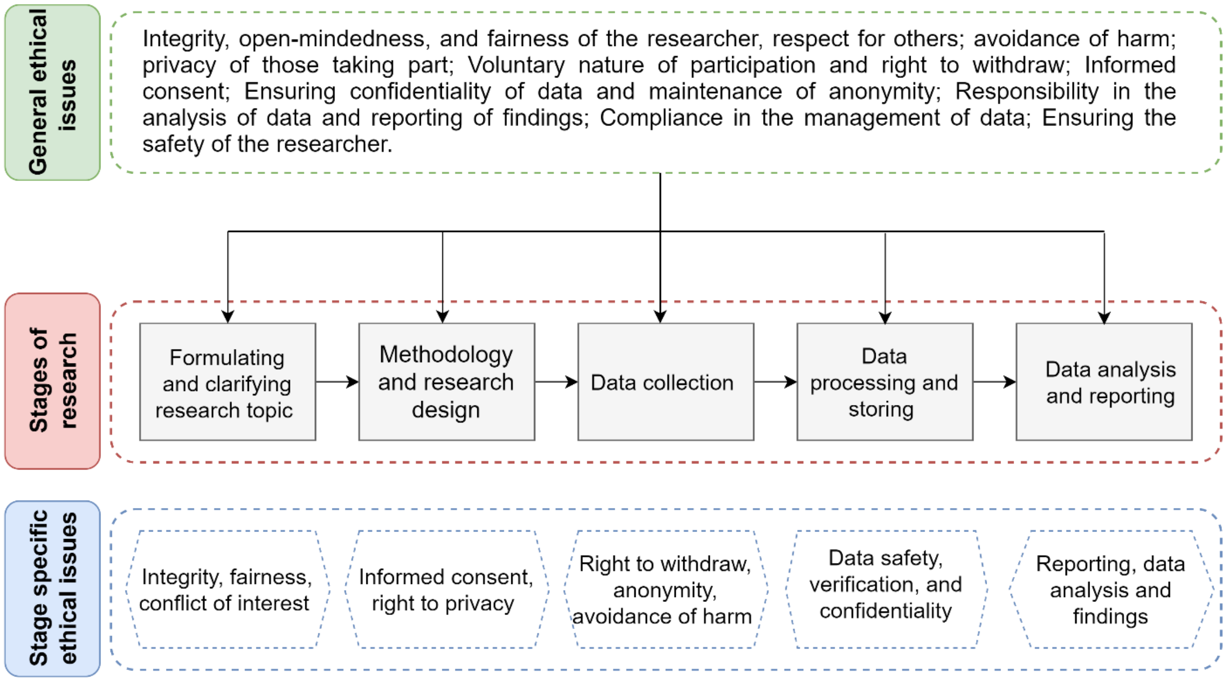


Figure 33 : Research ethics

3.14 Research Validation

The thesis validation process in this study, "Use of Building Information Modelling on the Life Cycle Cost of the Sustainable Building: The Case of Saudi Arabia", plays a critical role in ensuring the credibility of the findings. It involves a rigorous examination of data sources, methodological soundness, modelling and simulation accuracy, peer reviews, and expert validation. This phase is important in confirming the integrity and quality of the research, allowing for reliable conclusions and actionable insights in the field of sustainable construction practices in Saudi Arabia.

Data Validation: The research took great care in validating the data used throughout the study. Data from diverse sources, including case studies and survey responses, were thoroughly checked for accuracy and authenticity. In-depth interviews and surveys were conducted, and data were carefully analysed to ensure that they were a true reflection of the construction practices and cost dynamics in Saudi Arabia. By using multiple data sources and validating the findings, the research aimed to enhance the reliability and representativeness of the data.

Methodological Validation: The chosen research methodology, comprising case studies and simulation techniques, was methodically validated. These methods were carefully selected to address the specific research questions and objectives. The case study approach involved in-depth examinations of real construction projects in Saudi Arabia, allowing for a deep understanding of the subject matter. The simulation techniques employed for energy and life cycle cost analysis were based on industry-standard software tools, further ensuring the validity of the methods used.

Modelling and Simulation Validation: The research thoroughly validated the accuracy of the BIM models and simulation tools employed for cost and energy analysis. These models were built to represent the real-world scenarios of construction projects in Saudi Arabia. The simulation outcomes were cross-verified with actual project data and industry standards to validate their precision in replicating real-life conditions. Thorough testing and quality control measures were implemented to ensure that these models accurately reflected the complexities of construction projects.

Peer Review and Expert Validation: Peer review was an integral part of the research process. Subject-matter experts in the fields of construction, BIM, and sustainability were engaged to evaluate the research's methodology, data analysis, and findings. Their input and feedback helped validate the research by confirming its alignment with industry best practices and the specific context of Saudi Arabia. Furthermore, seven BIM specialists from eight evaluated the framework, highlighting its advantages for adopting BIM in the Saudi Arabian construction sector:

> "*It is well structured and provides an easy way to assess and manage LCC in KSA construction projects. The framework and standards will contribute significantly to implementing BIM for LCC management in KSA. Both construction professionals and researchers will find them valuable.* " **(ER1)**

> "*Implementing this standard will facilitate and accelerate the adoption of building information models and improve sustainability.* " **(ER2)**

> "*This framework establishes Integrated BIM in the KSA construction sector.* " **(ER3)**

> "*The framework is accurate as well as its relevance to our local context.* " **(ER4)**

> "*This Framework looks outstanding and could help enhance engineers capabilities to apply it to BIM and assist them in analysing and achieving sustainability and a circular economy.* " **(ER5)**

> " *Framework aim to illustrate and demonstrate how Building Information Modeling (BIM) can be used within construction industry of the KSA.* " **(ER6)**

> "*As a result of utilising BIM, stakeholders can collaborate more effectively throughout the construction process. Additionally, the framework facilitates cooperation among engineers across the project's lifecycle.* " **(ER7)**

Cross-Verification of Results: The research findings were cross-verified against established literature, industry reports, and international best practices. This validation process ensured that the research's conclusions and recommendations were consistent with existing knowledge and aligned with the current state of BIM adoption and sustainable construction practices in

Saudi Arabia. By integrating these aspects of research validation, this research paper has presented findings that are not only credible and reliable, but also highly applicable to the field of BIM and sustainable building practices in the unique context of Saudi Arabia.

3.15 Methodological Justifications

The methodology adopted in the thesis provides a comprehensive and rigorous approach to investigating the utilisation of BIM on LCC of sustainable buildings in Saudi Arabia. Employing a mixed-method research design, the thesis integrates quantitative, qualitative, and simulation studies to offer a multifaceted examination of the topic. This design is particularly suited to address the complex, layered nature of BIM implementation in the construction sector.

Quantitative methods form the foundation of the research, assessing the awareness, adoption, and extent of BIM usage across the Saudi Arabian construction industry. By employing statistical analysis of survey data, the study establishes a baseline understanding of the current landscape, which is critical for identifying enablers and constraints in BIM application.

Complementing the quantitative analysis, the qualitative component deepens the investigation through interviews and case studies. This approach is invaluable for uncovering the subtleties and complexities of BIM integration, such as contractual nuances, risk management, and adaptation challenges specific to the Saudi Arabian context. The qualitative data not only enriches the findings but also provides contextual depth that numerical data alone cannot capture.

Further enhancing the methodology's robustness, simulation studies are conducted on actual projects to demonstrate BIM's practical application and benefits. Simulations, which include the construction of 6D and 7D models and optimisation projects, offer empirical evidence of how BIM can influence project sustainability and LCC outcomes.

Ethical considerations are meticulously addressed within the methodology, ensuring adherence to academic standards and the respectful treatment of all participants, particularly in qualitative research scenarios involving direct interactions. The inclusion of pilot studies and thorough discussions on the validity and reliability of the research tools further underscores the rigorous academic standards upheld throughout the research process.

This chapter delineates the research methodology underpinning this thesis, providing a detailed framework that ensures consistency across subsequent analyses. It articulates the research philosophy, approach, design, and ethical considerations, integrating these components to fortify the study's foundation. Moreover, the chapter explicates how the methodologies facilitate the exploration of BIM in mitigating LCC within the Saudi Arabian construction sector, ensuring that the research objectives are achieved with rigor and precision. This methodological groundwork is crucial for the robust analysis presented in the following chapters.

3.16 Chapter Summary

Overall, the purpose of Chapter 3 was to highlight the research methodology. The current research was based on positivism research philosophy and linked with ontological, epistemological, and axiological assumptions. Based on the research objectives, a mixed method research design has been developed. The quantitative research was based on the deduction research approach to solve the research problem through survey strategy. Individual engineers working in the Kingdom of Saudi Arabia were the unit of analysis. In the qualitative research design, the case study approach was adopted. Through the abductive approach, multiple cases have been selected to achieve the study objectives. Finally, a simulation approach was adopted to highlight the complex interrelationship among all study variables. The results of all three research designs will be discussed in the next chapter (Chapter 4).

Chapter 4

Quantitative Data Analysis

Content from this chapter has been published:

Adopting BIM to Enhance Sustainability. The Saudi Arabia Construction Projects case study.
Alasmari, E., Martinez-Vazquez, P. and Baniotopoulos, C., 2023, June. Adopting BIM to Enhance Sustainability. The Saudi Arabia Construction Projects case study. In *IOP Conference Series: Earth and Environmental Science* (Vol. 1196, No. 1, p. 012111). IOP Publishing.

4 Chapter Four: Quantitative Data Analysis

4.1 Introduction

This chapter is primarily dedicated to presenting the results of the quantitative data analysis. It encompasses the analysis of survey results, specifically utilising the questionnaires adopted to assess the level of awareness regarding BIM in the KSA. The presentation of descriptive results aims to gauge the extent of BIM awareness in the KSA. Furthermore, the chapter includes an exploration of the enablers and constraints associated with the utilisation of BIM technology in government projects in the KSA. To achieve this, the chapter provides reliability statistics and Relative Importance Index (RII) results. Moreover, a cross-tabulation technique is employed to analyse the extent to which BIM technology is being employed in the KSA. Lastly, the chapter offers insights into the programs currently in use during the design phase in the KSA and their compatibility with BIM software.

4.2 Description of the Survey

A survey questionnaire was conducted to measure the awareness of engineers in the Kingdom of Saudi Arabia. Furthermore, the size of the target population for the field survey was the Saudi engineers registered with the Saudi Council of Engineers. Cohen, Manion and Morrison (2018) suggested that the larger the sample, the preferable, because it not only increases reliability, but also allows for the application of more complex statistics. Also, the size of the study sample will be determined according to the following Yamane (1967:886) formula:

- **Calculating the sample size:** n = N / (1 + N e2)

  n = the sample size

  N = the population size

  e = confidence level (1- per cent confident)

4.2.1 Rate of Response

The total number of workers in the engineering sector registered with the Saudi Council of Engineers up to the year 2020 reached about 55776 Saudi engineers and this represents the size of the study population. If the number of people in the sample represents 55776 Saudi engineers in the KSA (according to the council of Engineers), the margin of error is 5%, and the confidence level is 99%, then the result will be the required sample size of respondents needed, 656. In this study, the targeted sample size was calculated to be 655 respondents, based on the objective of achieving a 99% confidence level with a 5% margin of error. This calculation was predicated on the total population of 55,776 registered engineers in Saudi Arabia. However, the actual response rate exceeded initial projections, with 940 engineers participating in the survey. Exceeding the targeted sample size can enhance the statistical power of a study, providing more precise estimates and reducing confidence intervals, thereby bolstering the robustness and generalisability of the findings.

The relative importance index (RII) for some questions will be applied to determine the order of effect of the features according to the following mathematical formula (Chan and Kumaraswamy, 1997):

relative importance index $\boldsymbol{RII} = (\sum \boldsymbol{W}) / (\boldsymbol{A} * \boldsymbol{N})$

$\boldsymbol{W}$ = the weighting given to each element by the respondents (from 1 to 5).

$\boldsymbol{A}$ = the highest weight.

$\boldsymbol{N}$ = the total number of respondents.

4.2.2 Description of the Analysis

Multidisciplinary specialists rigorously evaluated the survey questions to confirm their alignment with the study's scope. This vetting process was part of a multi-stage methodology encompassing the survey's design, validation, and pilot testing. Respondents were engaged through two primary channels: direct email distribution and collaboration with the Saudi Council of Engineers for wider dissemination among engineering professionals in Saudi Arabia. To mitigate linguistic ambiguities, a supplementary Google Form was developed to facilitate the translation of terms between English and Arabic. Ethical adherence was maintained by subjecting the questionnaire to the University of Birmingham's established ethical review process under the registration number ERN-20-0402. The data of the questionnaire were analysed using Descriptive Statistics with SPSS software to: determine awareness of BIM dimensions in the KSA, determine enablers and constraints associated with the use of BIM technology in governmental projects in the KSA, and also quantify the extent to which BIM technology is used in the KSA. Furthermore, the analysis explored the programs that are currently used during the design phase of construction projects in the KSA and their compatibility with BIM software.

4.3 Results and Discussion

This section analyses the questionnaire responses according to the research objectives. The outcome of the Saudi Arabian level of BIM awareness and implementation will be discussed. The results of the descriptive analysis are compared to the responses to additional survey questions. BIM adoption rates offer insightful metrics into the depth of technological assimilation within the global construction sectors. An examination of data from various countries elucidates the disparities and similarities in BIM adoption over time. For instance, in 2016, both Australia and Denmark reported BIM adoption rates of 67% and 78%, respectively. Concurrently, Canada mirrored Denmark with a 78% adoption rate. Notably, China reported a 67% adoption rate in 2018, although it is pivotal to mention that this data was initially sourced from 2015.

Fast-forwarding to 2020, the United Kingdom registered a BIM adoption rate of 73%. In a retrospective look at 2015, the United States had already achieved a 79% adoption rate. However, Malaysia presented a more gradual adoption curve, culminating in a 55% rate by 2021. On the other hand, these figures should be interpreted cautiously, particularly the 33% adoption rate in Saudi Arabia based on a questionnaire. See Figure 34 for a visual representation.

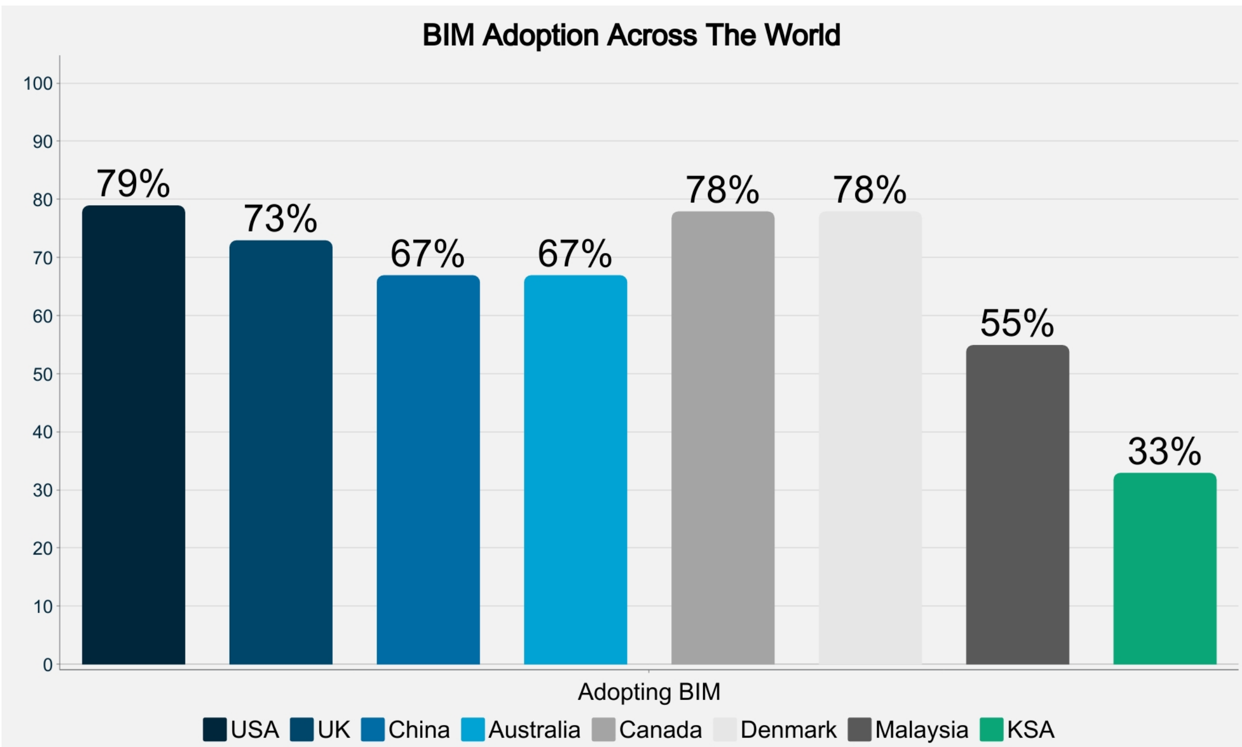


Figure 34: Adopting BIM across the world

The questionnaire was distributed to Saudi engineers in the KSA. It received 996 responses within three months of its distribution. 940 responses indicated an acceptance to participate in the questionnaire and 56 responses indicated a refusal. The questionnaire was sent in two ways: via social media with a link to the questionnaire and by email from the Saudi Council of Engineers. The questionnaire's respondents provided statistics on their level of awareness about BIM; 940 Saudi engineers responded to this question. According to the survey, 61% (n=572) are aware of BIM, whereas 39% (n=368) have not heard of it. This demonstrates that the majority of participants had heard of BIM. However, to acquire a better understanding of the issue, a comparison of responses to this and other questions has been made. According to the 10th Annual BIM Report (2020) published by the NBS, a survey was conducted among design and construction professionals regarding their awareness of BIM in the UK. The findings revealed that 99% of engineers in the UK are aware of BIM. In comparison, the awareness rate in the KSA stands at 61%, representing a 38% difference. This demonstrates a significantly higher awareness level in the UK relative to the KSA (see Figure 35).

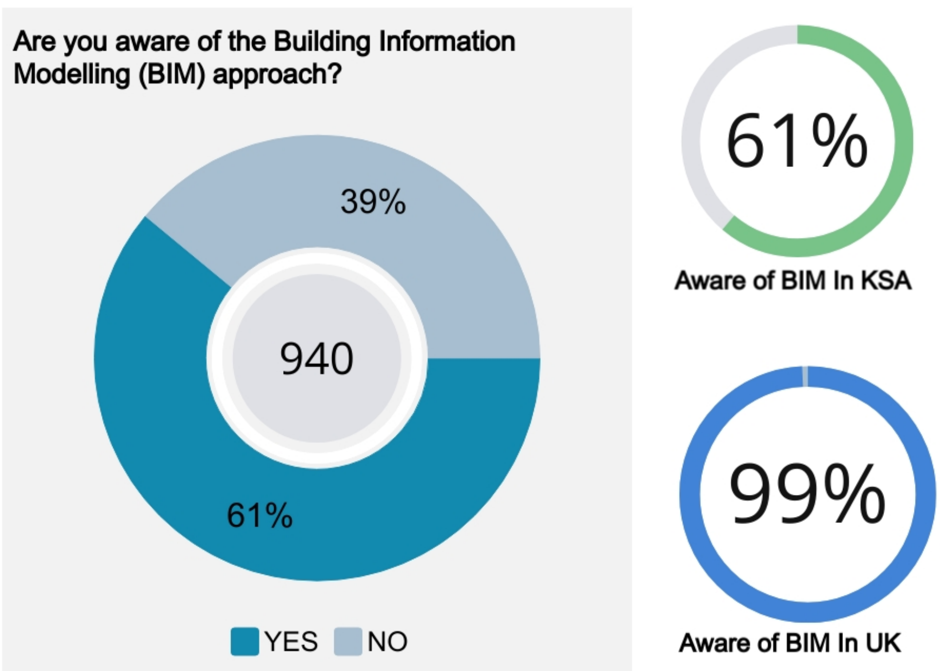


Figure 35: Pie chart of awareness of BIM in the KSA and the comparison between the KSA and the UK

The comparison between the KSA and the UK regarding the implementation of BIM requires a robust justification, given the marked differences in their economic, social, cultural, and environmental contexts. While both countries are active in the construction and infrastructure sectors, it is critical to clarify the basis and relevance of comparing their approaches to sustainability and BIM usage.

The rationale for juxtaposing KSA with the UK often hinges on contrasting a rapidly developing economy with a mature, industrialised one to extract diverse insights into BIM adoption and its sustainability impacts. KSA, with its ambitious mega projects like Saudi Vision 2030, represents a dynamic environment that is rapidly integrating modern technologies to spur its development. In contrast, the UK's established infrastructure and mature policies reflect a setting where BIM has been progressively refined and embedded within regulatory and operational frameworks due to long-standing urban and environmental challenges.

Understanding the distinct paths these countries take towards sustainability through BIM offers a comparative analysis that might suggest how newly implementing regions like KSA could accelerate their BIM integration based on lessons learned from more experienced contexts like the UK. Such comparisons aim to identify potential accelerators and barriers in BIM adoption that are context-specific, facilitating a tailored approach to BIM strategies that align with each country's unique developmental and sustainability goals. This approach underscores the importance of specifying and justifying the parameters of comparison to ensure that the insights gained are relevant and actionable.

In examining the professional backgrounds of the participants, a broad spectrum of occupations within the built environment sector is observable, as delineated in Figure 36. Most prominently, civil engineers emerge as the most represented group, accounting for 30.4% (n =

286) of all respondents. They are closely trailed by architects, comprising 20.6% (n = 194) of the total. Electrical engineers and mechanical engineers are also significantly represented with proportions of 14.4% (n = 135) and 12.6% (n = 118), respectively. On the other hand, professions such as project management see a decreased representation at 6.5% (n = 61). This diminishing trend becomes even more pronounced for roles like facilities managers and quantity surveyors who collectively represent a mere 1.7%—with 1.3% (n = 12) and 0.4% (n = 4), respectively. Interestingly, 11.8% (n = 111) of respondents were associated with professions that were not explicitly listed, prompting inquiries about the nature and variety of these "other" professions.

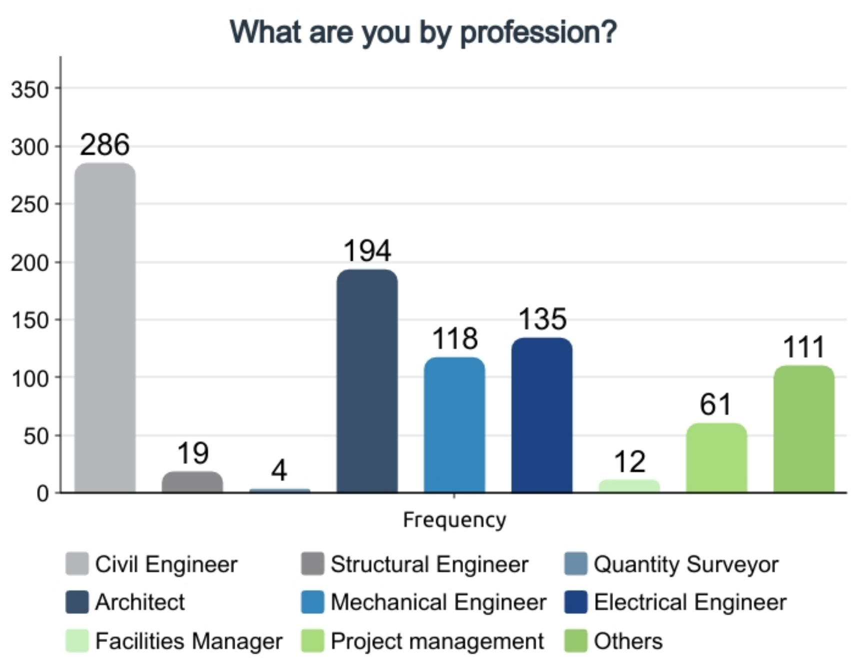


Figure 36: Description of respondents' profession

The table below (Table 11) shows the frequency and percentage distribution of the other professions stated by the respondents. Of the 111 (11.8%) respondents who stated other professions, 25 (2.7%) indicated they are computer engineers by profession, 19 (2%) are interior designers, 13 (1.4%) are electronic engineers, 11 (1.2%) are chemical engineers, 10 (1.1%) are industrial engineers and urban designers, respectively, 6 (0.6%) are environmental engineers, 4 (0.4%) are survey engineers and fire and safety engineers, respectively, 2 (0.2%) are marine, petroleum and sustainability engineers, respectively, while 1 (0.1) person is a project quality engineer.

Table 10: Description of other professions

	Frequency	Percentage
Biomedical engineering	2	.2
Chemical Engineer	11	1.2
Computer Engineer	25	2.7
Electronic Engineer	13	1.4
Environmental Engineer	6	.6
Fire and safety engineering	4	.4
Industrial Engineer	10	1.1
Interior design	19	2.0
Marine Engineer	2	.2
Petroleum Engineer	2	.2
Project Quality Engineer	1	.1
Survey Engineer	4	.4
Sustainability Engineer	2	.2
Urban Design	10	1.1

In Figure 37, the educational qualifications of engineers are delineated. It is evident that a significant majority, specifically 77.6% (n=729), possess a Bachelor's degree as their pinnacle of academic achievement. In contrast, a smaller fraction, amounting to 15.9% (n=149), have advanced their studies to attain a Master's degree. Interestingly, the number of engineers with diplomas, which stand at 3.4% (n=32), is marginally higher than those holding doctoral degrees, which is 3.1% (n=29). In contrast, one person has high school as their highest education level. Figure 37, which details the educational qualifications of the survey respondents, is crucial for understanding the context within which BIM technologies are being adopted. Educational level is a key indicator of the potential for advanced technological uptake, as higher educational qualifications are often correlated with greater proficiency in, and adoption of, complex innovations like BIM. This figure is not merely descriptive but serves as a critical component of analysis framework. By establishing the educational distribution of our respondents, we can better interpret the subsequent findings regarding BIM adoption and usage patterns. For instance, identifying a high prevalence of bachelor's degrees may explain potential gaps in advanced BIM skills, which are typically developed through higher education or specialised trainingThis figure underpins the analysis of whether educational attainment influences BIM adoption rates. The analysis showed a strong correlation between the level of education and the depth of BIM adoption. Engineers with at least a master's degree were 50% more likely to implement BIM comprehensively compared to those with only a bachelor's degree. This suggests that higher education levels potentially correlate with better understanding and capability to implement complex technologies like BIM.

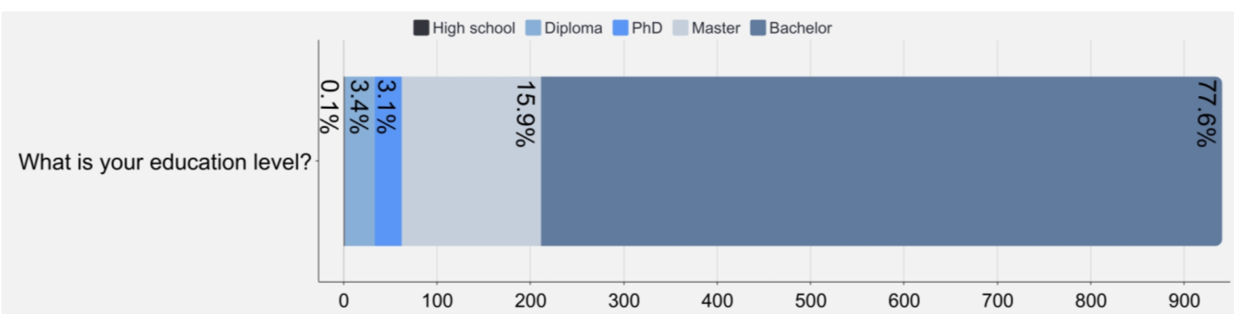


Figure 37: Description of respondents' education level

Diving into the employment sectors, 303 engineers, or 32.2%, are employed in the government sector. This is followed by 201 engineers (21.4%) who work as contractors, and 152 engineers (16.2%) who serve as consultants. Local companies in the KSA employ 112 engineers, accounting for 11.9% of the total. The private sector provides roles for 79 engineers, representing 8.4% of the dataset. Additionally, 50 engineers (5.3%) are positioned within the industrial sector, 21 engineers (2.2%) are affiliated with international companies, and 19 engineers (2%) are associated with development organisations. Notably, a mere 3 engineers, or 0.3% of the total, find their employment within the supply sector. See Figure 38.

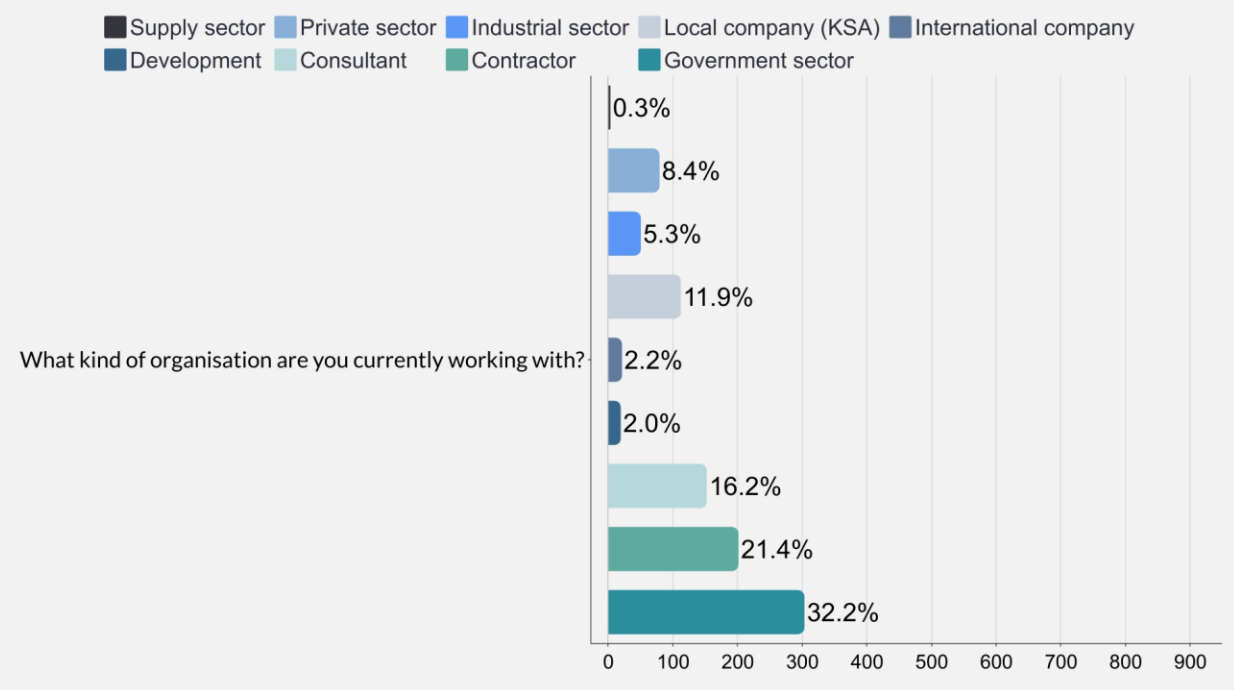
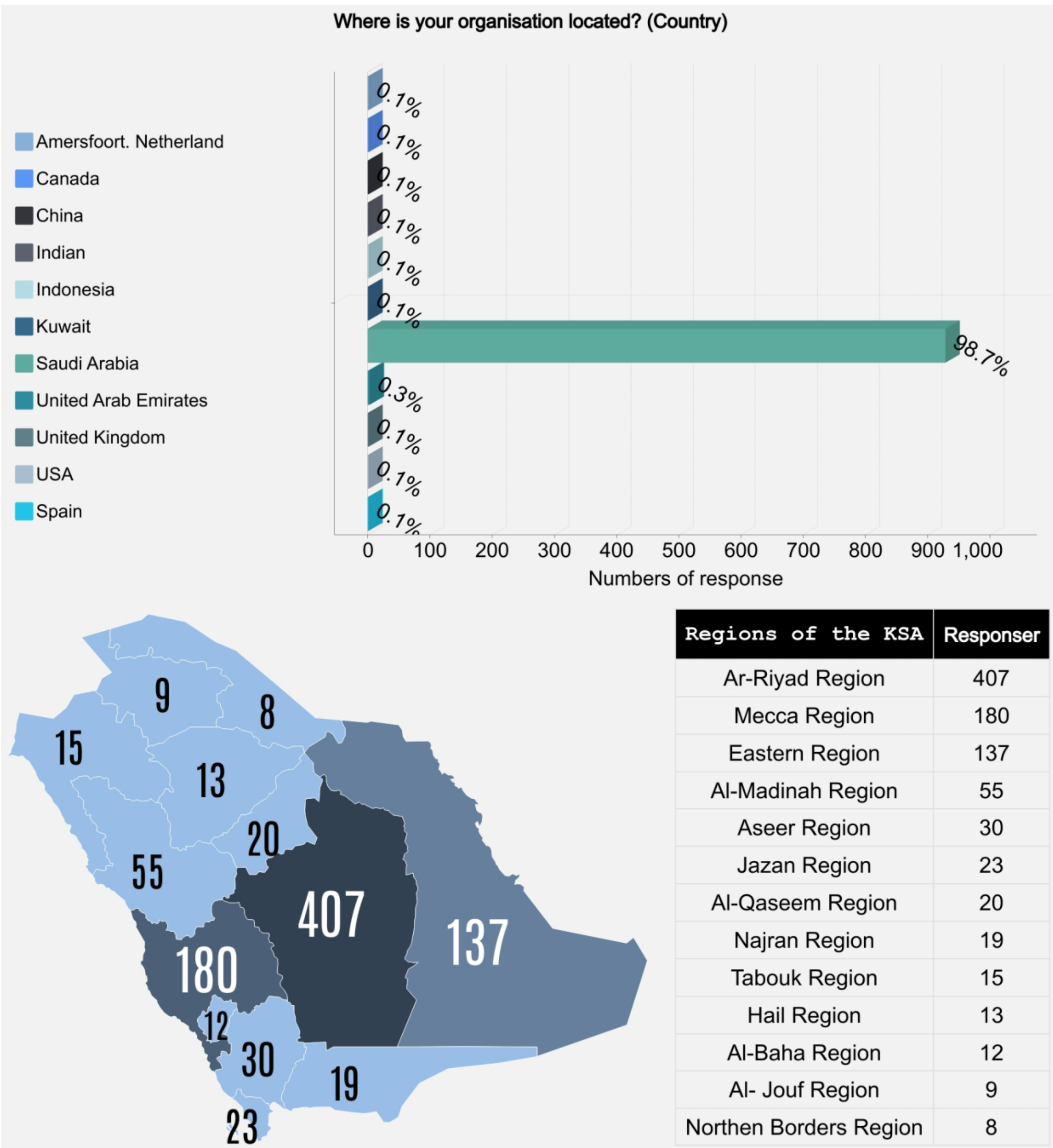


Figure 38: Description of employment sector of respondents

Almost all of the engineers (n = 928, 98.7%) are from Saudi Arabia, 3 (0.3%) are from the United Arab Emirates, while one engineer comes from each of the following countries respectively: Netherlands, Canada, China, India, Indonesia, Kuwait, United Kingdom, Spain, and the USA. The majority of respondents in the KSA were concentrated in three primary geographical regions: Riyadh, with 407 participants; Mecca, with 180; and the Eastern Region, accounting for 137 respondents. This concentration indicates the demographic and economic significance of these regions, as they are major urban centres with substantial populations. See Figure 39.



Regions of the KSA	Responser
Ar-Riyad Region	407
Mecca Region	180
Eastern Region	137
Al-Madinah Region	55
Aseer Region	30
Jazan Region	23
Al-Qaseem Region	20
Najran Region	19
Tabouk Region	15
Hail Region	13
Al-Baha Region	12
Al- Jouf Region	9
Northen Borders Region	8

Figure 39: Country of origin of respondents

As shown in the pie chart in Figure 40 below, 212 (22.6%) of the engineers have less than 2 years' experience in the construction industry, while 181 (19.3%) have no experience. 176 (18.7%) indicated they have 2 to 5 years' experience, 148 (15.7%) have 5 to 10 years' experience, 143 (15.2%) have 10 to 20 years' experience, while 80 (8.55) have more than 20 years' experience.

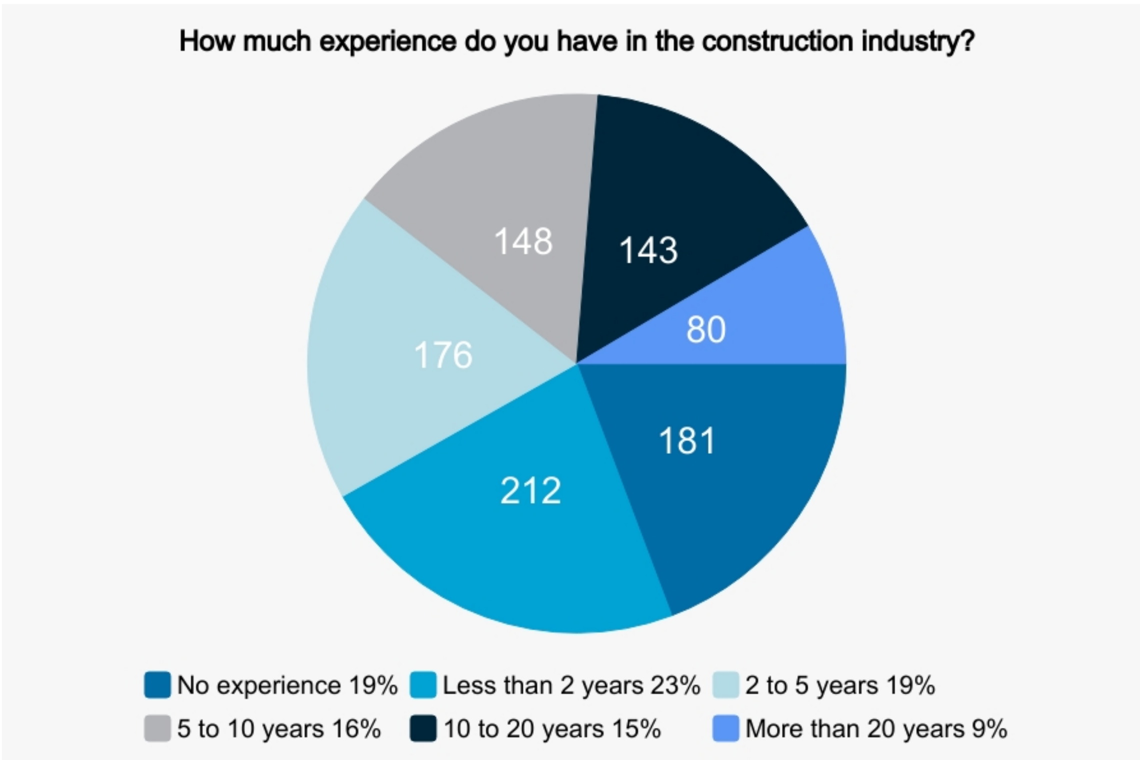


Figure 40: Experience of respondents

In assessing responders about their knowledge of BIM on a 1 to 5 point Likert scale, the data indicated a non-uniform distribution: 32% (276) at level 1, 22% (190) at level 2, 31% (266) at level 3, 16% (140) at level 4, and 10% (86) at level 5. This variation raises questions about the efficacy of current BIM education and training programmes. On the other hand, the UK National BIM Report by NBS (2019) presents a more optimistic view with 57% confidence in BIM skills among engineering professionals, although the 20% lack of confidence and 12% ambivalence suggest room for improvement. Such disparate findings necessitate a deeper examination of contextual factors influencing BIM proficiency across different demographics. For more details see Figure 41.

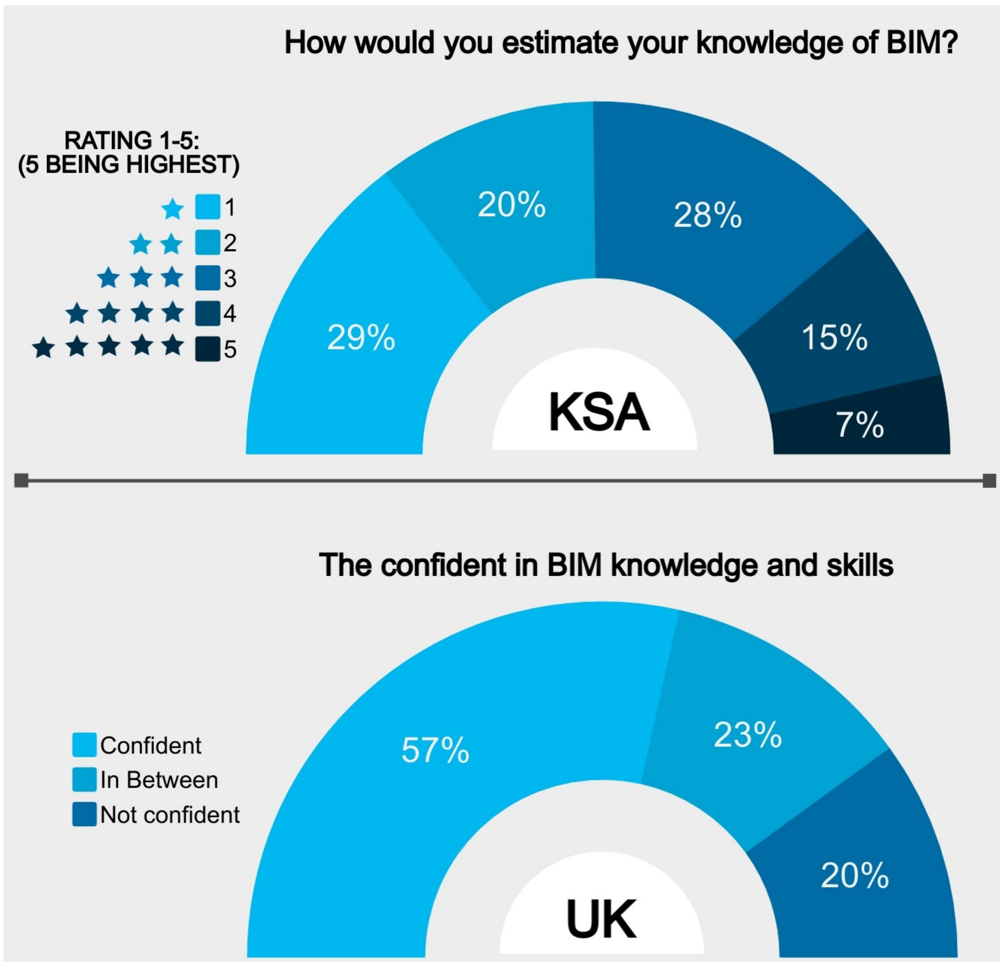


Figure 41: Estimate of knowledge of BIM and comparison between the KSA and the UK

In evaluating the percentage of the organisations that were adopting BIM, the data show that 41.2% (378) of engineers reported their organisations do not currently use BIM, 26.2% (246) indicated plans for future adoption, 14.7% (138) confirmed its use in all projects, 13.9% (131) have commenced usage, and a mere 4% (38) restrict its use to small-scale projects. These statistics signify potential barriers to BIM adoption, ranging from lack of expertise to possible financial constraints. In contrast, the UK Digital Construction report by NBS (2021) suggests a more progressive state of BIM integration, with 71% of organisations actively employing it, 24% planning to adopt it within five years, and only 5% rejecting its future use. Figure 42 provides further details.

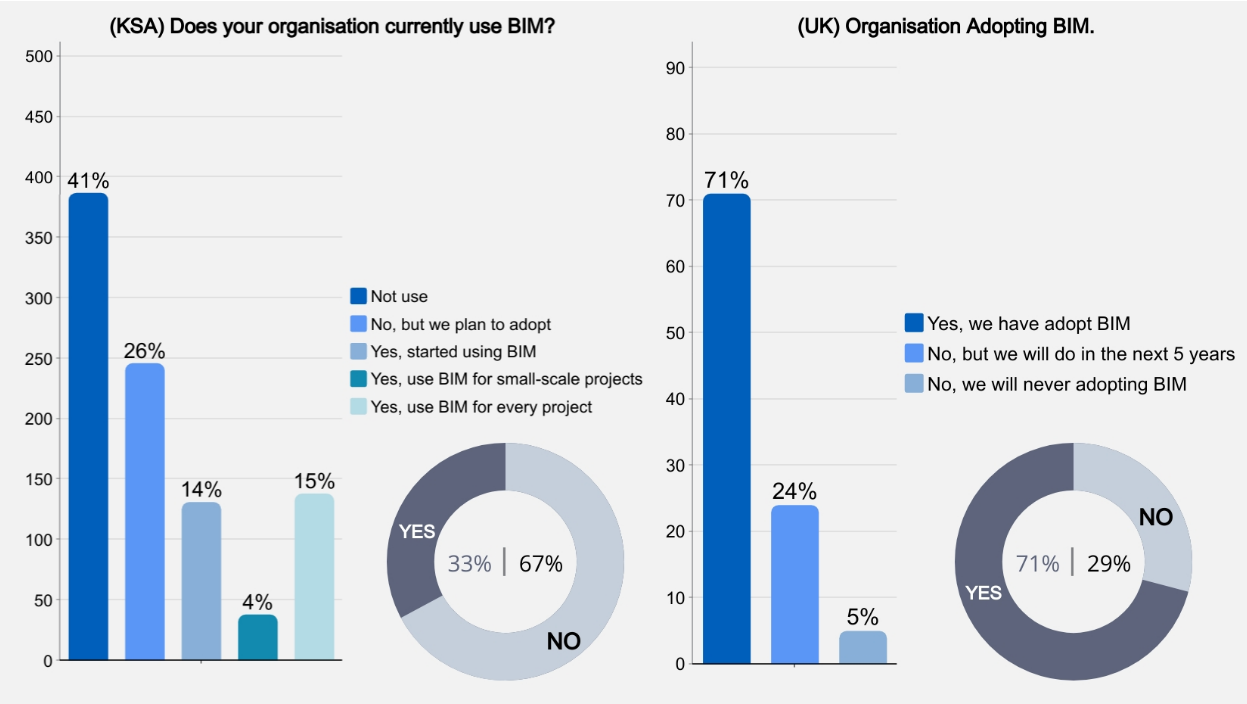


Figure 42: Adopting BIM and comparison between the KSA and the UK

The government sector is the largest adopter of BIM for small-scale projects (24%), while the contractor sector is the largest adopter of BIM for everyday projects (31%). The contractor sector and the government sector account for half (50%) of the organisations that use BIM for everyday projects. The consultant sector accounts for the majority of the sectors that have just started using BIM (22%). A significant association has been observed between sectors and the usage of BIM ($\chi2(14) = 39.47$, $p<.001$).

Professions in civil engineering account for the majority (22%) of those who use BIM for every project. Others include architects (19%), electrical engineers (17%), and mechanical engineers (16%). Despite some professions having higher levels of adoption than others, there is no evidence that profession influences the extent to which BIM technology is adopted in Saudi Arabia ($\chi2(34) = 44.47$, $p=.108$).

Table 11 shows that 370 (39.4%) of the engineers indicated they do not know if their regular consultants/contractors use BIM, 340 (36.2%) indicated their regular consultants/contractors do use BIM, while 230 (24.5%) indicated their regular consultants/contractors do not use BIM. 34 (3.6%) of the respondents have been using BIM for more than 20 years. Further analysis reveals 103 (11%) respondents have been using BIM for 2 to 5 years, 59 (6.3%) have been using it for less than 1 year, 51 (5.4%) have been using it for 6 to 9 years, 35 (3.7%) indicated their organisation has been using BIM between 10 to 13 years, while 15 (1.6%) indicated their organisation has been using BIM between 14 to 20 years.

More than half of the respondents (67.3%) indicated they do not use BIM in any type of buildings. 90 (9.6%) stated their organisation uses government office buildings for BIM, 53 (5.6%) indicated their organisation uses residential buildings, 3.6% indicated their organisation has their infrastructure, 3.2% indicated their organisation uses commercial/retail buildings for BIM, 2.9% indicated their organisation uses the industrial buildings for BIM, 2.2% indicated they use residential, education, healthcare and transportation buildings for their BIM, 1.9% indicated their organisation uses educational buildings, 1.3% indicated their organisation uses transportation buildings, 1.2% uses healthcare buildings, 1.1% indicated their organisation uses residential buildings for BIM, while one person indicated their organisation uses the great Mosque of Mecca.

Table 11: Descriptive statistics

		Frequency	Percentage
Are your regular Consultants / Contractors using BIM?	Yes	340	36.2
	No	230	24.5
	Don't Know	370	39.4
How long has BIM been used in your organisation?	Has not been using BIM	643	68.4
	Less than 1 year	59	6.3
	2 to 5 years	103	11.0
	6 to 9 years	51	5.4
	10 to 13 years	35	3.7
	14 to 20 years	15	1.6
	More than 20 years	34	3.6
For what types of building does your organisation use BIM?	Government office building	90	9.6
	Residential	53	5.6
	Education	18	1.9
	Transportation	12	1.3
	Industrial	27	2.9
	Commercial/ Retail	30	3.2
	Healthcare	11	1.2
	Infrastructure	34	3.6
	Not use	633	67.3
	Residential	10	1.1
	Residential, education, healthcare, transportation, industrial, commercial.	21	2.2
	The Great Mosque of Mecca	1	.1

More than half of the engineers (n = 613, 65.2%) like BIM and would continue to use it, 209 (22.2%) are hesitant, 54 (5.7%) do not like BIM and are thinking of stopping its use, while 6.8% of the engineers do not know if they like BIM or not. The engineers were asked who should support the adoption and implementation of BIM. 320 (34%) stated the Saudi Council of Engineers should support the adoption, 294 (31.3%) indicated that the responsibility should be shared between the construction sector and the government, 210 (22.3%) indicated that the government should support the adoption and implementation of BIM, 73 (7.8%) stated that construction sector companies should support the adoption, 23 (2.4%) stated that the responsibility should be shared between the clients, 16 (1.7%) stated that the responsibility should be shared between the construction sector, Saudi Council of Engineers, clients, and the government. Meanwhile, one of the engineers stated that responsibility should be shared between the client and the government (0.1%), between the construction sector (0.1%), the government and Saudi Council of Engineers (0.1%), and between the Education and Training Sector and Clients as well as designers.

Approximately 1 out of 4 engineers indicated that the budget value for projects their organisation is currently implementing is about $80M+ and 18.2% indicated their organisation has a budget value for projects between $1M and 10M. 141 (15%) of the engineers stated their organisation has a budget value for projects between $100,000 and $500,000, 98 (10.4%) of the engineers stated that their organisation has a budget value for projects between $10M and $30M, 90 (9.6%) of the engineers stated that their organisation has a budget value for projects between $500,000 and $IM, 73 (7.8%) of the engineers stated that their organisation has a budget value for projects between $30M and $50M, 41 (4.4%) of the engineers stated that their organisation has a budget value for projects between $50M and $80M, 9 (1.0%) of the engineers stated that their organisation has a budget value for projects less than $100,000, 1 person stated that their organisation has a budget value of approximately $250M+, while 73 (7.8%) of the engineers stated that they do not know their organisation's budget value for projects. See Table 13.

Table 12: Descriptive statistics

		Frequency	Percentage
How open are you to adopting BIM?	I liked BIM and I will continue using it.	613	65.2
	I didn't like BIM and I am thinking of stopping using it	54	5.7
	Hesitant	209	22.2
	I don't know	64	6.8
Who should support the adoption and implementation of BIM?	Government	210	22.3
	Saudi Council of Engineers	320	34.0
	Construction sector companies	73	7.8
	Clients	23	2.4
	Responsibility is shared between the construction sector and the government	294	31.3
	Responsibility is shared between the client and the government.	1	.1
	Responsibility is shared between the construction sector, Saudi Council of Engineers, clients, and the government	16	1.7
	Responsibility is shared between the construction sector, the government,	1	.1

	and Saudi Council of Engineers		
	Responsibility is shared between the Education and Training Sector	1	.1
	Clients as well as designers	1	.1
What is the budget value for projects your organisation is currently implementing?	$100,000-500,000	141	15.0
	$500,000-1 M	90	9.6
	$1 M-10 M	171	18.2
	$10 M-30 M	98	10.4
	$30 M-50 M	73	7.8
	$50 M-80 M	41	4.4
	$80 M +	243	25.9
	$250 M +	1	.1
	Less than $100,000	9	1.0
	I don't know	73	7.8
How much is the project budget that your organisation has applied to building information modelling?	$100,000-500,000	164	17.4
	$500,000-1 M	98	10.4
	$10 M-30 M	88	9.4
	$30 M-50 M	62	6.6
	$50 M +	142	15.1
	$1 M-10 M	147	15.6
	$250 M +	1	.1
	$80 M +	1	.1
	Less than $100,000	3	.3
	I don't know	234	24.9
Do you consider BIM to be available for application to all scales of a project?	Yes	745	79.3
	No	156	16.6
	Other	39	4.1

How much do you expect the return-on-investment proportion to increase as a result of applying BIM to projects?	1 - 10 %	189	20.1
	10 - 30 %	392	41.7
	30 - 50 %	165	17.6
	Above 50 %	120	12.8
	0.50 %	1	.1
	I don't know	67	7.1

The analysis indicated that 164 (17.4%) of the engineers stated their organisation's project budget for BIM is about $100,000 to $500,000. 147 (15.6%) of the engineers stated that the project budget for which their organisation has applied for building information modelling is about $1M to $10M. 142 (15.1%) of the engineer stated that the project budget for which their organisation has applied for building information modelling is about $50M, 10.4% indicated that their organisation has applied BIM for the project with a budget of about $500,000 to $1M. Also, 9.4% indicated that their organisation has applied BIM for the project with a budget of between $10M and $30M, and 6.6% indicated their organisation applied between $30M and $50M. Another engineer indicated their organisation applied BIM for the project with a budget of $80M and $250M+, respectively, while 234 (24.9%) do not know the value of the project budget for BIM. 79.3% consider BIM to be available for application to all scales of a project, 156 (16.6%) indicated BIM is not available for this application, while 39 (4.1%) do not know. The respondents indicated that applying BIM to projects should yield 10% to 30% return-on-investment, 189 (20.1%) indicated a yield of 1% to 10% return-on-investment, and 165 (17,6%) indicated a yield of 30% to 50% return-on-investment. 12.8% indicated that applying BIM to projects should yield above 50% return-on-investment, one person indicated it should yield 0.5%, while 67 (7.1%) do not know.

Table 14 below shows the Mean and Standard Deviation on the different benefits of using BIM.

All of the benefits were rated from a scale of 1 to 5 with 1 being the lowest and 5 the highest. On average, minimising changes (M = 3.53, SD =1.21), sustainability analyses (M = 3.54, SD =1.23), remove any omission (M = 3.50, SD =1.21), quality management (M = 3.77, SD =1.22), operations and maintenance (M = 3.67, SD =1.24), facility management (M = 3.64, SD =1.21), and thermal design (M = 3.51, SD =1.22) have a higher benefit as they all have an approximate mean value of 4. Logistics management (M = 3.39, SD =1.21), established life cycle (M = 3.39, SD =1.21), life cycle cost (M = 3.46, SD =1.25), daylight analysis (M = 3.43, SD =1.29), and transparency cost (M = 3.49, SD =1.23) have an average benefit as they all have an approximate mean value of 3.

Table 13: Benefits of using building information modelling (BIM)

	Mean	Std. Deviation
Minimising changes	3.5340	1.21488
Sustainability analyses	3.5436	1.22592
Remove any omission	3.4957	1.21272
Quality management	3.7691	1.21969
Logistics management	3.3936	1.21069
Established life cycle	3.3904	1.21480
Life cycle cost	3.4596	1.25012
Operations and maintenance	3.6702	1.23654
Efficient use of energy	3.5351	1.22706
Facility management	3.6426	1.21137
Daylight analysis	3.4255	1.28553
Thermal design	3.5128	1.21967
Transparency cost	3.4862	1.22922

4.4 Determining the Awareness of BIM Dimensions in Saudi Arabia

The cross-tabulation Table 15 shows if engineers from Saudi Arabia and other countries are aware of the BIM approach. Of the 929 engineers who are from Saudi Arabia, 563 indicated they are aware of the BIM approach, while 366 indicated they are not aware of this approach. Out of the engineers who come from Saudi Arabia, 60.6% are aware of building information modelling, while 39.4% are not aware of BIM. Out of the 11 engineers who are from other countries, 9 (81.8%) indicated they are aware of BIM, while 2 (18.2%) are not aware. Of the 572 engineers who are aware of the BIM approach, 98.4% are from Saudi Arabia, while 1.6% are from other countries. Of the 368 engineers who are not aware of BIM, 99.5% are from Saudi Arabia, while 0.5% are from other countries. Engineers from Saudi Arabia who are aware of the building information approach make up 59.9% of the sample and engineers from Saudi Arabia who are not aware of the BIM approach make up 38.9% of the sample. Engineers from other countries who are aware of the building information approach make up 1% of the sample, while engineers from other countries who are not aware of the building information approach make up 0.2% of the sample.

Table 14: Cross-tabulation by country and awareness of BIM

		Are you aware of the Building Information Modelling (BIM) approach?		Total
		Yes	No	
Saudi Arabia	Count	563	366	929
	% Within Country	60.6%	39.4%	100.0%
	% Within Are you aware of the Building Information Modelling (BIM) approach?	98.4%	99.5%	98.8%
	% Of Total	59.9%	38.9%	98.8%

Other Country	Count	9	2	11
	% Within Country	81.8%	18.2%	100.0%
	% Within Are you aware of the Building Information Modelling (BIM) approach?	1.6%	.5%	1.2%
	% Of Total	1.0%	.2%	1.2%
Total	Count	572	368	940
	% Within Country	60.9%	39.1%	100.0%
	% Within Are you aware of the Building Information Modelling (BIM) approach?	100.0%	100.0%	100.0%
	% Of Total	60.9%	39.1%	100.0%

χ^2 (1, N = 940) = 2.054, p = .152

A chi-square test of independence was performed to determine the relationship between the respondent's country and their awareness of the BIM approach. The result showed no significant association exists between the respondent's country and their awareness of the BIM approach, χ^2 (1, N = 940) = 2.054, p = .152.

The result, however, indicates that both engineers from the KSA and engineers from other countries are aware of the BIM approach. About 248 (44%) of the respondents who are aware of the BIM approach have never used it before. It is also observed that 14 (3.8%) of the respondents who are not aware of the BIM approach have actually used it before. This statistic indicates an awareness gap that exists among the respondents. A chi-square test reveals that there is a significant association between awareness and usage of BIM ($\chi2(1)$ = 262.81, $p<.001$). The use of BIM is dependent on its awareness.

It is further observed that awareness and usage are positively and significantly correlated (rs = .532, $p<.001$). A significant correlation exists between self-reported knowledge and perceived awareness (rs = .620, $p<.001$) as well as self-reported knowledge and usage of BMI (rs = -600, p<.001). This significant relationship indicates that awareness and usage are aligned with the respondent's knowledge of BIM. In this context, a high number of the respondents in Saudi Arabia have not used BIM before despite them having its awareness and this leads to low self-estimated knowledge. Evidence exists to suggest that the level of education of the respondents influences awareness of the BIM approach ($\chi2(4) = 35.96$, $p<.001$).

The column proportion of respondents with Bachelor's, Master's, and PhD who are aware of the BIM approach is significantly higher than those with a diploma and high school level of education. Similarly, there was sufficient evidence to suggest that the level of education influences the knowledge of BIM ($\chi2(16) = 48.82$, $p<.001$).

4.5 Determining Enablers and Constraints Associated with the Use of BIM Technology in Governmental Projects in Saudi Arabia

Table 16 shows the reliability of the different benefits of BIM by using Cronbach's alpha. The Cronbach's alpha value always ranges between 0 and 1; values closer to 1 are said to have higher internal consistency for the measure contained in the scale. A dataset showing Cronbach's alpha with a value greater than 0.7 is said to have high internal consistency. This data includes 15 different benefits of BIM; the Cronbach's alpha value is 0.970, indicating high internal consistency for the 14 variables.

Table 15: Reliability statistics

Cronbach's Alpha	N of Items
.970	15

A relative importance index was used to rank the importance of the different benefits of BIM. Table 17 below shows the ranking results for each of the benefits of the BIM approach. The relative importance index allows identifying the most important benefit of BIM based on the responses from the engineers. The relative importance index value can be categorised into five levels and they include high (H) (0.8 ≤ RII ≤ 1), high-medium (H–M) (0.6 ≤ RII ≤ 0.8), medium (M) (0.4 ≤ RII ≤ 0.6), medium-low (M-L) (0.2 ≤ RII ≤ 0.4), and low (L) (0 ≤ RII ≤ 0.2). 15 benefits measured on a 5-point Likert scale were used and a total of 940 engineers gave answers for each of the benefits. Based on the stated ranking above, all of the variables have a high-medium importance level for the benefits of the BIM approach.

However, Quality management was ranked first (RII = 0.754), Time saving was ranked second (RII = 0.743), Cost estimation was ranked third (RII = 0.738), Operations and maintenance were ranked fourth (RII = 0.734), Facility management was ranked fifth (RII = 0.729), Sustainability analyses was ranked sixth (RII = 0.709), Minimising changes was ranked seventh (RII = 0.707), Efficient use of energy was ranked eighth (RII = 0.707), Thermal design was ranked ninth (RII = 0.703), Remove any omission was ranked 10th (RII = 0.699), Transparency cost was ranked 11th (RII = 0.697), Life cycle cost was rated 12th (RII = 0.692), Daylight analysis was rated 13th (RII = 0.685), and Logistics management was rated 14th (RII = 0.679). The last or 15th benefit rank is the Established life cycle (RII = 0.678). The result, however, shows most of the variables are important as there are no variables that fall between medium and low importance.

Table 16: Relative importance index

	RII Value	Importance	Importance Level
Time saving	0.743	2	H-M

Cost estimation	0.738	3	H-M
Minimising changes	0.707	7	H-M
Sustainability analyses	0.709	6	H-M
Remove any omission	0.699	10	H-M
Quality management	0.754	1	H-M
Logistics management	0.679	14	H-M
Established life cycle	0.678	15	H-M
Life cycle cost	0.692	12	H-M
Operations and maintenance	0.734	4	H-M
Efficient use of energy	0.707	8	H-M
Facility management	0.729	5	H-M
Daylight analysis	0.685	13	H-M
Thermal design	0.703	9	H-M
Transparency cost	0.697	11	H-M

The use of a RII in this study effectively prioritises the benefits derived from BIM based on the perceptions of engineers. The segmentation into five importance levels (from low to high) facilitates a nuanced understanding of how these professionals value different BIM attributes. Notably, all surveyed benefits fall within the high-medium category, reflecting a generally high valuation of BIM's capabilities across the board. Table 17 employs the RII to elucidate the hierarchy of benefits associated with BIM, as perceived by engineers. This index categorises the benefits into five distinct levels of importance, ranging from low to high, based on engineer responses. All identified benefits fall within the high-medium category, indicating a generally favourable evaluation of BIM's impact.

4.6 Quantifying the Extent to which BIM Technology is used in the KSA.

Table 18 below shows the cross-tabulation of respondent's countries and how long they have been using BIM in their organisation. Concerning how long engineers have been using BIM, the proportion of engineers who have not been using BIM and are from the KSA is 99.2% (638). The proportion of engineers who have not been using BIM and are from other countries is 0.8% (5). The proportion of engineers who have used BIM for less than 1 year and are from the KSA is 100% (59), while none of the engineers from other countries have used BIM for less than I year. The proportion of engineers who have used BIM for 2 to 5 years and are from the KSA is 96.1% (99). The proportion of engineers who have used BIM for 2 to 5 years and are from other countries is 3.9% (4).

The proportion of engineers who have used BIM for 6 to 9 years and are from the KSA is 100% (51), while none of the engineers from other countries have used BIM for between 6 to 9 years. The proportion of engineers who have used BIM for 10 to 13 years and are from the KSA is 100% (35), while none of the engineers from other countries have used BIM for between 10 to 13 years. The proportion of engineers who have used BIM for 14 to 20 years and are from the KSA is 93.3% (14). The proportion of engineers who have used BIM for 14 to 20 years and are from other countries is 6.7% (1). The proportion of engineers who have used BIM for more than 20 years and are from the KSA is 97.1% (33). The proportion of engineers who have used BIM for more than 20 years and are from other countries is 2.9% (1).

Concerning the engineer's country, the proportion of engineers who are from the KSA and have not been using BIM is 68.7% (638), while the proportion of engineers who are from other countries and have not been using BIM is 45.5% (5). The proportion of engineers who are from the KSA and have been using BIM for less than 1 year is 6.4% (59), while none of the engineers from other countries have used BIM for less than 1 year.

The proportion of engineers who are from the KSA and have been using BIM for 2 to 5 years is 10.7% (99), while the proportion of engineers who are from other countries and have been using BIM for 2 to 5 years is 36.4% (4). The proportion of engineers who are from the KSA and have been using BIM for 6 to 9 years is 5.5% (51), while none of the engineers from other countries have used BIM for 6 to 9 years. The proportion of engineers who are from the KSA and have been using BIM for 10 to 13 years is 3.8% (35), while none of the engineers from other countries have used BIM for 10 to 13 years. The proportion of engineers who are from the KSA and have been using BIM for 14 to 20 years is 1.5% (14), while the proportion of engineers who are from other countries and have been using BIM for 14 to 20 years is 9.1% (1).

The proportion of engineers who are from the KSA and have been using BIM for more than 20 years is 3.6% (33), while the proportion of engineers who are from other countries and have been using BIM for more than 20 years is 9.1% (1). Engineers who have not been using BIM and are from the KSA make up 67.9% of the sample, while those who are from other countries but have not been using BIM make up 0.5% of the sample. Engineers who have been using BIM for less than 1 year and are from the KSA make up 6.4% of the sample. Engineers who have been using BIM for 2 to 5 years and are from the KSA make up 10.5% of the sample, while those who are from other countries make up 0.4% of the sample.

Engineers who have been using BIM for 6 to 9 years and are from the KSA make up 5.4% of the sample. Engineers who have been using BIM for less than 10 to 13 years and are from the KSA make up 3.7% of the sample. Engineers who have been using BIM for 14 to 20 years and are from the KSA make up 1.5% of the sample, while those who are from other countries make up 0.1% of the sample. Engineers who have been using BIM for more than 20 years and are from the KSA make up 3.5% of the sample, while those who are from other countries make up 0.1% of the sample.

Table 17: Cross-tabulation table by country and how long engineers have used BIM in their organisation

		Country		
		Saudi Arabia	Other Country	Total
Has not been using BIM	Count	638	5	643
	% Within How long has BIM been used in your organisation?	99.2%	.8%	100.0%
	% Within Country	68.7%	45.5%	68.4%
	% Of Total	67.9%	.5%	68.4%
Less than 1 year	Count	59	0	59
	% Within How long has BIM been used in your organisation?	100.0%	0.0%	100.0%
	% Within Country	6.4%	0.0%	6.3%
	% of Total	6.3%	0.0%	6.3%
2 to 5 years	Count	99	4	103
	% Within How long has BIM been used in your organisation?	96.1%	3.9%	100.0%
	% Within Country	10.7%	36.4%	11.0%
	% Of Total	10.5%	.4%	11.0%
6 to 9 years	Count	51	0	51
	% Within How long has BIM been used in your organisation?	100.0%	0.0%	100.0%
	% Within Country	5.5%	0.0%	5.4%
	% Of Total	5.4%	0.0%	5.4%
10 to 13 years	Count	35	0	35
	% Within How long has BIM	100.0%	0.0%	100.0%

	been used in your organisation?			
	% Within Country	3.8%	0.0%	3.7%
	% Of Total	3.7%	0.0%	3.7%
14 to 20 years	Count	14	1	15
	% Within How long has BIM been used in your organisation?	93.3%	6.7%	100.0%
	% Within Country	1.5%	9.1%	1.6%
	% Of Total	1.5%	.1%	1.6%
More than 20 years	Count	33	1	34
	% Within How long has BIM been used in your organisation?	97.1%	2.9%	100.0%
	% Within Country	3.6%	9.1%	3.6%
	% Of Total	3.5%	.1%	3.6%
Total	Count	929	11	940
	% Within How long has BIM been used in your organisation?	98.8%	1.2%	100.0%
	% Within Country	100.0%	100.0%	100.0%
	% Of Total	98.8%	1.2%	100.0%

4.7 Programs Currently used During the Design Phase of Construction Projects in the KSA and their Compatibility with BIM Software

Figure 43 below shows the frequency and percentage distribution of the different engineering software programs used by the participating engineers' organisations. Almost all of the respondents (n = 859, 91.4%) indicated that their organisations use AutoCAD, 378 (40.2%) indicated their organisation uses Autodesk Revit (Architecture Structure and MEP), 224 (23.8%) uses SAP software, 107 (11.4%) uses ArchiCAD, 101 (10.7%) uses STAAD, 62 (6.6%) uses Bentley systems Architecture software, 52 (5.5%) uses DDS-CAD, 5.2% uses Allplan, 4.8% uses Tekla Structures, 3.3% uses VICO Constructor, while 30 (3.2%) stated other software.

Some of the other software listed includes 3D max, BIM360, Civil 3D, Etab /Safe, Fusion 360, solid works, GIS, HAP, eQuest, SketchUp, in house BIM extension to Sketchup, Infrawork, blue beam, sketch up, naviswark, Maintenance system, MapInfo, MATLAB, Maximo, Navisworks, Oracle (ERP), Rhino3d, Sherpont, Sketchup (BeeahBIM-Plugin), Solid Works, 3d max, and SCADA. In contrast, the BIM report by NBS, Digital Construction (2020) reveals that for software use in the UK, approximately 50%, of engineers use Autodesk Revit for design, 13% use Autodesk CAD, 16% ArchiCAD, and 7% Autodesk CAD LT.

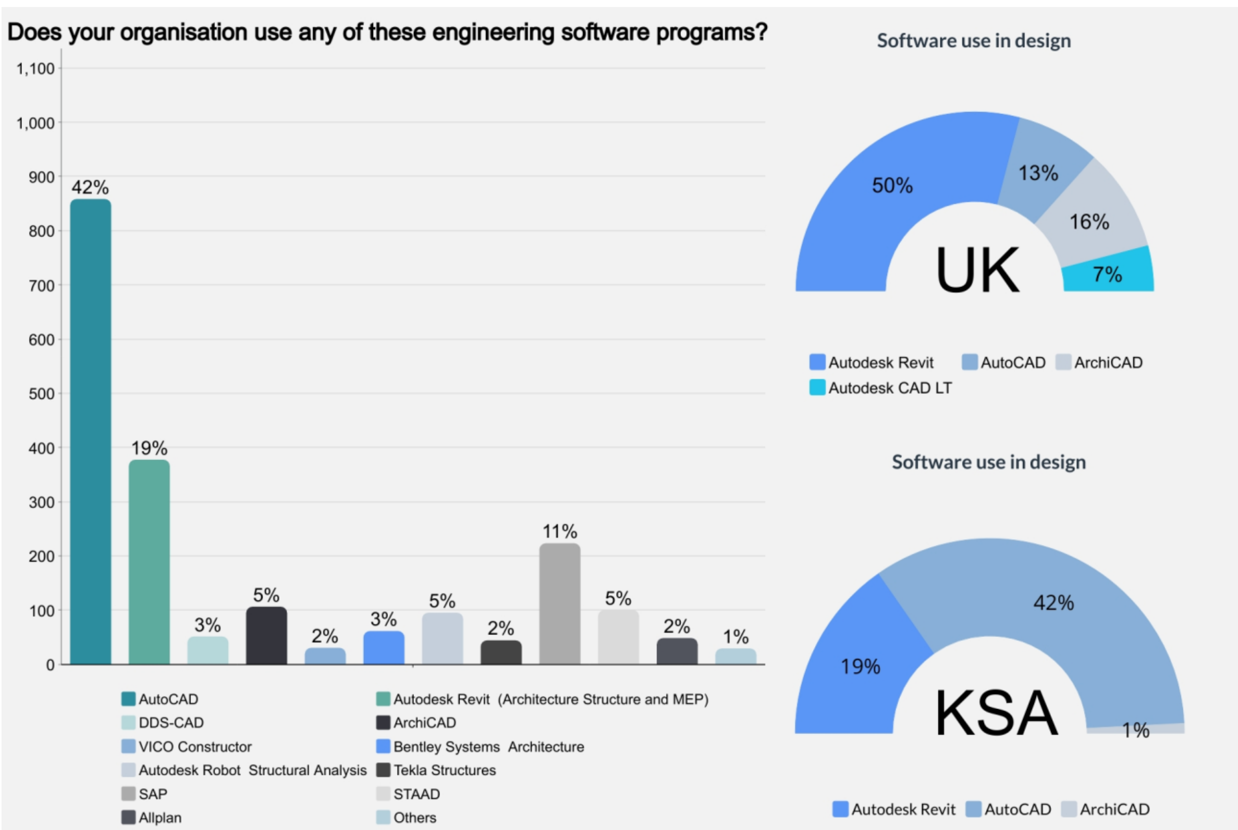


Figure 43: Different engineering software programs used in organisations

Table 18 below shows the frequency and percentage distribution of the current BIM applications level used within the engineer's organisation. 821 (87.3%) of the respondents indicated that CAD is used for Engineering Drawing, 353 (37.6%) indicated that 2 Dimension is used for Engineering Drawing 2D Draft, 441 (46.9%) indicated that 3 Dimension is used for engineering and can show 3D drawing, 126 (13.4%) indicated that 4 Dimension is used for schedule time of construction, 92 (9.8%) indicated that 5 Dimension is used for a cost estimate, 63 (6.7%) indicated that 6 Dimension is used for sustainability, while 63 (6.7%) also indicated that 7 Dimension is used for facility management.

Table 18: Current BIM level used within the engineer's organisation

	Frequency	Percentage
CAD (CAD is used for Engineering Drawing)	821	87.3 %
2D modelling (2 Dimension is used for Engineering Drawing 2D Draft)	353	37.6 %
3D modelling (3 Dimension is used for engineering and can show 3D drawing)	441	46.9 %
4D modelling (4 Dimension is used for schedule time of construction)	126	13.4%
5D modelling (5 Dimension is used for a cost estimate)	92	9.8 %
6D modelling (6 Dimension is used for sustainability)	63	6.7 %
7D modelling (7 Dimension is used for facility management)	63	6.7 %

The data presented in Table 18 reveals several critical insights into the adoption and utilisation of different dimensions of Building Information Modeling (BIM) within an engineering organisation. The high frequency and percentage (87.3%) of CAD usage for engineering drawing indicates a robust baseline integration of digital tools in engineering tasks. However, the adoption rates decrease significantly as the dimensions increase, reflecting a potential gap in the application of more complex BIM functionalities.

Notably, the relatively lower percentages for 5D, 6D, and 7D applications (cost estimation, sustainability, and facility management respectively) suggest that while technical capabilities for drawing and scheduling (3D and 4D) are being adopted, the integration of BIM into broader aspects of project lifecycle management remains limited. This discrepancy highlights areas where further development and training could significantly impact the efficiency and sustainability of projects. Such data can be pivotal in directing organisational strategies towards more comprehensive BIM training and implementation, focusing not just on technical proficiency but also on lifecycle management and sustainability.

4.8 Analysis Findings

Chapter 4 elucidates a moderate awareness level of 61% for BIM among construction professionals in the KSA, which sharply contrasts with the nearly universal awareness observed in more advanced BIM markets like the United Kingdom. This chapter reveals that among those acquainted with BIM, only 15% of the 35% who employ it do so comprehensively across all project stages, indicating a fragmented adoption pattern. This superficial integration is primarily hindered by several barriers including inadequate training (42%), organisational resistance (33%), and insufficient infrastructure (25%).

The impact of organisational support on BIM adoption is significant, with rates climbing to 55% in entities with explicit managerial backing, in stark contrast to 20% in those lacking such support. This disparity underscores the pivotal role of organisational culture and leadership in the adoption of new technologies. The findings point to a considerable gap in both foundational knowledge and initial practical engagement with BIM technologies within KSA.

Survey data reflect a moderate to high level of BIM awareness among engineers in KSA, yet with varied depths of application insight. This supports the study’s aim to quantify BIM knowledge and pinpoint educational shortcomings. While a baseline awareness exists, a deeper understanding and practical application of BIM are deemed crucial for maximising its benefits in the KSA construction sector.

When compared with regions like the UK, where BIM adoption is more mature, it is clear that KSA is progressing positively yet has ample scope for accelerated development. This could be facilitated by targeted educational programs and supportive policies, similar to successful models observed in other regions. Theoretically, these insights enrich the existing body of literature on technology adoption in construction by highlighting the influence of socio-economic factors and organisational culture. Practically, they suggest that stakeholders in the KSA construction sector should emphasise comprehensive training and development initiatives to enhance BIM adoption.

This chapter defines 'awareness' as the recognition and familiarity with BIM technologies among construction professionals in Saudi Arabia, which encompasses knowledge of BIM’s existence and a general understanding of its benefits to the construction process. In contrast, 'knowledge' entails a more profound understanding and practical proficiency in applying BIM technologies effectively within projects, including integration into existing workflows and optimisation of project outcomes. Although 61% of respondents reported awareness of BIM, only 29% demonstrated substantial knowledge, identifying a critical industry barrier. The observed gap hinders full adoption and operational integration of BIM, as corroborated by literature that identifies common obstacles such as training deficiencies, resistance to change, and the high costs associated with full implementation. To narrow this gap, targeted educational initiatives and extensive professional training are imperative, focusing not only on the technical aspects of BIM but also on strategic implementation in project management and operations. Future research should evaluate the effectiveness of these educational measures, exploring their customisation to surmount organisational and cultural barriers within the construction sector. Moreover, longitudinal studies could measure the impact of such training on the enduring adoption and advanced utilisation of BIM over time.

4.9 Chapter Summary

Chapter four has been useful in providing a quantitative analysis of BIM awareness, enablers and constraints, technology adoption, and program compatibility within the context of Saudi Arabia. The results derived from survey data indicate a notable level of BIM awareness among engineers in the region. The findings reveal that while there is a considerable awareness of BIM technologies among engineers, the actual adoption rates and depth of knowledge vary significantly. Factors influencing adoption include educational background, organisational support, and perceived benefits of BIM in improving project outcomes. Additionally, this chapter has illustrated the preferences of various professionals regarding BIM benefits and assessed the adoption and application of BIM in government projects and design phases. The information from the quantitative data lays a solid foundation for the subsequent exploration of BIM's impact on LCC in the KSA, which is the primary focus of Chapter Five. Building upon the quantitative findings, the following chapter (Five) will focus on the qualitative analysis, providing a more comprehensive view of BIM's role in the region's construction industry.

Chapter 5

Qualitative Data Analysis - BIM on LCC in the KSA

Content from this chapter has been published:

An analysis of the qualitative impacts of Building Information Modelling (BIM) on Life Cycle Cost (LCC): A qualitative study on Saudi Arabia.

Alasmari, E., Martinez-Vazquez, P. and Baniotopoulos, C., 2023. An Analysis of the Qualitative Impacts of Building Information Modelling (BIM) on Life Cycle Cost (LCC): A Qualitative Case Study of the KSA. *Buildings*, *13*(8), p.2071.

5 Chapter Five: Qualitative Data Analysis - BIM on LCC in the KSA

5.1 Introduction

This chapter executes a qualitative examination of the impact of BIM on LCC within the context of the Kingdom of Saudi Arabia (KSA). The chapter provides a comprehensive exploration of the practical implications and real-world significance of BIM in the construction sector. The chapter commences with a detailed description of the interviews conducted to capture their opinions from industry experts, practitioners, and stakeholders. Subsequently, it investigates the in-depth analysis of these interviews, employing coding techniques to extract meaningful patterns, themes, and perspectives concerning BIM's effects on LCC. Additionally, this chapter evaluates the risks and challenges linked to implementing BIM for LCC optimisation while highlighting the advantages that this transformative technology offers.

5.2 Description of Interviews

The interviews were intended for BIM practitioners and experts in the Saudi Arabian construction industry. Several criteria were defined for selecting the BIM expert participants, including construction industry experience with BIM, efforts to adopt BIM in existing projects, and actual BIM implementation experience, cost management, project management, design, and operational management practices. Therefore, semi-structured interviews were chosen because the required information and knowledge were available from the BIM experts. There are several factors involved in preparing the interview questions, ranging from the aim of the interview and the depth of knowledge provided by the BIM expert, to obtaining answers to the thesis objectives that were not covered by the questionnaire, to achieve a deeper understanding of BIM's impact on LCC. Furthermore, the method of administering the interviews was face-to-face with the participants. The interview questions were divided into five primary stages, and each section contains questions pertaining to that stage, as noted in Table 19. Also, see Appendix 3 for the Application for Interview Questions.

Table 19: Succession of interview questions directed to the BIM experts (Alasmari, Martinez-Vazquez and Baniotopoulos, 2023a)

Section	Description
1	Participants' Background
2	Building information modelling (BIM)
3	Life Cycle Cost estimation (LCC)
4	Impact of BIM on LCC
5	Impact of the types of contracts on BIM

The study conducted interviews with 30 BIM experts between January and March 2022. Experts in BIM were contacted and invited to participate. The interviews took place in four regions of the KSA, which required time and effort to travel between the regions (Central Region, Western Region, Eastern Region, and Northern Region). The interviews were conducted in Arabic and the recordings were translated from Arabic to English. Voice Recorder-VOZ software was utilised to record the interviews.

5.3 Analysis

Data analysis entails the examination of complicated objects by identifying their fundamental themes. The analysis was conducted with codes, ideas, and categories by using the software NVivo 11. This software enables the collecting and storing of qualitative and quantitative data from the outset as well as their categorisation and codification. The initial phase of data analysis in this study consisted of coding and categorising the collected data. In the subsequent phase, the researcher reviewed themes, defined and named the major themes, and produced the results.

5.4 Coding

The responses were categorised based on the participants' initials, as shown in Table 20, which lists their specifics and identities. To maintain consistency in the study's qualitative analysis, coding processes were carried out. Using NVivo 11 software, the manual coding illustrated in Table 20 was executed. This code essentially outlines the participants' roles, their experience in the construction sector, and their familiarity with BIM. The main themes depicted in Figure 48 facilitate the qualitative analysis.

Table 20: Interview code and data of BIM specialists

No	Participants' Code	Position	Experience in Construction	BIM Experience
1	DAA	Owner of the Office of Al-Yusifi Value Engineer	30 years	30 years
2	DAB	Assistant Professor	12 years	12 years
3	DABI	Assistant Professor in the Geomatics Department	15 years	7 years
4	DI	Co-professor	8 years	8 years
5	DMA	Project Office Manager	12 years	4 years
6	DY	Director of the Digital Operations Department	18 years	14 years
7	DYA	Director of the General Administration	11 years	4 years

		of Modern Building Methods		
8	EAM	BIM and Digital Transformation Lead	26 years	12 years
9	EAH	BIM Manager	10 years	10 years
10	EA	Technical Director	22 years	10 years
11	EAA	Director of the Projects Development and Support of District Buildings Department	25 years	2 years
12	EAAO	Director of the Engineering Design Department	21 years	3 years
13	EAD	BIM Specialist	8 years	8 years
14	EB	Project Manager, Civil Engineer	18 years	6 years
15	EF	Structural Engineer	15 years	6 years
16	EH	Head of Studies and Cost Control Department	16 years	11 years
17	EHT	BIM Lead	15 years	7 years
18	EIE	CEO AIDIGITS Group	32 years	25 years
19	EK	Program Manager	5 years	5 years
20	EMAD	Senior BIM Manager	8 years	8 years
21	EMAH	Director of Engineering Management	18 years	5 years
22	EMBT	Central Judge and Head of Facility Management	5 years	2 years
23	EMD	Project Manager	19 years	7 years
24	EN	Project Manger	5 years	8 years
25	EO	BIM Manager	21 years	18 years
26	ERF	BIM Specialist	16 years	6 years
27	ESA	Undersecretary for the Presidency in Technical and Operational Affairs	16 years	4 years
28	EY	Project Control Engineer	1.5 years	2 years
29	EZA	Consultant Mechanical Engineer	14 years	2 years
30	FAR	KAFD Maintenance Manager	7 years	5 years

The qualitative analysis focused on five major themes: Building Information Modelling (BIM) and Life Cycle Cost (LCC), Contract Type and LCC, BIM and Risks, Challenges, and Advantages of BIM. See Figure 44.

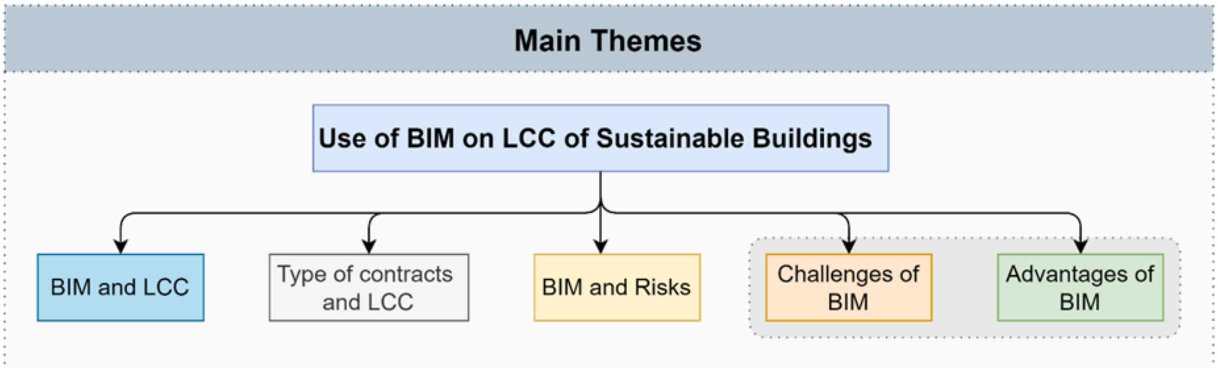


Figure 44: Identifying main themes

As illustrated in Table 22, the five primary themes were subdivided into various subthemes. The following sub-themes emerged out of the study: accuracy of data, efficiency of LCC, expensive software, failure of projects, automation, coordination, project update and control, visualisation, contract effect, initial cost, knowledge of BIM, lack of regulations, motivating factors, owner's choice, un-availability of data, and value study. A total of 168 codes were extracted. See Figure 45 for reference.

Table 21: Five primary themes and their subthemes

No	Main Themes	Sub-themes
1	Building information modelling (BIM) and Life Cycle Cost (LCC)	▪ Coordination ▪ Efficiency of LCC ▪ Visualisation ▪ Knowledge of BIM ▪ Value study
2	Type of contract and LCC	▪ Failure of projects ▪ Contract effect ▪ Owner's choice
3	BIM and Risks	▪ Accuracy of data ▪ Un-availability of data
4	Challenges of BIM	▪ Lack of regulations

		▪ Expensive software
5	Advantages of BIM	▪ Automation ▪ Coordination ▪ Project update and control ▪ Initial cost ▪ Motivating factors

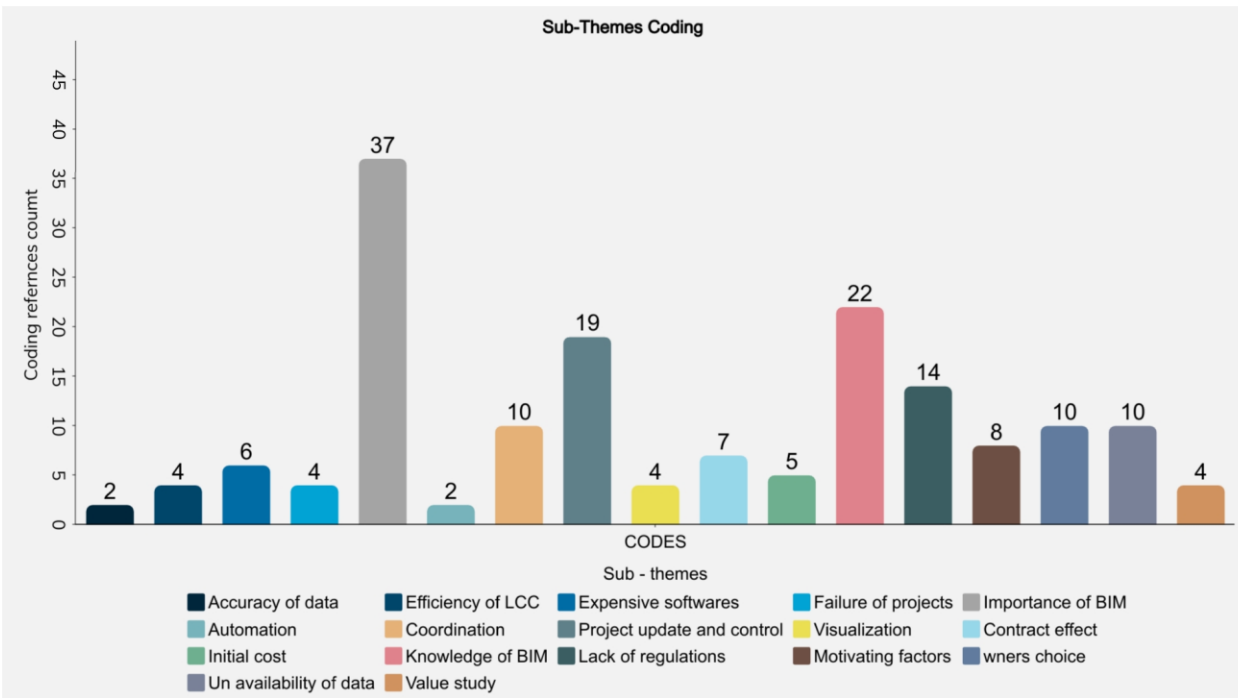


Figure 45: Sub-themes' coding with references

5.5 Building Information Modelling (BIM) and Life Cycle Cost (LCC)

BIM is a method for producing and managing information throughout the whole life cycle of a construction project. Utilising a variety of applicable technologies, a comprehensive digital depiction of every aspect of the construction project is created as part of this operation. This digital description most likely includes information-rich, three-dimensional objects and accompanying structured data such as construction materials with specification, execution, and handover details. BIM is an intelligent software modelling technique that engineers, architects, and contractors can use to cooperate on building design, development, and administration. It provides real-time cooperation amongst all parties engaged in a construction project, resulting in substantial cost, safety, and productivity advantages.

> "*This is from the reality of many experiences. We say that the designer who most influences the project costs is the designer. From the beginning of the first line, the cost is calculated. Therefore, the designers must study BIM, and they are unfortunately not present in large numbers, neither in Saudi Arabia nor in the Gulf, not even in Arab countries. We have a problem in the Kingdom of Saudi Arabia and the Gulf countries. It is not in the life cycle but the initial cost*." **DAA**

The majority of interviewees in this survey agreed that the government in the Kingdom of Saudi Arabia is responsible for implementing BIM applications. However, several of the attendees highlighted that the owner is responsible for adopting BIM. Interviewees have stated, for instance:

> *"The owner is supposed to be responsible because, usually, the design comes to us and after the design, we use people who are experts in BIM to do the upper whether they were 3D, 4D, 5D, so I see that the owner or the person who will pay the costs of the project will be him, administrator."* **DAA**

> *“If we take logic into account, who stands to gain the most from the Revit program? The owner, who represents the owner in the majority of projects? The Ministry of Finance is intended to be the lawmaker, and it is supposed to demand that all costs and quantities from the BIM model be extracted.”* **DY**

> *“Each project owner is responsible for implementing this technology. But how do we require the owner of the projects to apply this technology? I think,*

and I'm talking about government projects here, it is assumed that at the approval stage there will be some kind of proof of the ability to manage the project for the concerned authorities, and part of the proof of the entity's ability to manage its project optimally is the use of technologies similar to BIM technology or BIM technology itself." **EAA**

In this study, 96.7% of the interviewees unanimously reported that estimating LCC in the project is important during the design phase of the decision-making process (see Figure 46).

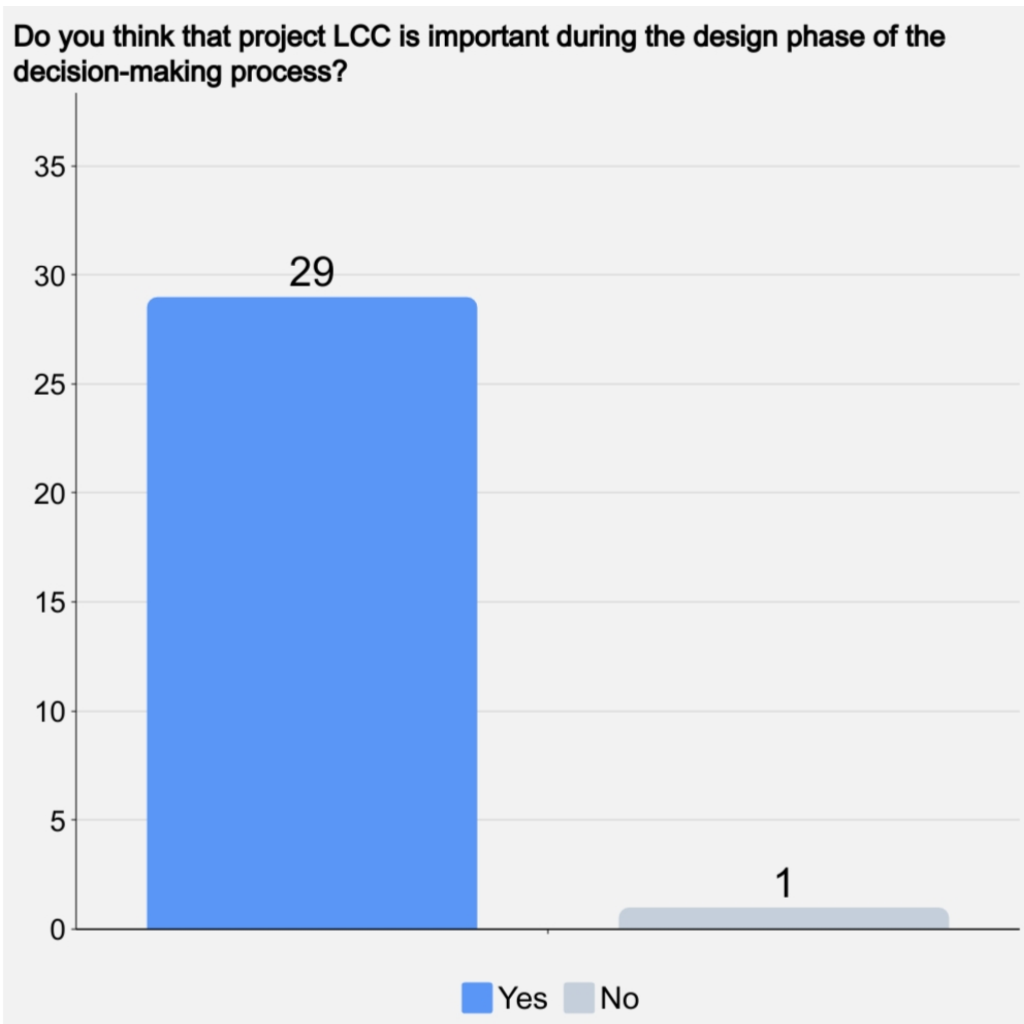


Figure 46: Importance of LCC estimation during the design phase

On the other hand, in response to the question, “have you ever conducted an LCC analysis of a project?”, the interviewer noted that 48% of respondents had not performed an LCC analysis, whereas the other 52 % had. This shows that a sizable proportion of those polled had conducted LCC analysis in the course of their project-related tasks. See Figure 47.

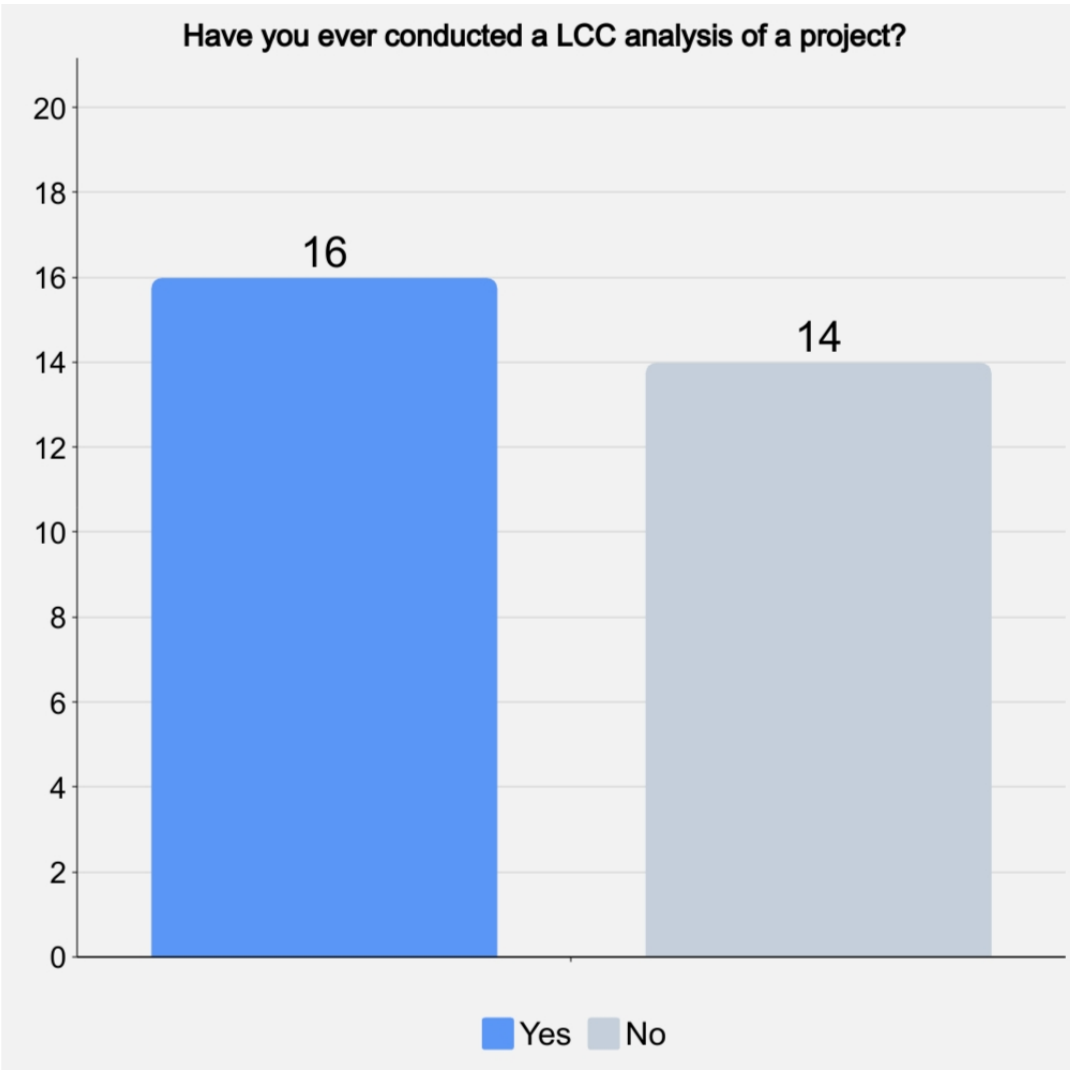


Figure 47: Experience with LCC Analysis in Project Management

The Figure 48 depicts an overview of respondents' degrees of experience with specific BIM dimensions, as well as the related percentages. Experience with 3D BIM accounts for 40% of the total responses, with 6D accounting for 33.33% and 5D accounting for 30%. Very few respondents claimed having experience with either nD (3.33%) or 7D (6.67%) BIM; in contrast, 13.33% and 6.67% of respondents, respectively, reported having experience with 2D and CAD.

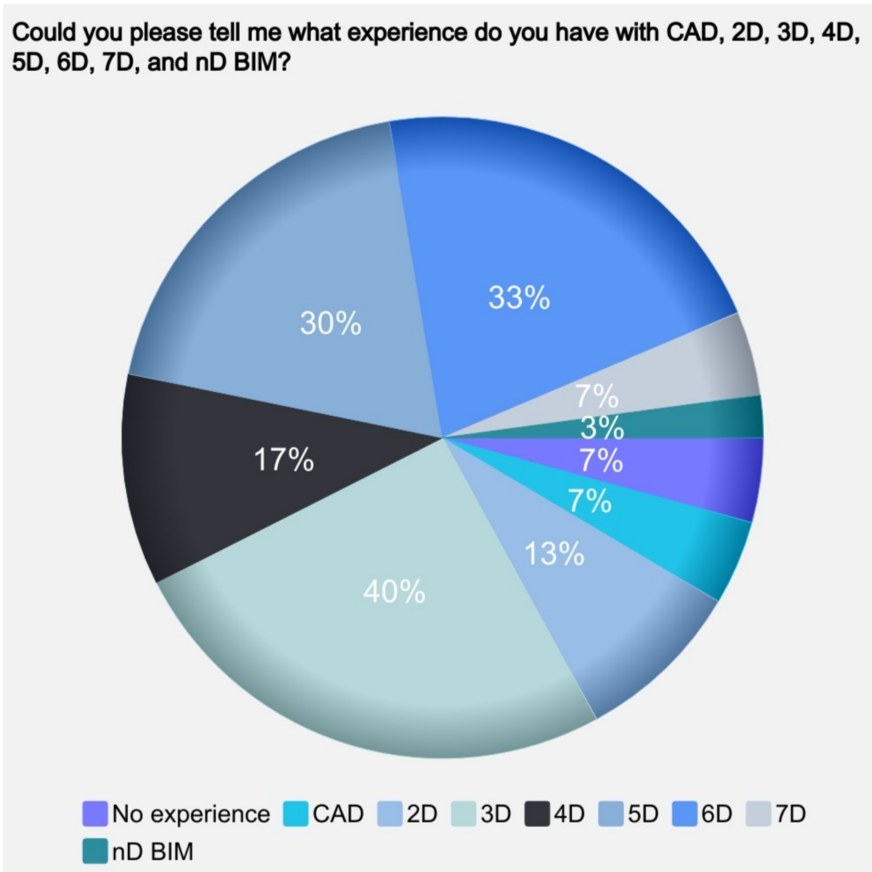


Figure 48: Experience the Level of BIM

5.6 Type of Contract and LCC

The BIM approach has been utilised in construction ventures for over a decade although its execution varies from project to project. The type of construction contract is a significant component that influences the BIM application scope. A construction contract is an agreement to provide design and construction services within the context of construction investment. The investment phases in conventional projects, such as Design-Bid-Build, are linear. In this form of investment, the client does not participate in the document creation process. In design-bid-build projects, the designer does not consult with the contractor because the two entities work in two distinct phases. In design-build contracts, the price remains the most common consideration for choosing the best proposal. When respondents were asked what they thought about the relationship between the kind of contract design, implementation, and operation and its real effect on the project final cost, a correlation between the perceived and actual relationship was found. The majority of respondents believe that contract design does impact the final price.

> "*I do not believe it has any effect because each project is unique. Direct attribution is not useful in some projects, and some projects must download the FIDIC contract, and some projects require a design, so it will be more generic disagree. There is a clear direct effect because some contracts require only direct attribution to be effective. I will lose if I put them in FIDIC, and there are other contracts where cost-plus is preferable to asking for additional information, so I tell each instance to put it."* **DY**

> "*The risk of a fixed-price contract is the quality. As for the design and build contract, its risk is on the cost, in the sense that production is completely unknown because you have to design and build at the same time and there might be some problems you are not aware of and have to make a change. As for the design-bid-build contract, perhaps the best of them is that you understand the sequence correctly and everything is coordinated and done in a better way and take its time, so it's an estimate and cost estimate in high accuracy. This is the difference between the three contracts.*" **EAM**

"*Design and build contracts are the ones with high risk, and the risk will be on the designer because he is the contractor himself. For a fixed price contract, the risk will be very low for the owner and it will be good for the contractor, but sometimes the problem is in the schedule. The traditional contract is considered the worst among them because it is a take-back and a conflict is high between the contractor, owner, and designer, and the project falters. In general, if the project is a government project, the best contract is designed and built for the BIM application because the whole work is in one organisation. And the work is from design, documentation, and bedding till the construction, one entity that does all the work, so it will be the best in terms of being less risky and the best in BIM application. And the impact on the final cost and quality is also considered; the traditional contract is the worst because the changes in it will be many. As for a fixed price contract, it is good, but the best is design and build in terms of costs because the designer will not make a design that is expensive in the advanced stages.*" **DI**

"*The procurement law now in the Kingdom prohibits contracts in most government projects in that the design and construction be for the same contractor. The fixed cost is not present in the government procurement system, and a new idea has now been put forward, which is the BOT, and there are some projects that are now starting to have a partnership with a private company design, operation, and transfer is present. I expect that the idea of fixed cost & time is another type of contract; if it exists through the procurement system, then I expect that it will be better for the contractor and the entity.*" **EAA**

"*The projects that are a comprehensive type of contract (design, procure, construct, and operate) from my perspective are the most rewarding and effective projects, provided that the client has a strong mechanism and team for management, participation, and control.*" **EIE**

On the other hand, Integrated Project Delivery (IPD) requires all parties involved in a project to collaborate and share risks, obligations, and profits. In IPD projects, a subcontractor of important building elements is invited to enter into a joint agreement with the ordering party. In Design-Bid-Build contracts, Building Information Modelling (BIM) is used as a modern management technique. The BIM technique enhances collaboration and expedites decision making. The construction phase makes increased use of BIM documents created during the design phase. The optimal contexts for deploying BIM are design-build and IPD projects in which stakeholders collaborate more. In Saudi Arabia, many projects do consider the high LCC.

> "*I saw many projects that failed during the use of the project, whether a building, a mosque or a pipeline, and the reason is that they did not calculate the life cycle cost that will be in the future. We have a long way to go, and I return to saying that if the data is unavailable, there will be no life cycle cost, not even BIM*." **DAA**

> "*From my point of view, its operating costs are very high and, unfortunately, our maintenance culture is only when there is collapse or failure. Keep in mind that the cost is already high. If the idea of maintenance is adopted, it will increase even more.*" **DAB**

> "*There are projects in which the construction cost is not high, but you may discover at a later stage, such as operation and maintenance, that their cost is high.*" **EY**

In this instance, 96.7% of respondents concurred with the given statement. However, when queried about the prevalence of Life Cycle Cost (LCC) assessments in actual projects, half reported the absence of such evaluations, while the remainder affirmed their inclusion. See Figure 49.

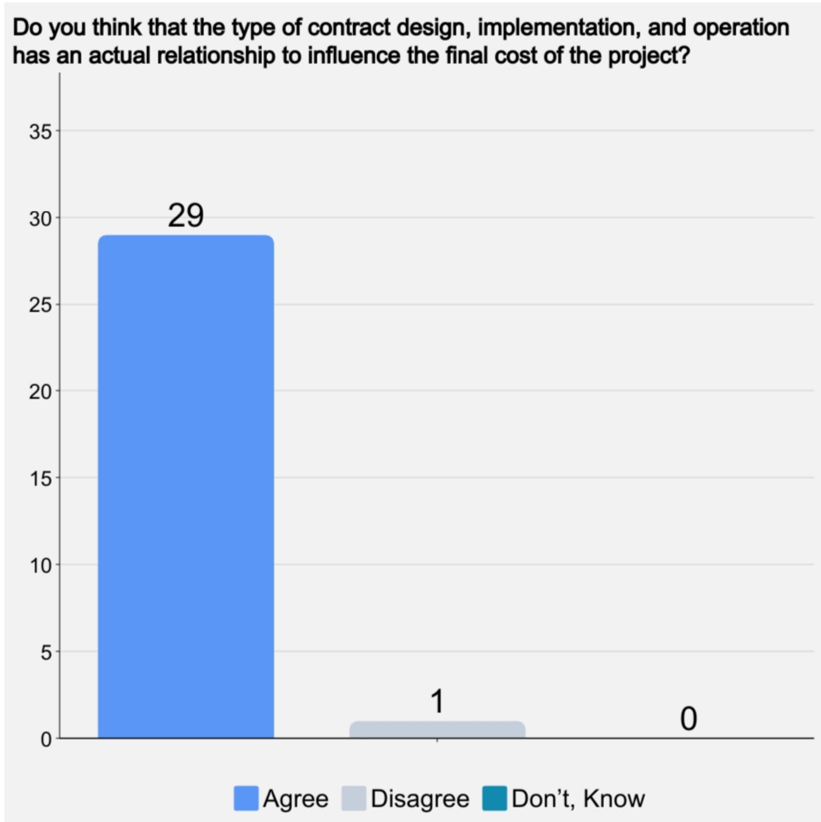


Figure 49: Type of contract on the final cost

The ISO 19650 standard best defines the BIM process and accompanying data structures on a global scale. Even though the most pressing concerns around BIM contracts are well understood, no solid best practice standards have yet been established in the construction industry. When creating or negotiating BIM-related contracts, it is crucial to remember the requirements of the ISO 19650 standard. To employ BIM, the parties must identify their goals and deliverables and devise a strategy for achieving them.

> "*My use of programs is not continuous, but from time to time according to the project; for example, some programs such as Naviswork that help in this process*." **ESA**

> "*We used Primavera programs, and there are other programs, but I don't remember them*." **EN**

"*We relied on calculating costs in the traditional manual way and on mathematical equations in the Excel file*." **EMAD**

Each project participant in Saudi Arabia often signs a standard contract with their business that includes a specific BIM provision. When asked who is responsible for adopting the BIM application in the Kingdom of Saudi Arabia, a uniform BIM technique does not exist. There is also little direction as to who is responsible for particular tasks.

"*Currently, there is no entity, and an independent entity is supposed to be established to handle this matter. As I said earlier, the Building Technologies Program, one of the Ministry of Housing programs, adopts this subject. Aside from your question, let's take, for example, the issue of sustainability. The issue was a little lost once in the Ministry of Municipal and Rural Affairs and once in the Ministry of Housing (these two ministries have now merged), until the government established the sustainable construction program under the umbrella of the Ministry of Housing (which has now merged), it was adopting this subject, so I think that the subject of BIM will be the same way*." **DMA**

"*There is no specific party; every client is requesting the application of BIM, and let's talk about the clients who are related to the projects of Vision 2030 as well as the projects that are related to the investment fund. Almost every client in these projects is now requesting the application of BIM in the projects; this is a party that decided it depends on this system it has. If we take, for example, municipality projects, trust projects, or other governmental projects, we see that there is no obligation for them to use BIM. I expect the best. Naturally, the municipality's adoption itself is that they require the contractor or designer to submit a model or model for the* *building that is being implemented for things to be clearer and for the plans to be from this model*." **EAH**

A few respondents did believe that the ministry is responsible for adopting BIM, whereas others also believed that the private sector should jump in to take matters in hand.

> "*I expect, and Allah knows best, that it is the Ministry of Municipal and Rural Affairs, as well as the Ministry of Housing, which is now affiliated with the Ministry of Municipal and Rural Affairs as well as the Engineers Authority*." **EAAO**

> "*We can divide it into two parts: the governmental part, whether it is the government support in the municipalities because they are supposed to impose certain laws, for example, they do not receive important buildings unless they have a Revit model because this will help in the future development of these buildings. This is about the government; in that they can set laws and specifications for receiving government buildings. The second part is for private companies because this benefits them financially and saves them time; as a private company or contractor, instead of working with AutoCAD and working on the building, he faces problems, so he has to repeat the work. The human being in the project, for example, the people on the site, may be delayed, instead of working on a second project, so that he will return to work on the same project. Private companies should switch to Revit because it will greatly cost human life. After all, I see that Revit is easier to create; I mean, if I drew an AutoCAD diagram for a whole day, I can draw the same diagram on Revit in two or three hours, and this saves time and also allows a larger group of people to work on other projects. So, it is divided between the laws and private companies*." **ED**

This must be considered while defining the permissible level of regions of obligation and liability limitations. BIM can provide a solid foundation for building operations by, for example, supplying a consistent data set for facility management. In addition, contracts for BIM services will vary substantially based on the objectives and requirements of the employer. Moreover, every project requires a unique collection of solutions due to its unique set of circumstances. Existing documentation and instructions should be regarded as checklists rather than templates.

> "*One of the objectives of BIM, that if the project does not need to use 6D because this requires bringing higher-level efficiencies, and thus higher salaries, and then the cost, so the efficiency of the project, which is one of the goals of BIM, is to reduce costs; and it was one of the methods we used to reduce costs before the start of the project, as before we start the project, we evaluate if we are going to use 3d, 4d, 5d, or 6 levels based on the value and size of the project*." **EMAD**

The set-up of the BIM system, along with human error and poor communication, constitute a substantial threat to the success of a project. Utilising complex systems for construction projects has significant drawbacks. BIM is transforming the design, engineering, and construction industries on a global scale. Despite this, there are still numerous impediments to its application in the private sector. While performing a study in Saudi Arabia, various obstacles to effective BIM deployment were found. BIM implementation is loaded with major dangers and barriers, but also offers a huge opportunity. A 3D model can provide an image that is substantially more informative than a thousand AutoCAD lines. Some clients may assume that BIM is not applicable to their project since it is neither large nor complex. After the construction phase, the BIM model is also valuable as a model for operations and facilities management. Furthermore, BIM provides a platform for effective project management and work.

"*One of the most important benefits is that communication between the project team is better*." **DI**

"*The initial benefit is avoiding a collision and a plumbing and electrical disagreement between the architect and the builder. The second benefit is that it saves time and money and improves quality, yet we are already utilising it. A lot of collaboration; we cooperate with those on-the-job sites pouring and laying foundations as well as those in the factory. We have three factories: one for the toilets, one for the precast, and one for the Hollow Core slabs. We gained greatly from the BIM application because of the coordination between them, in addition to the construction and others. We deliver the model to them so they can examine it and observe things like the armature bars and where they are positioned*." **DMA**

"*I did not find it better than a government paper study; the British government stated that the benefits of using BIM are two: lower production costs and producing carbon dioxide, which is sufficient for me*." **DY**

5.7 BIM and Risks

The risks associated with the deployment of BIM in building projects are referred to as technical, managerial, financial, and legal risks. On the one hand, interoperability between applications and software is a big concern when deploying BIM. There is a problem with transferring data from an old BIM to a newer version since different project teams use the same BIM model; when transferring data or installing a new version, there is also a possibility of losing data. Consequently, actor risk and team risk are two broad forms of managing risk. Actor risk refers to a person's reluctance to leave their comfortable environment, the time it takes to become familiar with new technologies or a lack of prior expertise with BIM; although BIM implementation will be discouraged by these factors.

However, lack of training and a conservative leadership style can put the organisation at risk. One of the risks of deploying BIM in an organisation is that it will be expensive. Updating software and infrastructure, as well as providing staff training, causes significant upfront costs.

> "*If you use AutoCAD in the design or one of the BIM tools, such as the Revit, it will show you "Quantity accurate 100%" as soon as you press extract bill of quantity, whereas if you use the Lump Sum method, each contractor will mark up 10, 15, 20% for you according to the project. For example, if we say that the project costs one million SAR and you have allocated one million SAR for the budget, then I was surprised by the calculation of the quantity in AutoCAD that you have variation orders of 150 thousand. If you use Rivet, make an extract, and take a bill of quantities contract and the design is final, there is no modification to the plans and then the end cost will be the same as before*." **EMAD**

It is extremely risky to apply BIM if no national BIM standard exists in the construction industry. Legal provisions for intellectual property, cyber security, and ownership of the data model are lacking in the BIM process and procedure. A standard contract for BIM projects does not exist and there is no system for resolving disputes between parties involved in the project. This will put the project team in danger because of a lack of clarity about who is responsible for what.

> "*In my opinion, the only thing we are missing now in Saudi Arabia is regulations; everything is ready and awareness is starting to increase. I remember that when I started teaching in 2017, I was in one valley and people were in another, but now the matter is different. There is more awareness, but we lack the regulations that the project imposes, whatever*

they are; if there are regulations and rules that should be implemented, even in phases like in Dubai or the UK, it would be a good thing." **DAB**

5.8 Challenges

Due to its multiple advantages and favourable effects on project outcomes, building information modelling (BIM) is becoming a mainstream tool in the construction industry. However, adoption is still modest and progressing slowly. In order for BIM deployment to be successful, there must be a methodical approach to controlling risks and challenges. To assess, evaluate, and propose an effective risk response strategy, an organisation must first identify the potential danger. Failure to perceive the risk could lead to the failure of the project. The BIM installation risk assessment and risk response strategy are highly dependent on a comprehensive set of risk variables.

"*The biggest challenge from my point of view is that people are still clinging to what they are used to, which is the old school, and we can say social resistance to BIM. The other thing is the application of the technology itself. We find that there is a little lag in it, and this is for one reason: the BIM technology itself, if we talk about platforms like Revit or Bentley, it has become expensive*." **DI**

"*In general, it is competent personnel; for example, I have been looking for a BIM manager to join me in the company for a long time and am having difficulty finding one qualified. All those applying are Revit users; some are intermediate and others advanced, but the market still requires more qualified people, which is one of the issues because the other challenges might be easily overcome if people were to see the relevance of BIM. This will impact cost and time, but let's focus on the product first*." **DMA**

BIM may be a means for architects and other professionals to gain more work and make their work more profitable in the face of constant pressure on their rates. Those who have adopted BIM have shown that the process is worthwhile, even if it is not always simple. In Saudi Arabia, attaining or acquiring such personnel with relevant BIM expertise is difficult. It may be more cost-effective and less dangerous to implement BIM.

> "*As for the experience side, we lack the expertise and practitioners of BIM in the labour market. This is one of the main points. The reason for this is the lack of clear legislation to adopt BIM in all projects. BIM in Saudi Arabia*." **EY**

> "*The two most significant problems are a lack of awareness and knowledge of BIM and its utility and application at all stages of the project. As a result, there is no complete understanding of the system*." **ESA**

> "*Accreditation by the government, such as the Ministry of Works and the Ministry of Utilities, at the private sector level. Most large corporations are now state-owned enterprises that have gotten involved in BIM such as the scope of work required. However, when licensees, municipalities, and other enterprises are obliged to deliver using BIM systems as a delivery system rather than panels, the concept of dealing with BIM data and its capacity to complete the work as a workflow will change slightly*." **EO**

Table 22 compiles critical insights on the barriers to adopting BIM in Saudi Arabia, as identified by leading BIM experts and relevant stakeholders. It presents a detailed analysis of each challenge, providing a comprehensive understanding of the obstacles faced within the Saudi construction . The most significant challenge, accounting for (29%), is the lack of knowledge about BIM, reflecting a fundamental gap in understanding and awareness of BIM methodologies. This is closely followed by challenges related to training (15%) and regulatory barriers (10%), which are intrinsically linked to the primary challenge of knowledge deficit. The lack of specific BIM legislation in Saudi Arabia, also at (10%), further exacerbates these issues. Additionally, technical and procedural hurdles, including the absence of BIM standards, mandates, and a centralised system, along with the transition challenges from 2D to 3D modelling, are challenges to adopting BIM. These aspects underscore the infrastructural and technical requirements for BIM integration.

Table 22: Key Barriers to BIM Implementation in Saudi Arabia, Insights from BIM Experts and Stakeholders

Challenges	Percentage
Lack of knowledge of BIM	29%
Training	15%
Regulations	10%
Lack of BIM legislation in Saudi Arabia	10%
Cost and Time.	8%
The cost of software is expensive	6%
Convincing stakeholders of BIM's importance	6%
Lack of BIM standards and mandates	6%
Lack of skilled workers	4%
Transition challenges from 2D to 3D	2%
No centralised system of BIM	2%

5.9 Advantages of BIM

Advantages of BIM include early detection of design problems and improved scheduling throughout all phases of construction. Using BIM to design and manage construction projects is a unique method. As a result of this collaboration between professionals and clients, better project decisions are made. BIM can capture every nuance of a project in three dimensions, whereas traditional two-dimensional modelling methods cannot. By using 3D visualisation, augmented reality, and simulations, clients have a thorough project overview. For technical persons, step-by-step instructions and 3D representations of the required work can be provided. An enhanced environmental analysis conducted by design engineers may consider building orientation, energy use, and daylight. BIM can facilitate an energy-saving, waste-management, and water-conservation strategy. Building Information Modelling (BIM) is a technology that enables the construction of more aesthetically pleasing and durable structures. Using BIM, it is feasible to analyse design selections in virtual reality and model natural illumination to optimise window and skylight placement. The adoption of reality capture technology during construction can improve the precision of the final result.

> "*I believe that the use of Building Information Modelling has numerous advantages, the most essential of which is, of course, achieving the aims of all stakeholders, whether an owner, a consultant or a contractor, or even if it is in a PMO. All stakeholders are involved in it, which reduces costs, saves time, allows for faster and wiser management, and uses contemporary technology in the modification or even follow-up on existing projects or even after project management is completed, which is facility management*." **EMAD**

> "*The benefits are sharing the information with the rest of the stakeholders, meaning the design*." **EMAD**

> "*As for the benefits of applying BIM, there are many including that you reduce repetitive work and errors to a large extent, and also that you are correctly doing life coordination*." **EAT**

5.10 Discussion

The stakeholders' lack of familiarity with BIM is one of the biggest issues spotted in the analysis. The government of Saudi Arabia is expected to be in charge of implementing BIM in the country and most respondents said that the owner should be forced to use BIM. BIM helps the owner decide what type of material, shape or alterations to make; visualisation in a building design helps greatly. Regulations are the only thing that is lacking in Saudi Arabia right now. This is by far its most significant barrier. There is currently no entity and an independent entity is expected to be developed to deal with this issue. Thus, persuading developers, decision makers, and engineering and manufacturing offices of the relevance and advantages of utilising BIM can help its adaptation. Figure 50 shows the most frequently found words in the project analysis.

Figure 50: Word frequency cloud

Due to a lack of knowledge, many stakeholders have no idea what BIM represents regarding contracts. There are fewer errors and variation orders and project success rates are better. The most important motivating factors are clear expectations from the client and the opportunity to be green and sustainable. When it comes to speed and efficiency, the BIM system is effective. Construction projects in Saudi Arabia that do not use BIM technology might have significant financial consequences. There are no current contracts that require the use of the BIM system. Using BIM does not appeal to a significant portion of users. Because of this, its inclusion in the contract increases the project price. The project participants, particularly in the design engineering offices and the implementation contractors, must be rewarded for their efforts. Figure 51 represents the most frequently found words under the importance of BIM.

Figure 51: Importance of BIM - word theme cloud

An organisation's strategy dictates how much a project life system costs and how much it costs to implement. While BIM may take longer to develop than the conventional way, it saves time in implementation and operation. Implementation and operation have a significant disparity. Although the traditional technique is faster and more convenient, it is neither more accurate nor more efficient than BIM. There is little doubt that the BIM design stage is more accurate and faster, but it takes longer. Modelling in the implementation stage provides more efficient knowledge.

Following the word cloud frequency analysis detailed earlier, a cluster analysis was conducted. This method groups naturally emerging clusters for more in-depth examination. In this study, clustering served as a data analysis tool to evaluate BIM's significance in the LCC of sustainable buildings. This analysis was steered by the four previously mentioned themes. Subsequently, each theme was delved into in relation to the clusters, leading to the creation of mind maps, as illustrated in Figures 56-59. These mind maps visually structure the thematic analysis hierarchically, showcasing the relationship between questions and interviewees' answers for each theme.

Figure 52 highlights the primary theme: the integration of BIM with life cycle cost. This figure illustrates four associated sub-themes: LCC, BIM knowledge, visualisation, and coordination. The extensive modelling potential of BIM underscores the significance of thorough financial planning throughout a project duration when paired with LCC.

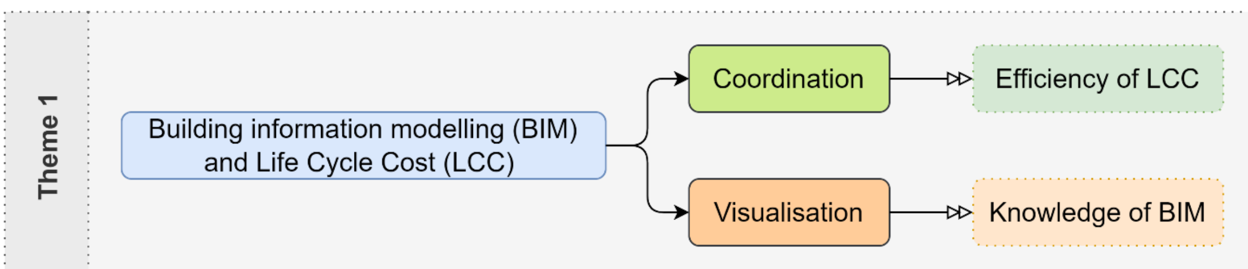


Figure 52: Mind map related to Theme 1

Figure 53 displays various sub-themes connected to contract types and LCC. These sub-themes encompass contract duration, value assessment, the synergy between BIM and LCC, BIM's efficacy in improving project completions, and more. It is worth mentioning that contracts for sustainable buildings might further refine the existing array of contract types and LCC.

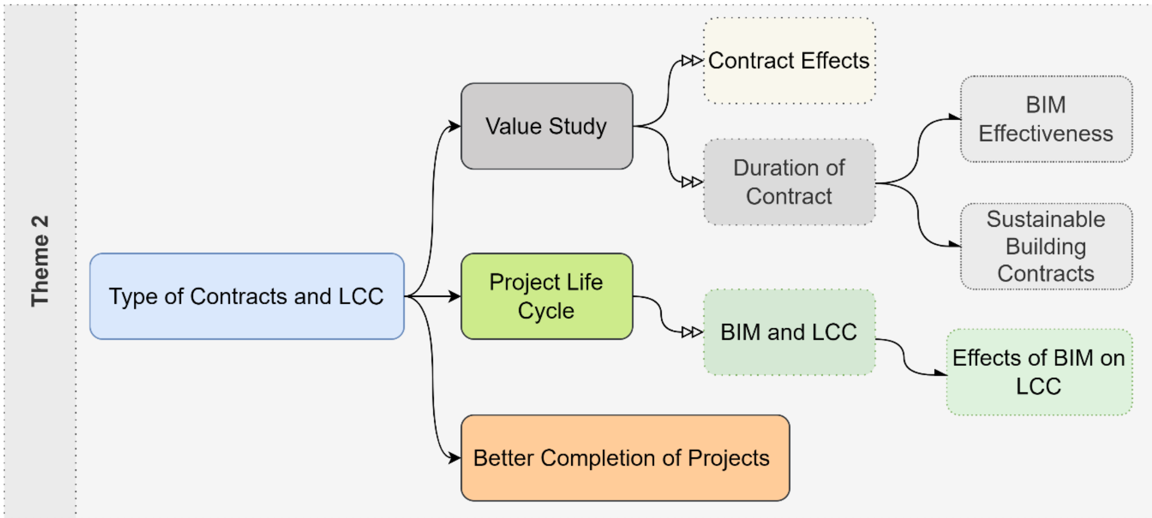


Figure 53: Mind map related to Theme 2

The third primary theme examined concerns the application of BIM and the risks tied to it. Four sub-themes related to this are illustrated in Figure 54. Among these, there is a suggestion that data precision might pose challenges. Additional sub-themes touch on high implementation costs, training expenses, the significant upfront investment needed, and data unavailability.

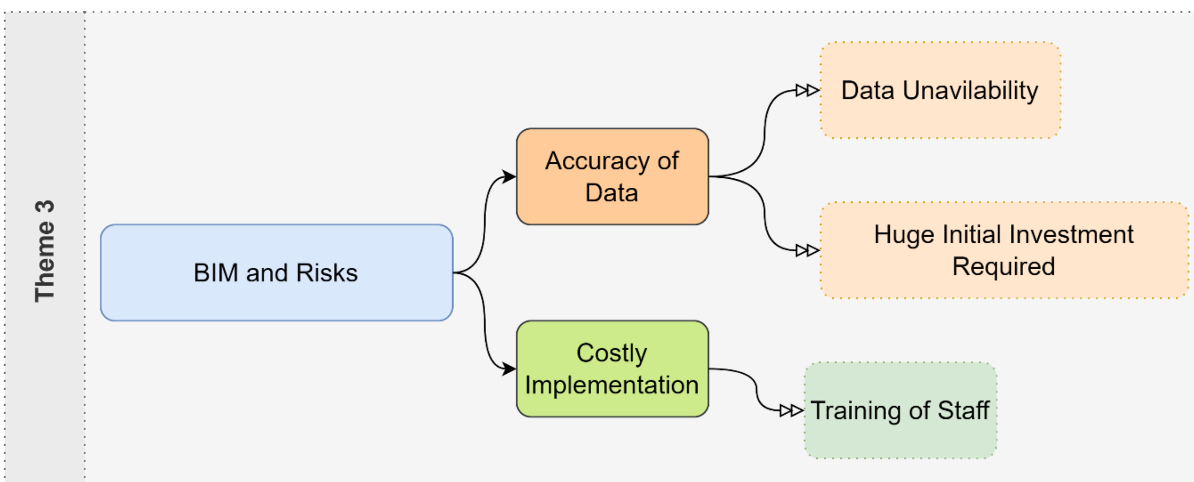


Figure 54: Mind map related to Theme 3

While BIM offers numerous advantages, it also presents several challenges, such as the absence of standard regulations, substantial management resources, expensive software, and the costs associated with training and large-scale BIM deployment. Among the notable benefits in this assessment is automation. The mind map in Figure 55 also underscores the efficiency and coordination benefits of BIM. Such benefits can condense the traditional project phases (from planning to design to construction), leading to cost savings and quicker revenue realisation. By streamlining coordination and optimising results, the duration of the standard project can be considerably reduced, which not only trims expenses, but can also accelerate revenue, bolstering the project financial feasibility.

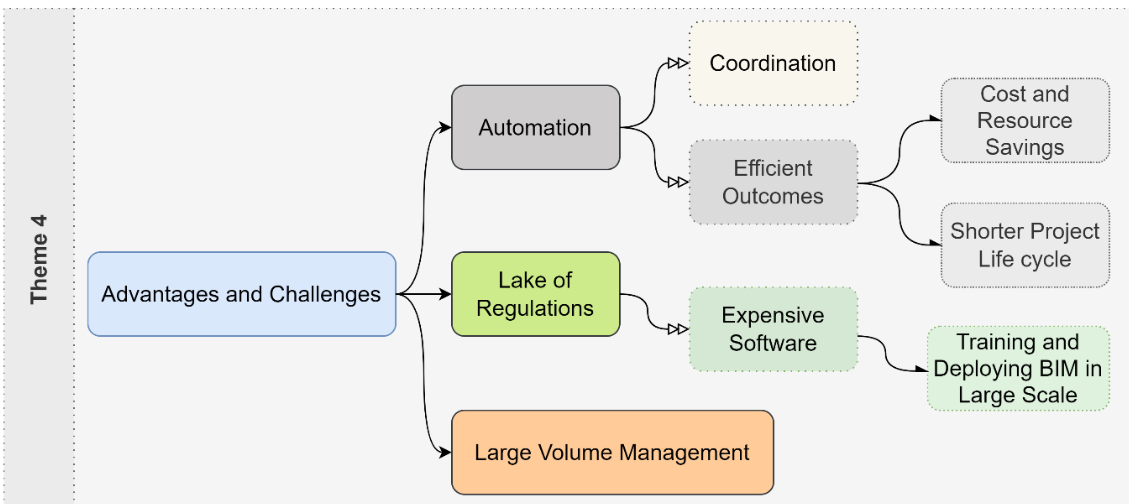


Figure 55: Mind map related to Theme 4

Moreover, this study indicated that BIM is commonly used throughout the planning and design phases in Saudi Arabian construction organisations, but only a minority of organisations estimate cost and time during implementation. Regarding the extent to which a contract type influences the use of BIM in projects, participants' opinions varied. On the other hand, there is unanimity that there is no standard for building information modelling implementation in the

Kingdom of Saudi Arabia that is commensurate with the project implementation process. There is a weakness in the application of BIM to calculate the LCC of the project. Respondents believe that the reason for this is the lack of a clear standard and a framework through which data on the construction can be transferred between all phases of the project.

The analysis highlights a significant obstacle arising from stakeholders' limited understanding of BIM functionalities and benefits. This challenge is aggravated by the lack of a regulatory body tasked with the standardisation and enforcement of BIM adoption within the industry. The pivotal role of government is clear; enforcement through rigorous regulations and the creation of an autonomous oversight authority could drive the essential transformation of the industry. BIM's potential to improve decision-making through enhanced visualisation and informed choices regarding materials and design modifications presents an opportunity that should be leveraged through strategic regulation.

This study employs word clouds and cluster analysis to provide innovative insights into stakeholder perceptions, underscoring the thematic importance of BIM. These methods not only enable a deeper comprehension of complex data but also act as effective tools for engaging stakeholders and policymakers. The visual data representation through these techniques aids in elucidating the multifaceted advantages and challenges associated with BIM in an accessible manner.

The findings underscore a notable gap in current contractual practices, which rarely require BIM usage, often due to the misconception that it leads to higher project costs. Nonetheless, the data indicates that BIM can significantly diminish errors, change orders, and enhance project success rates, potentially reducing costs over time. This contradiction points to the urgent need for targeted educational programs and advocacy to alter industry perceptions and promote BIM integration into standard contractual frameworks. Despite the initial investment and the steep learning curve associated with BIM, the long-term benefits, highlighted by cost savings and efficiency improvements during both implementation and operation, are substantial. Traditional methods, while initially faster, fail to provide the accuracy and efficiency BIM offers.

This necessitates strategic investments in training and technology to harness these long-term benefits. It is crucial for Saudi Arabia to implement a comprehensive BIM framework that covers all phases of a project's lifecycle, standardising data exchange practices and lifecycle cost calculations to bridge the existing gaps in knowledge and application. Moreover, policy-driven incentives could be crucial in hastening BIM adoption and integrating it into mainstream construction practices.

5.11 Chapter Summary

This chapter has focused on the qualitative data analysis and discussion derived from interviews with industry experts, stakeholders, and practitioners in the KSA. The analysis emphasises the impact of BIM on LCC within the Saudi Arabian construction sector. Stakeholders' perspectives on BIM, LCC, and their interplay are explored. The chapter identifies several key findings including the critical issue of stakeholders' limited familiarity with BIM, the anticipated role of the Saudi Arabian government in implementing BIM, and the need for regulations in the country.

Challenges associated with BIM adoption are discussed such as a lack of clear standards, training costs, and data availability. The chapter's thematic analysis is visualised through mind maps that hierarchically structure the discussion around four primary themes: integration of BIM with LCC, contract types and LCC, application of BIM and associated risks, and the benefits of BIM including efficiency and coordination.

Chapter Five provides valuable qualitative data analysis findings, which will serve as a foundation for the case studies and simulations explored in the following chapter (Chapter Six). Chapter Five is linked to Chapter Six as it will help understand the real-world implications of BIM adoption.

Chapter 6

Qualitative Data Analysis - Case Studies and Simulation

Parts of content from this chapter has been published:

An analysis of the qualitative impacts of Building Information Modelling (BIM) on Life Cycle Cost (LCC): A qualitative study on Saudi Arabia.

Alasmari, E., Martinez-Vazquez, P. and Baniotopoulos, C., 2023. An Analysis of the Qualitative Impacts of Building Information Modelling (BIM) on Life Cycle Cost (LCC): A Qualitative Case Study of the KSA. *Buildings*, *13*(8), p.2071.

6 Chapter Six: Qualitative Data Analysis - Case Studies

6.1 Introduction

The main purpose of this chapter is to present the qualitative data analysis results. In this chapter, two types of qualitative data analysis results are presented, case study. In the case study analysis, four cases are selected from different construction sites in the KSA: residential, football stadium, cultural centre, and hospital emergency unit. This chapter also presents the simulation results. Based on four cases, one case is selected (residential) and the simulation analysis.

6.2 Case Study Analysis

6.2.1 Background of the Cases

The Saudi construction industry is the largest in the Middle East and has had significant growth since 2015. According to Shash and Habash (2020), the industry contributed to a total gross outcome of 6.35% between 2011 and 2015, which rose to 7.05% in 2020, implying a jump in value from US$105.6 billion in 2015 to US$148.5 billion in 2020. The most common types of contract used in Saudi Arabia are the lump sum and unit price, with owners and contractors using both contracts in about 94% and 91% of their projects, respectively (Shash and Habash, 2020). Government owners typically use these two types of contracts. In essence, the government purchasing regulations demand that all agencies use lump sum or unit prices in their purchases including construction projects (Alhazmi *et al*., 2021). Their popularity is due to how owners allocate budgets for building investments. Owners believe that the allotted budgets are sufficient, and they desire to gain commitment from contractors, but due to poor quality and ambiguity, numerous change orders typically drive costs higher, thereby developing conflicts and disputes. For instance, increasing funding for government projects is difficult and time-consuming (Alhazmi *et al*., 2021). The majority of contractors (60%) and the majority of owners (60%) experience disputes at least monthly, but most government owners (55.89%) report a dispute each month (Shash and Habash, 2020). Contractors also tend to subcontract, which further creates room for more conflicts and disputes. In addition, private owners break their projects into various packages, awarding each package to a contractor and this also creates room for more disputes and conflicts. In addition, there are ambiguities in project documents, which are exacerbated by poor project management practices (Shash and Habash, 2020). In fact, the dispute frequency within the Saudi construction industry is higher compared to similar industries in other countries.

In the Kingdom of Saudi Arabia, irrespective of the contract type chosen, there are five implementation phases of construction projects: planning, design, construction, operation and maintenance, and renovation. During the planning stage, the feasibility of the project is conducted as well as developing objectives and goals (Alhazmi *et al*., 2021; Hamida and Hassanain, 2020; Cao, Kamaruzzaman and Aziz, 2022). It is a critical stage of the project and the team is tasked with identifying timelines and establishing scope and costing parameters (Mering *et al*., 2017; Sarhan *et al*, 2019; Alotaibi, Sutrisna and Chong, 2016). The budget is estimated. The design phase entails designing the blueprint for the project, which includes coming up with the project implementation process including engineering specifications (Alhazmi *et al*., 2021; Hamida and Hassanain, 2020; Cao, Kamaruzzaman and Aziz, 2022). The construction phase is the actual construction process, which entails implementing the project design. It entails the actual implementation and team involvement in accomplishing the project goals, tasks, and milestones (Alhazmi *et al*., 2021; Hamida and Hassanain, 2020; Cao, Kamaruzzaman and Aziz, 2022). The operation phase is once the project is completed and has served its intended purpose. For example, a building will house businesses and bridges will be used for providing vehicle transit. The operation phase allows the investor to recoup the initial cash outlays (Albogamy and Dawood, 2015; Badran, AlZubaidi and Venkatachalam, 2020; Tomek and Matějka, 2014; Wetzel and Thabet, 2015). The maintenance phase is done during the operation phase to ensure that the final product is optimally providing the service it was intended for without compromising quality and safety (Alhazmi *et al*., 2021; Hamida and Hassanain, 2020; Cao, Kamaruzzaman and Aziz, 2022). See Figure 56.

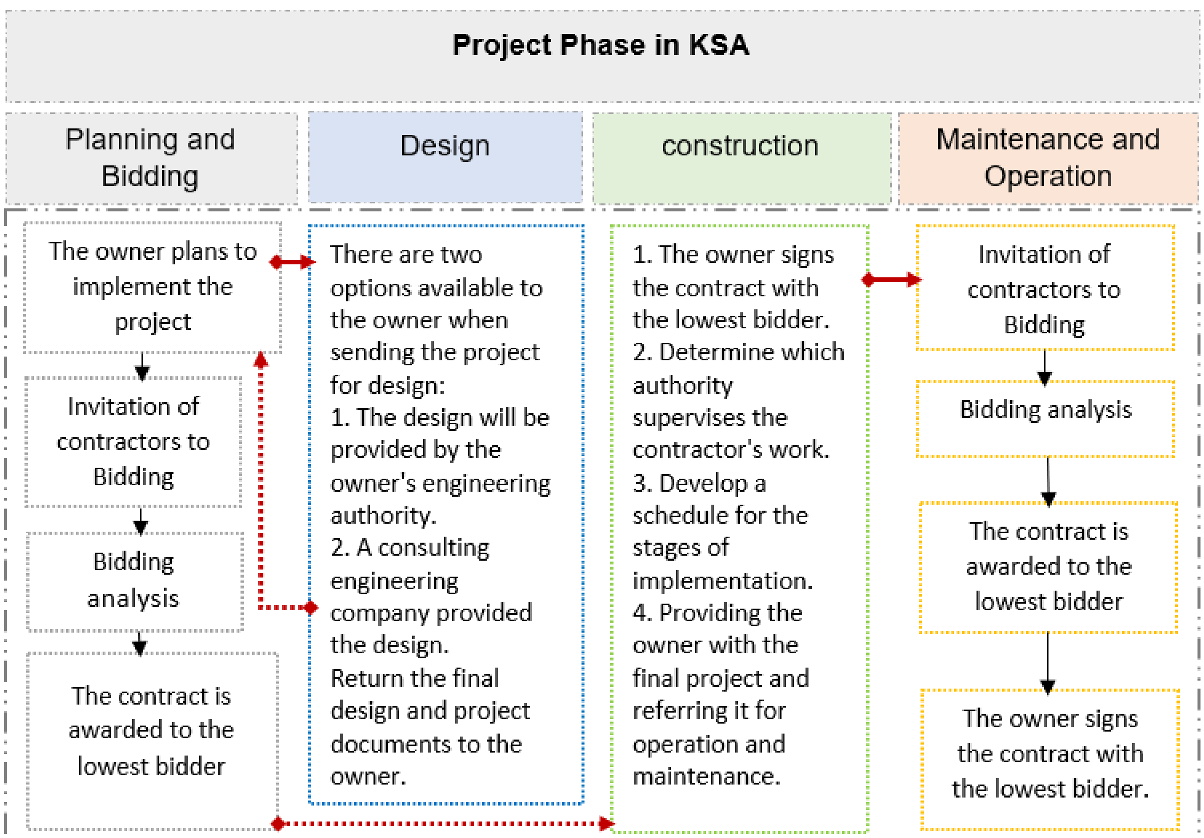


Figure 56: Process of implementing the project in the KSA

6.2.2 Methodology of The Cases

This Chapter examines diverse case studies across various construction sites; four projects were selected based on their diversity in function and scale, encompassing a residential project, a football stadium, a cultural centre, and a hospital emergency unit. These projects represent a broad spectrum of the Saudi construction industry, providing a comprehensive insight into the application of BIM across different types of construction activities.

The study employs an exploratory sequential mixed-methods research design, beginning with a quantitative analysis followed by a qualitative deep dive. This methodological approach enables a layered understanding of BIM's impact, facilitating the integration of varied data and analytical perspectives. The choice of different settings underscores BIM's adaptability and relevance, with each case study exemplifying potential enhancements in LCC and sustainability.

The rationale for this project lies in its pertinence to Saudi Arabia's evolving construction sector, which increasingly utilises BIM technologies. This research supports national initiatives aimed at optimising LCC and boosting sustainability, contributing to the economic and environmental goals of Saudi Arabia's development strategy.

6.2.3 Case Study 1: Residential Project (900 units) in the KSA

As a precaution, the author has provided a description of the study rather than a specific name for the project. This is to protect the privacy of both the project and the owners involved to maintain a high level of confidentiality. Any terminology that could reveal the project identity has been substituted with a generic term. The case study is a residential development project for 900 residential structures equipped with essential equipment for building operations. Moreover, this project involves the construction of 900 residential units including fences, external gates, and groundwater tanks, as well as the settlement of the site including determining the levels of housing units in accordance with the levels of the roads for the entire project. See Figure 57.

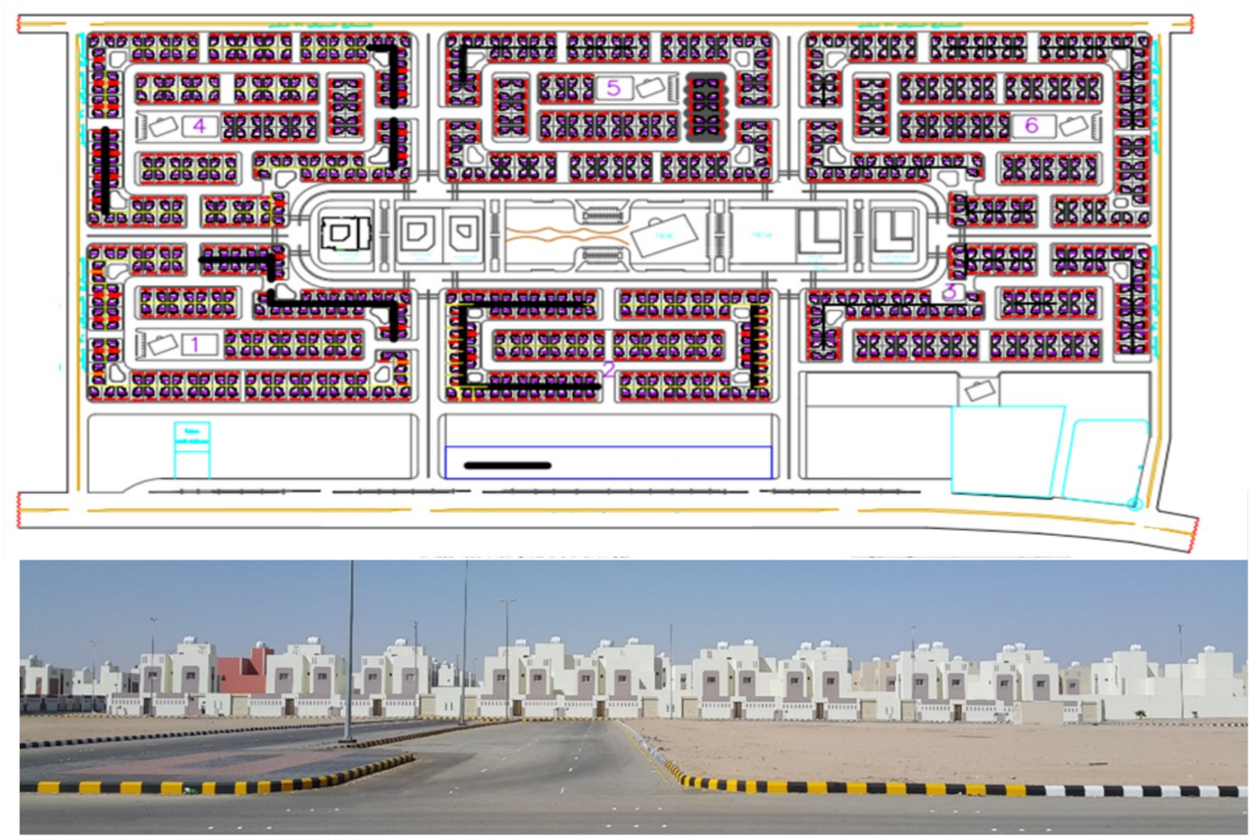


Figure 57: Site plan and panoramic elevation of the project

A residential unit has one and a half floors. The residential unit consists of 3 bedrooms, a sitting room, a living room, three bathrooms, and a kitchen and the building area for the unit of around 294 m². A reinforced concrete slab was used in this construction technique. Concrete 350 kg/m³ One-way Hardy Slabs are made up of concrete blocks of 25 mm that are inserted into each other to form a slab. In order to secure these blocks once they are stacked, formwork is arranged around them and reinforcement is placed between them. The wall is connected horizontally every 60 cm with a hollow block and two 8 mm iron bars. See Figure 58.

Figure 58: Design of the residential unit's ground floor, first-floor plan, and perspective

Based on the contract deadline, the project should have been finished by 2012. However, it was delayed by two extra terms resulting in a delay of 3 years. As a result of the expansion of the scope of work, the project cost increased. For the first extension period, the owner of the project agreed to extend it for 16 months; due to this decision, the project budget increased by $7,019,257.98. The project was also extended for an additional 18 months due to the increase in the contract terms for some items not covered under the contract and this cost amounted to $1,635,840.50.

During 2015, the project was delivered with an increase in the contract implementation period of 1003 days, which represents about 92.87% of the basic contract period and a 9.89% increase in costs. In the process of completing this project, it is important to note that a significant reason for the delay in its delivery was the need for a thorough analysis and study of the project, which led to many changes and additions throughout the process. See Table 23.

Table 23: Information on implementing the project

Information on project			
Project Contract Value	**Contract Period**	**Final Project Value**	**Increase of Cost**
$86,740,933.6	1080 Days	$95,327,964.06	9.89%
Consultant Contract Value	**Area**	**Type of Contract**	**Level of BIM Used**
$5,426,034	1,185,000 m²	Unit Price	2D
Contract Signing Date	**First Receipt of Project according to Contract**	**Final Receipt of Project**	**Extra Time of Contract Period**
26/07/2009	17/07/2012	16/04/2015	1003 Days

6.2.3.1 The Disadvantage of not Using BIM

As a result of not using BIM, this project had increased in cost, time, and citizen benefit from the housing. In this case, the project underwent several changes during its design and implementation phases, which are listed below:

1. Approximately **$8,657,721.81** was spent on the new works that do not have a parallel in the contract. See Table 24.
2. As a result of the lack of an optimal topography survey and level survey of the site and the lack of a 3D model of the survey area, the owner of the project added a new item (retaining walls). The new item was implemented by square meters of reinforced concrete (reinforced concrete foundation, retaining walls). In order to meet the requirements of the difference in level between the housing units, this revised clause had been implemented.
3. Due to the lack of use of BIM, an item was added (automatic vertical rolling garage doors size 3*2.7) for 900 units that needed to be remembered when engineering calculated quantities manually.
4. The owner of the project added a new item (a wooden frame to hold the window air conditioner and kitchen hood) The specifications are made of solid Swedish wood with a thickness of one inch and a width that matches the wall thickness for 900 units.
5. The project owner added to the project (Cast Iron Cover). Cast iron is used in the cover of tanks with 60 x 60 cm dimensions, weighing no less than 80 kilograms for 900 units.
6. The owner of the project added concrete-coloured tile flooring for outdoor use to the project. Supply and installation of concrete colour tile flooring for outdoor use that has 40 x 40 x 4 cm dimensions, to create a walking path with a normal cement layer ten centimetres below it.

Table 24: Information on the cost of changes in scope of the project

Changes in scope of the project	Cost
The value of the additional work is unparalleled in the contract	$7,019,257.98
The value of the project increases	$1,635,840.50
Project savings value	$0.00
Total	**$8,655,098.48**

According to the case study, the delay was caused mainly by inadequate planning by the project owner and a lack of as-built drawings during the study and design phases. As a consequence, the cost of project elements increased. Moreover, the process of offering the project as a public competition and procuring it introduced a strong focus on the cost of bids. This focus neglected the effects of technical data on the project and the bidders. Consequently, the orders for the project when it was under implementation frequently changed.

The absence of BIM in mega-project residential projects, such as a 900-unit development in the KSA, introduces significant inefficiencies and potential for error throughout the project lifecycle. Without the centralised coordination afforded by BIM, interdisciplinary clashes frequently occur, necessitating costly and time-consuming rework during construction phases. Such challenges are compounded by inefficient communication among stakeholders—architects, engineers, contractors—which often leads to misinterpretation of design intentions and subsequent delays and errors in execution.

Furthermore, traditional 2D visualization methods fall short in conveying complex architectural and engineering concepts to non-technical stakeholders, increasing the likelihood of revisions due to misunderstandings. BIM’s automated clash detection capabilities are crucial for preempting physical conflicts in design, a process absent in traditional methods, where such issues may remain undetected until the construction stage. Additionally, BIM facilitates the integration of heterogeneous data sources, enhancing decision-making and operational efficiency across the project's life, from inception through to facility management.

The lack of BIM not only hampers immediate project execution but also affects long-term facility management, where access to comprehensive, accurate digital documentation can significantly streamline maintenance and operational tasks. Consequently, the omission of BIM technology in such projects can severely diminish overall productivity and increase the LCC of building projects, underscoring the pivotal role of digital modelling tools in contemporary construction management paradigms.

6.2.4 Case Study 2: Implementation of a Football Stadium in the KSA

The stadium project is located in Riyadh city in the Kingdom of Saudi Arabia, which was implemented in the year 2020. The project consists of several components (a VIP stage, bleachers, players' dressing room, players' lounge, control room, commentary box, bench, stadium manager's office, and toilets). The capacity of the stadium is 336 seats for the crowd, 22 seats for journalists, and 30 seats for VIPs. This project has two floors. The ground floor consists of the VIP entrance, VIP lounge, coffee room, offices, storerooms, two waiting areas, changing rooms, showers, the toilets, and a meeting room for players' and match officials' needs. The first floor is divided into a reception hall for VIP audiences, a grandstand for spectators, toilets, and a platform where winners receive their awards after the ceremony. Further, the stadium building space area is approximately 2736 square meters. See Figure 59.

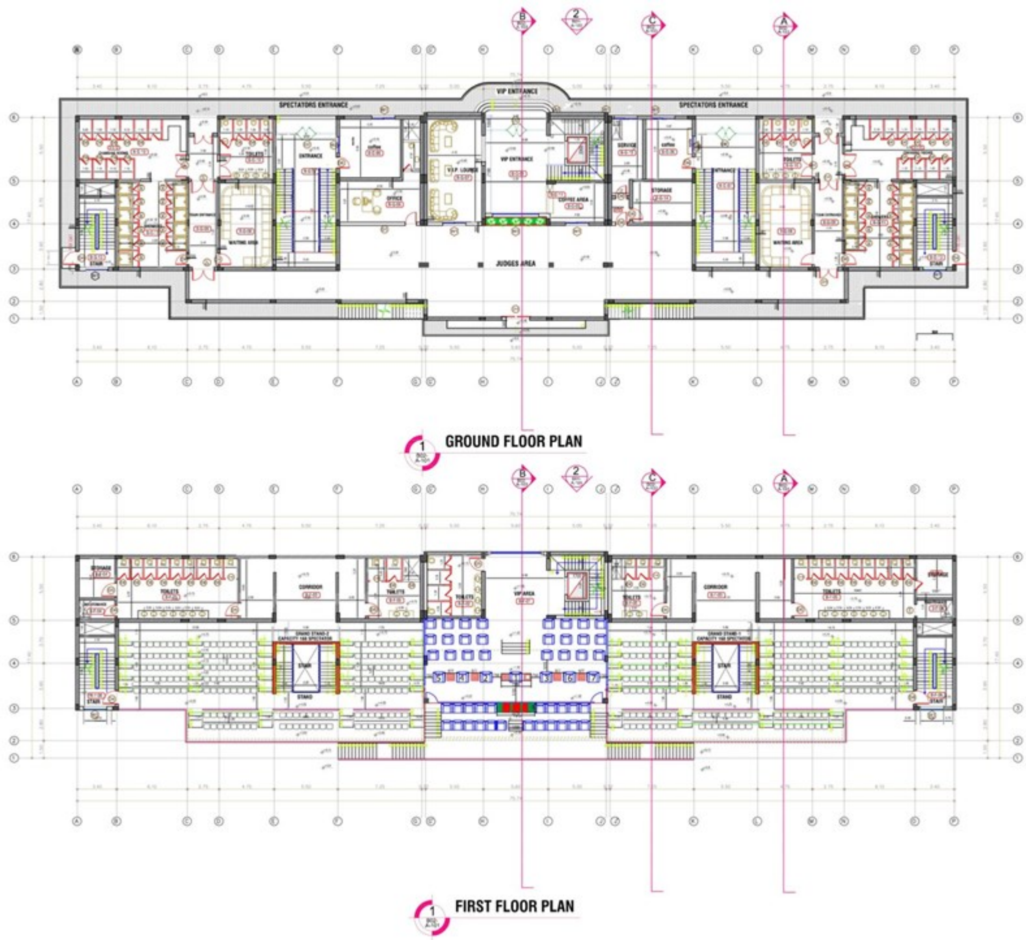


Figure 59: Design of the ground floor and first floor

Construction components of the project include reinforced concrete for the grandstands, which is made up of 350 kg/m3. Additionally, concrete slabs consisting of 350 kg/m3 One-way Hardy Slabs are formed by inserting concrete blocks of 25 mm into one another to form the ceiling slab. Furthermore, hollow cement concrete blocks with a diameter of 20 cm were used in the construction of the walls. Galvanised steel umbrellas covered the grandstands measuring 150 x 150 x 3 cm. These were covered with polyethylene fabrics resistant to temperatures up to 80 degrees Celsius, wind speeds up to 120 km/h, and protection from ultraviolet and radiation up to 95%. A 60% reflective secure glass façade with a thickness of 20 mm was used in the VIP area. See Figure 60.

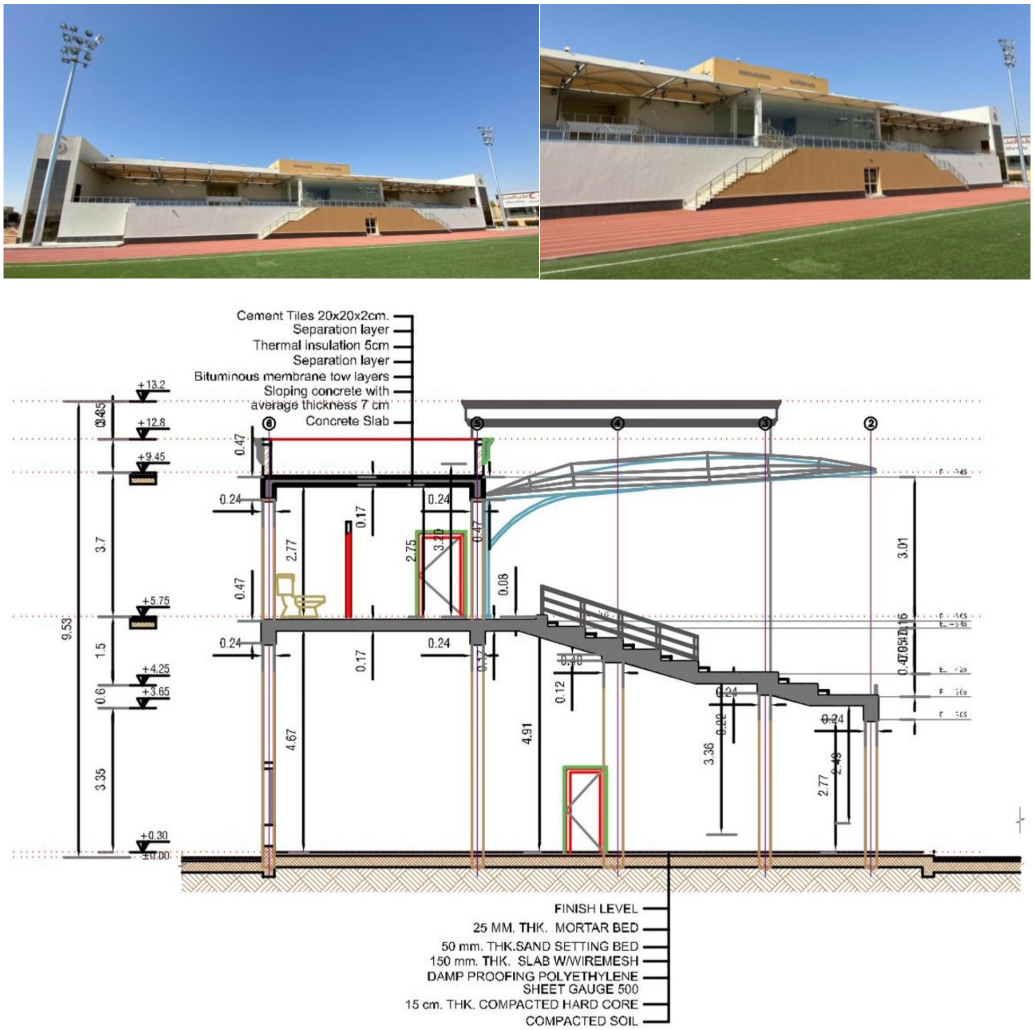


Figure 60: Perspective of football stadium and section to clarify building levels

In this case, the project was based on public bidding. One of the companies won the contract because they offered the lowest bid. Based on the terms of the primary contract, the project was expected to be completed in 2019. Nevertheless, a full year's delay occurred in the project and the scope of work had to be adjusted due to the lack of study of the project to meet the stakeholder's requirements. Due to the expansion of the scope of work, the cost of the project increased. This decision resulted in a $201,396.5 increase in the project budget as a result of the decision. See Figure 61.

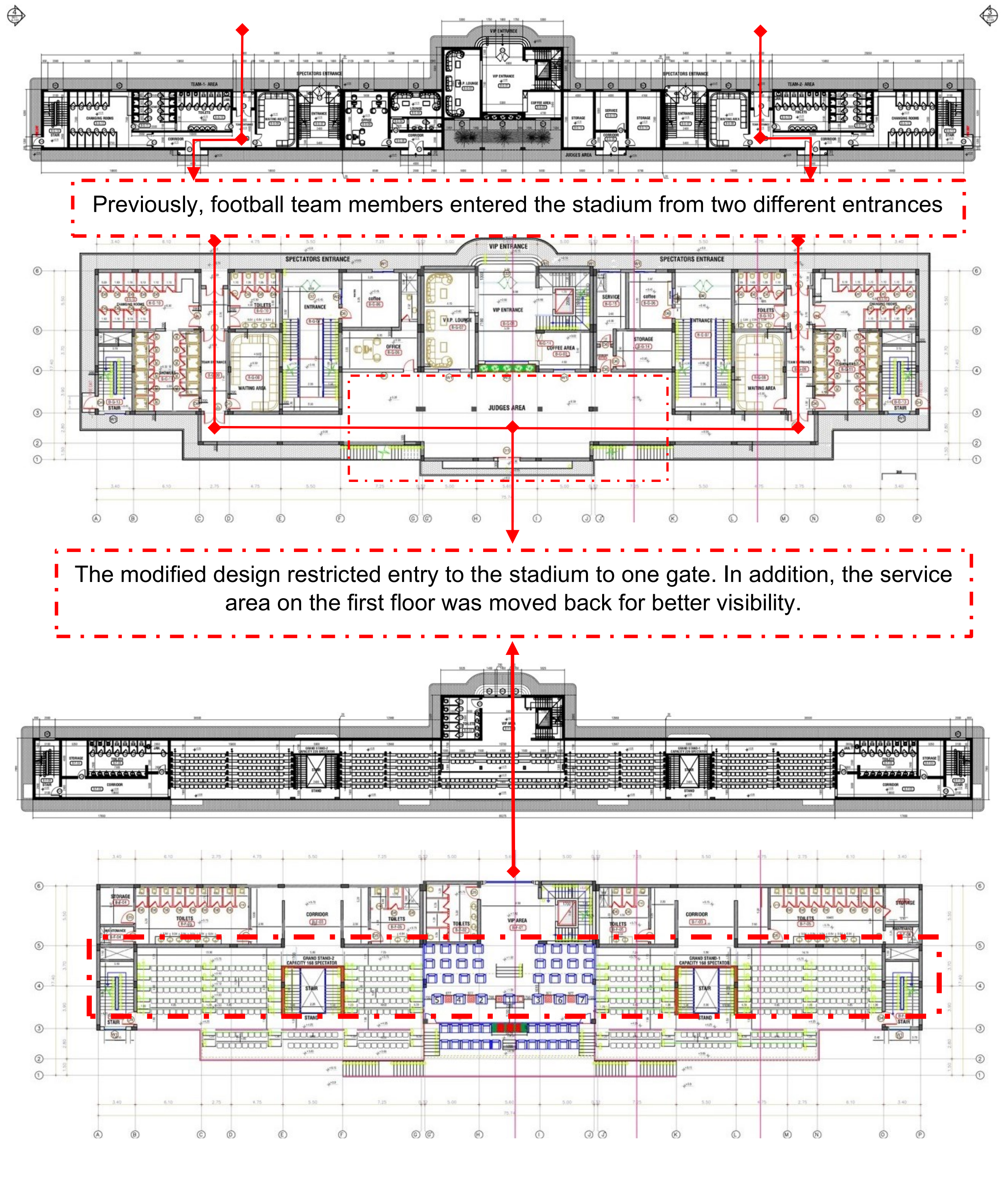


Figure 61: Changes made between the initial and approved design

The project was delivered in 2020 with an increase in the contract implementation period of 360 days, which represents approximately 100% of the main contract period, as well as an increase of 21.14% in basic costs as a result of the contract implementation period extension. It is important to note that one of the factors behind the delay in completing this project was the need for a comprehensive analysis and study that resulted in changes. See Table 25.

Table 25: Information on project implementation of the stadium

Information on Project implementation of the Stadium			
Project Contract Value	**Contract Period**	**Final Project Value**	**Increase of Cost**
$952,630.23	360 Days	$1,154,026.73	21.14%
Consultant Contract Value	**Area**	**Type of Contract**	**Level of BIM Used**
Consultancy by owner's engineering staff	2736 m²	Unit Price	2D
Contract Signing Date	**First Receipt of Project according to Contract**	**Final Receipt of Project**	**Extra Time of Contract Period**
19/02/2018	14/02/2019	09/02/2020	360 Days

The implementation of the football stadium in Riyadh, Saudi Arabia faced several challenges and delays due to various factors. One of the main causes of the delay was the lack of skilled engineers during the project design phase, which led to mistakes in understanding and meeting the project requirements. As a result, the scope of work had to be adjusted to align with the stakeholders' needs.

The use of BIM could have greatly benefited the project. BIM is a digital representation of the physical and functional characteristics of a facility. It allows stakeholders to visualise the project in a comprehensive manner, aiding in decision-making and ensuring that the design meets the required specifications. By utilising BIM, the stakeholders would have had a clearer understanding of the project's vision, enabling them to make informed decisions and select the most suitable design for the stadium.

In this particular case, the project's design was incompatible with the requirements of a sports facility. Therefore, modifications had to be made to the scope of work to align it with the stakeholders' needs. This adjustment resulted in an increase in the project budget, amounting to $201,396.5. Despite the challenges and delays, the project was eventually completed in 2020, with a contract implementation period extension of 360 days, representing a 100% increase compared to the original contract period.

The basic costs also increased by 21.14% due to the prolonged implementation period. The one-year delay in the project's completion had an impact on the overall budget. As mentioned earlier, the delay resulted in adjustments to the scope of work to meet the stakeholders' requirements. These scope modifications often lead to additional costs, which contributed to an increase in the project budget.

In the case study, it is stated that the project budget increased by $201,396.5 as a result of the decision to expand the scope of work. This increase can be attributed to various factors, such as prolonged construction duration, extended labor and material costs, revised design plans, and potential penalties or fees associated with the delay.

Additionally, the contract implementation period was extended by 360 days, representing approximately 100% of the original contract period. With the extension of the construction timeline, there are additional expenses associated with labor, equipment, and site management that can contribute to the increased budget.

The 21.14% increase in basic costs mentioned in the case study also indicates the financial impact of the contract implementation period extension. This increase accounts for the additional time and resources required to complete the project beyond the initially planned duration.

Overall, the one-year delay in the project's completion resulted in an increase in the project budget, affecting various aspects of the construction process and necessitating adjustments to accommodate the extended timeline and modified scope of work.

In conclusion, the implementation of the football stadium in Riyadh, Saudi Arabia faced delays and increased costs due to the lack of skilled engineers during the design phase and inadequate study of the project requirements. The use of BIM could have helped mitigate these issues by providing a comprehensive understanding of the project and facilitating better decision-making.

6.2.5 Case Study 3: King Abdulaziz Center for World Culture (Ithra) in the KSA

The project was completed in the King Abdulaziz Center for World Culture in Dhahran city in the Kingdom of Saudi Arabia in 2016. The project consists of several components including one tower building with 18 floors (a variety of cultural amenities, keystone, and plaza including an auditorium, a cinema, a library, an exhibition space, a museum, a cinema, an innovation forum, an oasis, a Great Hall, and an archive). It was designed in 2007 by the architectural company Snøhetta. Consequently, integrating the design and implementation phases of such a building took considerable time. It also achieved the LEED gold requirement of sustainability. See Figure 62 and Figure 63.

Figure 62: Perspective of King Abdulaziz Center for World Culture

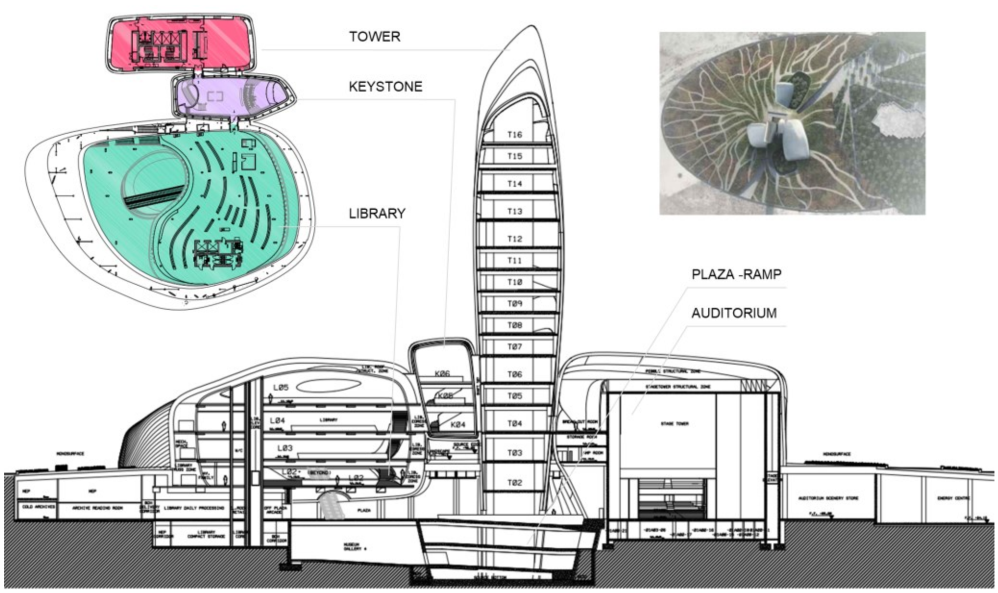


Figure 63: Ground floor and master section to clarify building levels

The King Abdulaziz project utilised BIM during both the design and implementation phases. As a result, the project final cost was as expected and there was no delay in the implementation schedule. In view of the fact that scheduling is so imperative to the success of a project, it is essential that schedules be properly classified. This is so they can be included in the estimation. Especially with larger projects, calculating all the elements from a 2D plan can be time-consuming. Consequently, BIM enabled the design process to be more collaborative and allowed for the creation of 3D, 4D, 5D and 6D in this project. See Table 26.

Table 26: Information on implementing the project (Ithra)

Information on Project King Abdulaziz Center for World Culture (Ithra)			
Project Contract Value	**Contract Period**	**Final Project Value**	**Increase of Cost**
$400,000,000	2008 - 2016	$400,000,000	0%
Consultant Contract Value	**Area**	**Type of contract**	**Level of BIM Used**
Consultancy by Saudi Aramco	100000 m²	Unit Price	4D, 5D, 6D
Contract Signing Date	**First Receipt of Project according to Contract**	**Final Receipt of Project**	**Extra Time of Contract Period**
20/05/2008	20/10/2016	20/10/2016	0

The structure of the building uses polygonal steel grids enclosed by steel supports and reinforced concrete slabs in an envelope structure. Seele (2022) indicated that individually shaped stainless-steel tubes are tightly wrapped around the subtle curves of the building exterior cladding, which totals 350 kilometres (Stainless steel tube façade 30,260sqm, Standing seam facade 28,600sqm). Accordingly, Seele (façade specialists) completed most of the construction work before moving each phase of the implementation process to the preparation phase. The planning process included detailing a 3D model, defining parameters, managing risks, integrating material expertise, and integrating logistics expertise. See Figure 64.

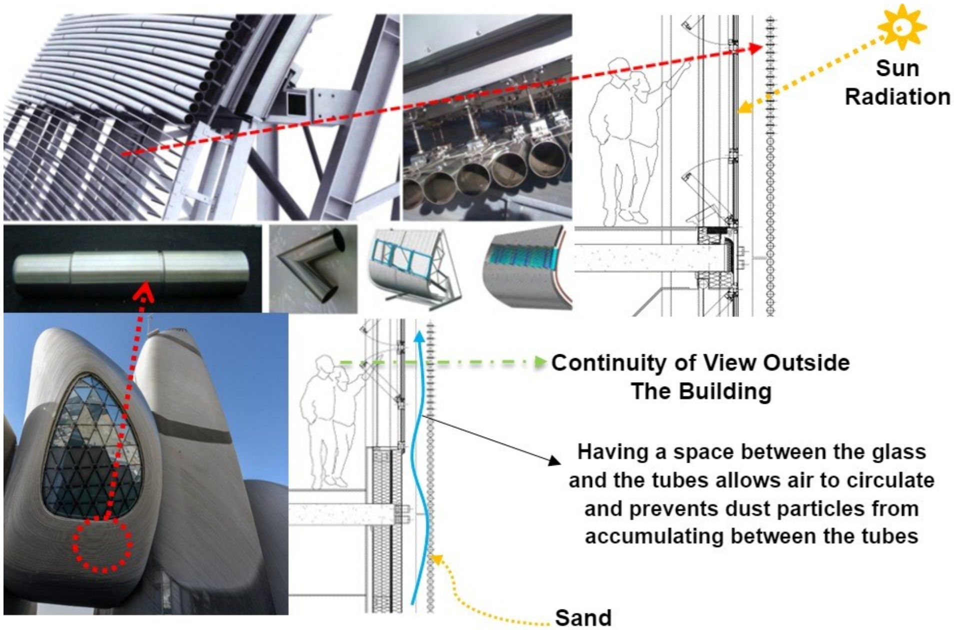


Figure 64: Proposed design for the building exterior façade

The construction of Ithra employs an array of materials that underscore a commitment to sustainability and innovation. The structural foundation is conventional, utilising steel and concrete, but it is in the specialised materials where a distinct focus on ecological responsibility is seen. TECU® products, for example, are fabricated entirely from recycled copper. This is significant given copper's unique characteristics: it is not only durable, but also fully recyclable, aligning with the principles of the Circular Economy. Similarly, the inclusion of Glued Laminated Timber from HESS TIMBER demonstrates a commitment to renewable resource management. Wood, as a construction material, is not just natural and renewable, but also completely recyclable. Such choices reflect a conscious effort to mitigate the environmental impact of building materials. Lighting is addressed through the use of LED products from Cooledge Lighting, which are generally more energy-efficient than traditional lighting systems.

The building exterior is equally impressive, featuring a façade that consists of 30,260 square meters of stainless-steel tubing. These tubes, with a total length of 350km, are 3D-curved, further contributing to the building aesthetic and functional objectives. Overall, the material selection for Ithra represents a balanced integration of durability, aesthetic appeal, and ecological responsibility. See Figure 65.

Figure 65: Internal façade TECU® Copper and HESS TIMBER Wood product

Throughout the design phase, it is evident that the project was very complex. As a result of utilising BIM during the design stage, some collisions were detected and avoided. This resulted in cost savings although the amount of the savings is difficult to estimate. For this project, several engineering software-compatible BIM were used, including Revit software and Tekla software, to coordinate the structural, mechanical, and electrical systems. See Figure 66.

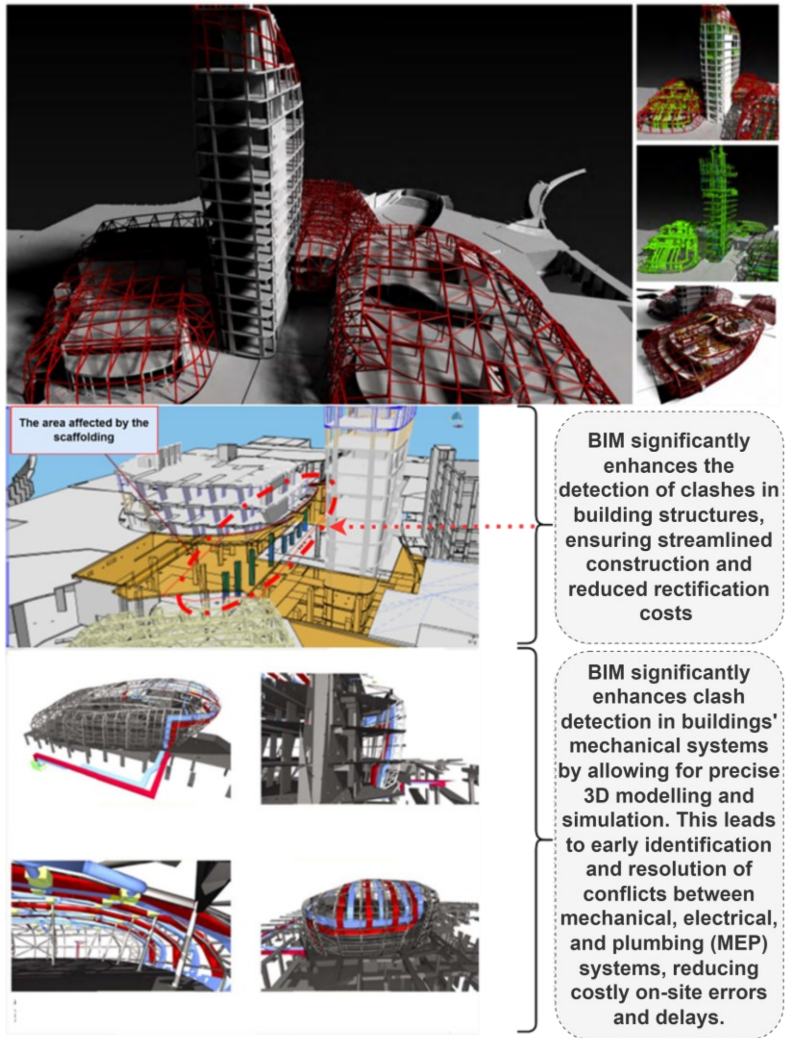


Figure 66: BIM collaboration to avoid clashes between engineering systems

In the King Abdulaziz Center for World Culture, the application of BIM during the design phase was instrumental in identifying and mitigating conflicts across various engineering systems, though quantifying the precise cost savings remains challenging. The integration of several BIM-compatible engineering tools, such as Revit and Tekla, facilitated the coordination of structural, mechanical, and electrical systems. This process not only prevented potential clashes but also supported the project in achieving LEED Gold certification—a globally recognized benchmark for sustainable buildings. This prestigious certification underscores the center’s commitment to environmentally responsible design, construction, and operational practices, including energy and water conservation, waste management, and the utilization of eco-friendly materials.

BIM’s role was pivotal, serving as a digital representation of the building's physical and functional characteristics, which enhances the collaborative design, coordination, and simulation efforts. For Ithra, BIM enabled the creation of 3D, 4D, 5D, and 6D models, improving visualisation, clash detection, cost estimation, and scheduling. This comprehensive modeling facilitated a streamlined and delay-free project execution. Moreover, sustainability and ecological responsibility were central to the material selection process. The use of recycled copper products, such as TECU®, for the structural foundation, and Glued Laminated Timber from HESS TIMBER—a renewable resource—alongside energy-efficient LED products from Cooledge Lighting, exemplifies the project’s dedication to minimizing environmental impact.

The complexity of the project required meticulous collaboration among various engineering disciplines. Through the use of BIM software like Revit and Tekla, the project team effectively coordinated the integration of structural, mechanical, and electrical systems, significantly reducing clashes and conflicts. This proactive approach to clash detection was crucial in avoiding unnecessary rework and delays during construction, thereby upholding the project’s efficiency and cost-effectiveness.

6.2.6 Case Study 4: B-1 Ward Renovation of Hospital and Emergency Multidisciplinary Unit in the KSA:

The project involves the renovation of an existing role in a hospital. In this project, there is a stage of removal and a stage of implementation. In the removal phase, the existing construction in B-1 Ward will be demolished and removed including partitions, doors, internal finishes, fixtures and accessories, casework assemblies, electrical conduits, cables, demolition of the plumbing system, HVAC, and devices to accommodate the redesigned layout. In accordance with the new design, the floor is rebuilt including civil works such as internal partitions, mechanical and electrical installations, and fire extinguishing systems. This project is being implemented at the moment, and it is expected that the project will cost $701,624.75, which will take two years to complete, as shown in Table 27.

Table 27: Information on renovation of hospital

B-1 Ward Renovation of Hospital and Emergency Multidisciplinary Unit			
Project Contract Value	**Contract Period**	**Final Project Value**	**Increase of Cost**
$701,624.75	2 years	Under implementation	N/A
Consultant Contract Value	**Area**	**Type of Contract**	**Level of BIM Used**
Consultancy by the staff of the Hospital	1680.33 m²	Unit Price	4D, 5D
Contract Signing Date	**First Receipt of Project according to Contract**	**Final Receipt of Project**	**Extra Time of Contract Period**
10/01/2022	10/01/2024	N/A	N/A

Design and implementation of hospital systems are, undoubtedly, one of the most complex engineering systems. As such, they need to be carefully studied and planned in light of the limitations and overlap among multiple services. In this project, the engineers adopted the application of BIM during the design phase. This helped avoid limitations such as incorrect specifications, errors in drawings, changes in the scope of work, omissions, and clashes between mechanical and structural systems. Additionally, it avoided delays in decision making, delays in bids, unclear instructions, and poor communication and coordination between engineers.

To record the implementation work items, Revit software was utilised to raise the project in three dimensions and export project quantities to Excel as 5D. This was done to facilitate the process without generating errors in quantities. In addition, it provided integration of information related to the procedures associated with the project, facilitating its updating and retransferring. This integration works to improve the effectiveness of the flow of information. See Figure 67.

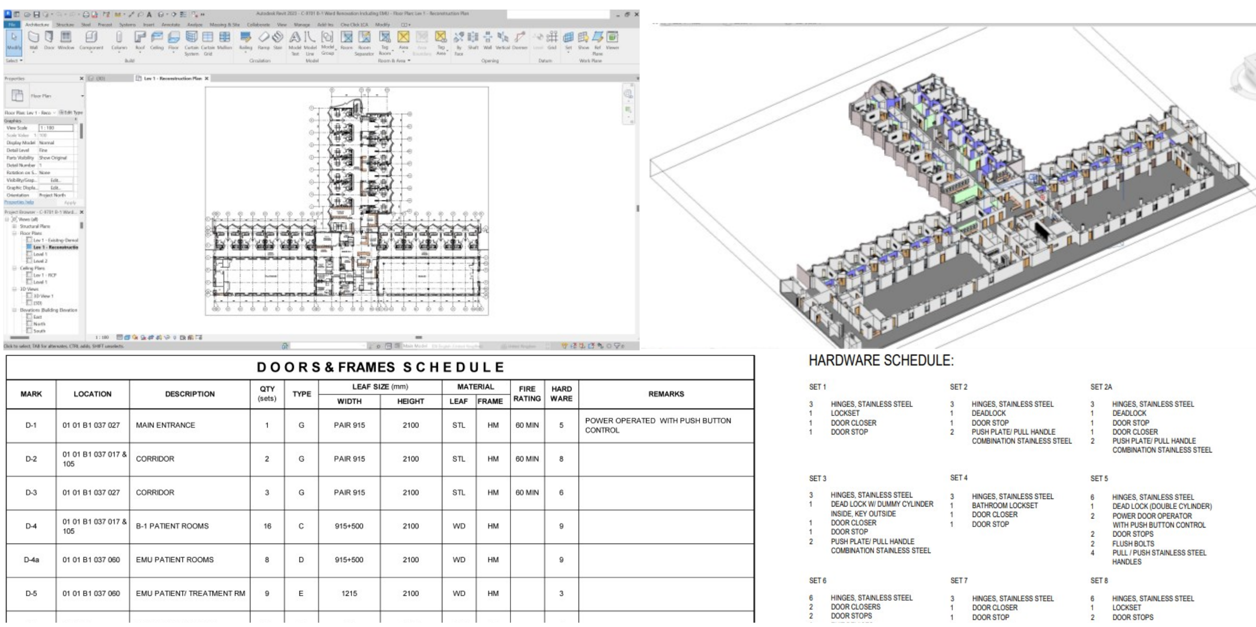


Figure 67: Design of the project using Revit-Software with Bill of Quantities (BoQ)

In this project, collisions and clashes were detected using Revit and Navisworks. Several clashes and errors were identified and corrected. See Figure 68.

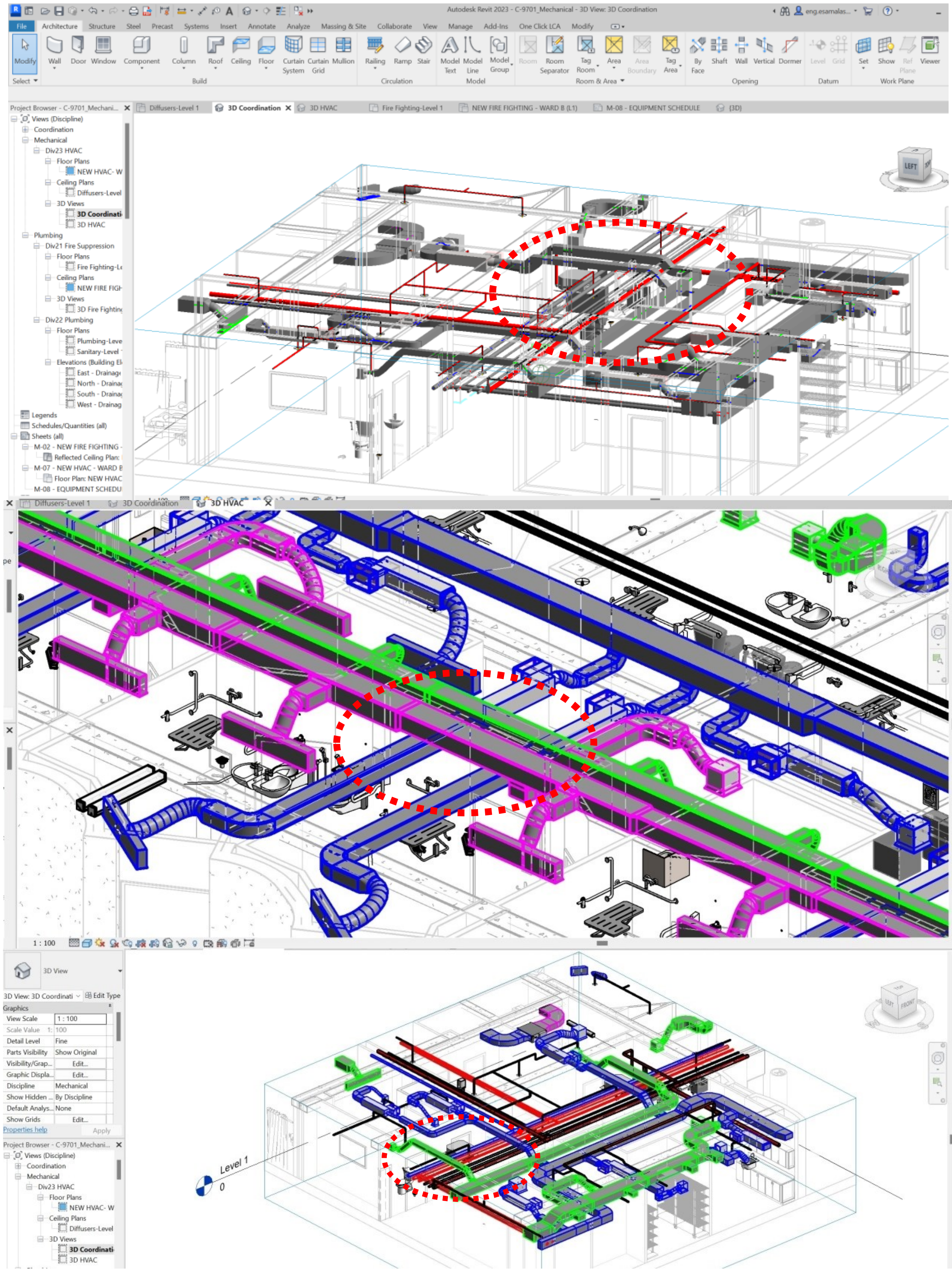


Figure 68: Different disciplines are represented in the 3D model to avoid a clash

In Figure 69, a 5D BIM model for this project is illustrated, which is capable of displaying the properties of the furniture or materials as well as integrating them with other software to calculate the LCC and sustainability of the project.

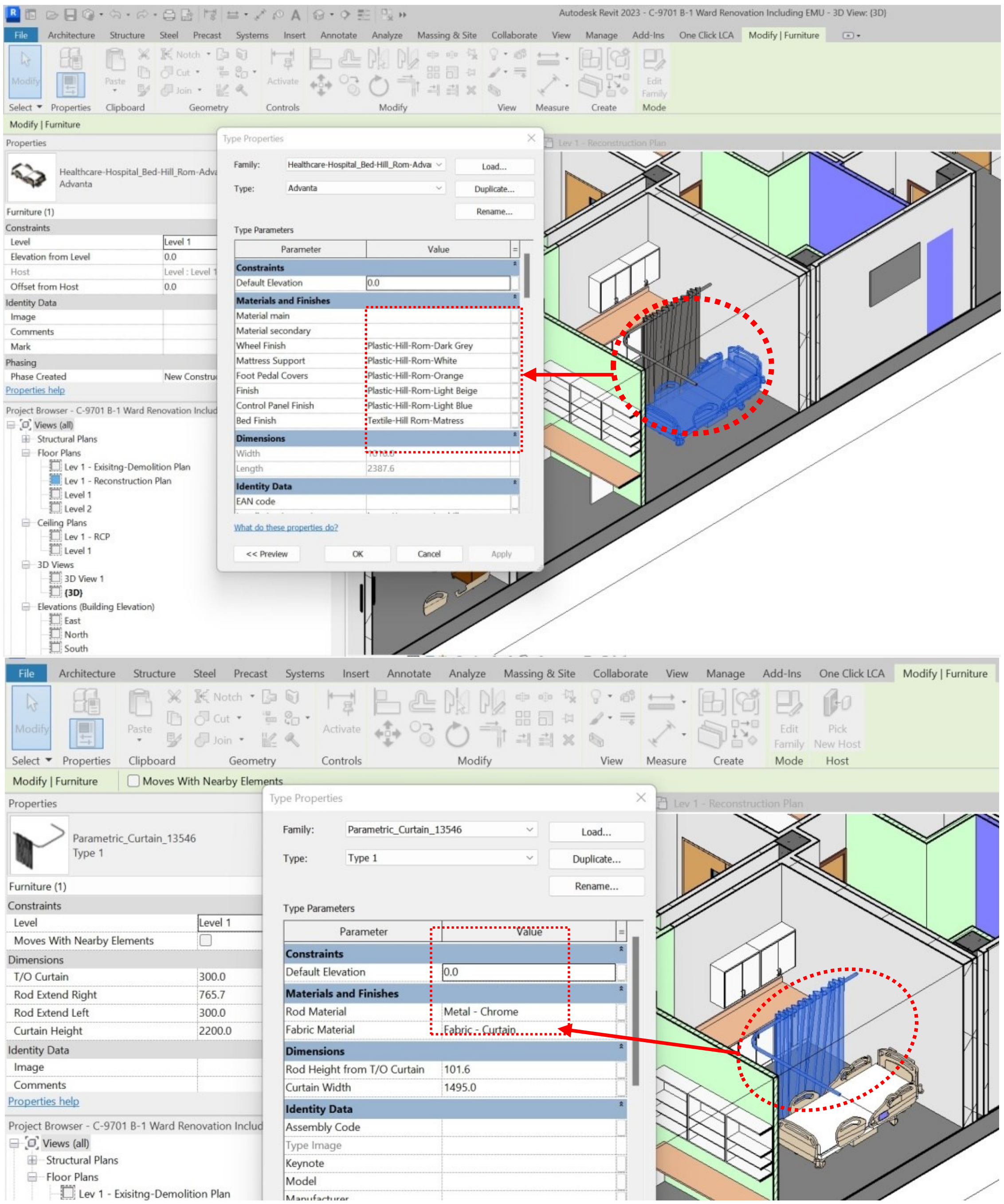


Figure 69: Materials are described using a detailed element in the BIM model

The pivotal role of BIM and specialized software in enhancing the efficacy of the B-1 Ward Renovation project cannot be overstated. These technological tools were instrumental in several key aspects of the project's success. Initially, the adoption of BIM software, including Revit and Navisworks, enabled the project team to construct a detailed 3D model of the renovation. This model was crucial for identifying and resolving clashes between various building systems—mechanical, electrical, and structural—early in the design phase. The early detection of these potential conflicts allowed for proactive solutions, thus mitigating costly and time-consuming rework during later stages of the project.

Further, BIM software greatly enhanced coordination and communication across different disciplines involved in the project. The visual and interactive nature of the 3D model facilitated a clear understanding of the project's design and intent among all stakeholders—engineers, architects, contractors, and consultants. This shared understanding helped in minimizing misunderstandings and bolstered collaboration, driving the team towards a unified goal. Moreover, the insights and data provided by the BIM software supported informed decision-making. Stakeholders could visualise the project in intricate detail, which enabled more precise and effective decisions regarding design modifications, material selections, and system configurations. This detailed visualization not only optimized the project's functionality and efficiency but also enhanced its overall performance.

The integration of BIM with specialised software, such as Excel, for accurate quantity extraction marked another technological advancement. This combination allowed for automatic extraction of detailed information about building components and materials from the BIM model, eliminating manual calculations and reducing the likelihood of human error. This seamless data transfer between the BIM model and quantity take-off software saved significant time and effort, which otherwise would have been spent on manual data entry or correcting errors. As the project evolved, any changes made to the BIM model were automatically reflected in the integrated software, ensuring that quantity take-offs and cost estimations remained accurate and up to date throughout the project lifecycle. This real-time update capability proved crucial in maintaining accurate budgets and cost controls as the project progressed.

The advanced data analysis capabilities afforded by the integration of BIM with specialized software further enhanced the project team's ability to perform comprehensive cost breakdowns, generate detailed reports, and conduct thorough analyses. This enabled a deeper understanding of the cost implications of various design decisions and alternatives, facilitating more strategic planning and execution. Additionally, the integration facilitated the extraction of quantities for accurate and efficient take-offs and cost estimations. By automating these processes, the team was able to improve overall cost control and budget management, reducing the prevalence of errors. The incorporation of time-related data (4D) into the BIM model also played a crucial role. It allowed the team to visualise the project timeline, optimise construction workflows, and manage scheduling more effectively. This capability to simulate the construction process within the model helped in identifying potential scheduling conflicts and optimizing project workflows, thereby enhancing overall project efficiency.

6.3 Case Study Analysis Summary

Analyses of the case studies where BIM was not utilised during the advanced stages of the project showed an increase in prices and a delay in project completion. This was primarily due to the high number of changes made to the project. Furthermore, in the first and second case studies, the construction methods used were strictly traditional, without achieving any sustainability criteria. In contrast, the third case study employed BIM, which contributed to the achievement of these criteria. Consequently, in the third and fourth case studies, the scope of the project did not change as a result of using BIM. The factors that have an impact on project delays and failures as a result of design modifications are summarised in Table 28.

Table 28: Overview of factors contributing to project failure due to design changes

N	Impact of designer performance	Impact of owner performance	Impact of contractor performance
1	Inaccuracy of quantities of project	Involve project users with design changes during the implementation	The contractor has not reviewed all designs
2	As the design is being implemented, it will need to be continuously modified	Waiting for the owner's decisions at the design approval stage	The inability of the contractor to resolve or avoid design issues
3	Project elements and components are not covered in the detailed drawing	Owner's failure to specify an official representative to coordinate the design team	Contractor's lack of technical skills and equipment when executing some designs
4	Technical specifications that are unclear	Substantial changes to designs requested by the owner at a late stage	Contractors lack the necessary skills to apply the design consultant's directives
5	As-planned drawings and bills of quantities are incompatible		
6	The designs are ambiguous and contain errors		

Based on the case studies, it has been concluded that owner leadership needs to promote BIM adoption across all project processes, and strategies should be developed in order to facilitate the maturation of the BIM execution plan during the design, construction, and operation phases. Significantly, the use of BIM during the project phases is expected to eliminate the majority of the delays mentioned above. Through the use of BIM, stakeholders are protected from delays, omissions, and errors in drawings. Additionally, BIM facilitates decision making, assists in detecting clashes, and enhances communication among all stakeholders during all phases of a project. This study will address delays related to clients, delays in decision making, delays in bid submission, and poor coordination. Moreover, the results of the comparison between the study cases, which are summarised in Table 29, confirm the effectiveness of BIM.

Table 29: Overview of the results of the case studies

Case studies	Type of project	Type of contract	Level of BIM	Increase of cost	Daily of project
Case Study 1	Residential	Unit Price	**2D**	9.89 %	Yes
Case Study 2	Stadium	Unit Price	**2D**	21.14 %	Yes
Case Study 3	Tower	Unit Price	**4D, 5D,6D**	0 %	No
Case Study 4	Hospital	Unit Price	**4D, 5D**	N/A	N/A

The residential project encountered considerable delays and cost increases, primarily attributed to scope changes and inadequate initial assessments. The absence of BIM was a significant factor in these challenges, underscoring the necessity for comprehensive pre-construction planning and the dynamic project management capabilities afforded by BIM. The project's budget surpassed initial estimates by nearly 10%, highlighting the limitations of traditional project management techniques in managing unforeseen alterations.

Contrastingly, the football stadium in Riyadh implemented BIM during the initial phases but not throughout the project lifecycle. This sporadic application of BIM provided limited benefits in delineating project specifications and requirements, yet it was insufficient to avert a delay of one year and a cost escalation exceeding 21%. This instance exemplifies the critical need for consistent BIM application throughout a project to effectively manage complex stakeholder expectations and architectural demands.

The King Abdulaziz Center for World Culture exemplifies exemplary BIM implementation, from design to operation. BIM facilitated a collaborative and integrated project environment, averting cost overruns and delays. Notably, the project achieved LEED gold certification, illustrating BIM's contribution to enhancing sustainability outcomes. This case study is crucial in demonstrating how advanced BIM adoption (including 4D, 5D, and 6D) can optimise project delivery and ensure adherence to environmental standards.

The ongoing B-1 Ward renovation at a hospital illustrates the pivotal role of advanced BIM tools in managing intricate renovations. Preliminary outcomes suggest the project's potential to adhere to budget and schedule constraints. This example underscores the importance of BIM in renovation projects, which often encounter unique challenges, such as integrating new designs with existing infrastructure.

This comparative analysis reveals insightful distinctions in the impact of BIM across varying levels of adoption. While the residential and stadium projects suffered from limited or absent BIM utilisation, resulting in considerable financial and operational inefficiencies, the cultural center and hospital renovations exhibit the profound benefits of thorough BIM integration. The detailed examination of these case studies illustrates the transformative potential of BIM in the construction industry, particularly when fully integrated across project phases. The Saudi construction sector, poised for rapid growth, stands to gain immensely from widespread BIM adoption, manifested in enhanced efficiency, reduced environmental impact, and improved stakeholder satisfaction. Moving forward, leveraging BIM could be pivotal in positioning KSA as a leader in technologically advanced and sustainable construction practices globally.

6.4 Chapter Summary

The chapter comprises four in-depth case studies: a residential project, a football stadium construction, the King Abdulaziz Centre for World Culture, and the renovation of a hospital's B-

1 ward. These case studies provide concrete data into the real-world application of BIM and its influence on construction projects. The findings indicate that the non-utilisation of BIM in advanced project stages often leads to increased costs, delays, and numerous changes in project scope. By contrast, projects where BIM was employed exhibited enhanced efficiency and reduced changes in scope. Factors contributing to project failure due to design changes are outlined. The case studies clearly demonstrate that BIM's role in managing LCC is profound and multifaceted. Projects utilising BIM benefited from reduced cost overruns, better scope management, and improved stakeholder collaboration, all of which are critical components in minimising the LCC of construction projects. Conversely, the absence of BIM often resulted in financial inefficiencies, delayed schedules, and scope mismanagement, thereby increasing the LCC. These insights strongly advocate for the adoption of BIM technologies to optimise the financial and operational performance of construction projects in KSA and beyond. The chapter emphasises research on the importance of owner leadership in promoting BIM adoption and the substantial benefits of incorporating BIM across all phases of a project, from design to operation. The qualitative analysis in this chapter paves the way for the in-depth simulation and optimisation analysis of a specific residential project in the following chapter (Chapter Seven).

Chapter 7

Simulation and Optimisation - Residential Project (900 units) in the KSA

Parts of the content from this chapter have been published:

Utilising BIM on LCC to Enhance Sustainability of Saudi Residential Projects Through Simulation. A Case Study at the Kingdom of Saudi Arabia.
Alasmari, E., Martinez-Vazquez, P., Baniotopoulos, C. (2024). Utilising BIM on LCC to Enhance the Sustainability of Saudi Residential Projects Through Simulation. A Case Study at the Kingdom of Saudi Arabia. 4th International Conference "Coordinating Engineering for Sustainability and Resilience" and Midterm Conference of CircularB “Implementation of Circular Economy in the Built Environment”. CESARE 2024. Lecture Notes in Civil Engineering, vol 489. Springer, Cham.

7 Chapter Seven: Simulation and Optimisation - Residential Project (900 units) in the KSA

7.1 Introduction

Chapter Seven explores the simulation and optimisation of a large residential project consisting of 900 units in the KSA. The chapter kicks off with the background to the case study, providing essential context for the project unique challenges and objectives. It proceeds to elaborate the methods of simulation and optimisation employed, highlighting the intricate process of building 3D to 5D models that serve as the foundation for analysis and decision making. The addition of a 6D model for alternative design scenarios expands the horizon of possibilities and cost considerations. The heart of the chapter lies in the analysis phase, focusing on energy costs using Autodesk® Insight 360. This includes a detailed exploration of alternative design Scenario 1 and its energy efficiency. Additionally, LCC analysis using Autodesk® Green Building Studio is examined. Sustainability and building circularity analysis, with the aid of One Click LCA, provide a holistic view of the project environmental impact. The chapter not only delves into data collection and evaluation, but also presents comparisons between Scenario 1 and Scenario 4, as will be discussed later.

7.2 Background of the Case Study

This case study examines a residential development project consisting of 900 residential structures along with the necessary amenities to facilitate building operations. This project involves the construction of 900 housing units as well as fences, external gates, and groundwater tanks. Additionally, during the site development process (see Figure 70), it is necessary to determine the relative level of housing units with respect to the road level.

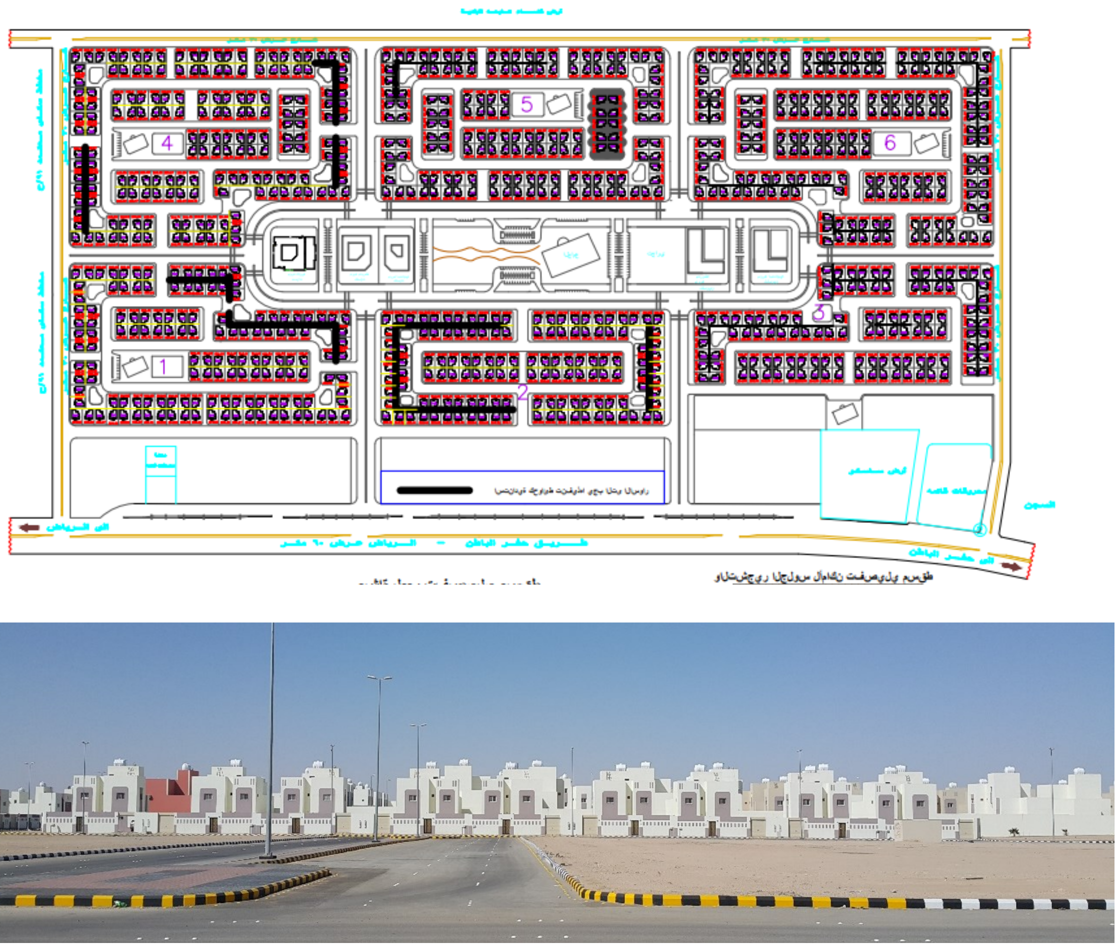


Figure 70: Panoramic elevation and site plan of the project

In the residential development, each unit consists of one and a half floors, with three bedrooms, a sitting room, a living room, three bathrooms, and a kitchen with a total building area of approximately 294 square meters. In the construction process, reinforced concrete slabs are used, specifically, one-way Hardy Slabs made from 25 mm concrete blocks. As these blocks are interlocked together to form the slab, formwork is placed around them for stability and reinforcement is placed in between the blocks. Every 60 cm, the wall construction is connected horizontally using a hollow block and two 8 mm iron bars (see Figure 71).

In the vast landscape of construction, where precision and efficiency intersect, Chapter Seven embarks on a comprehensive exploration. It casts a discerning eye on a particular residential project, encompassing a substantial 900 units, set within the KSA. This chapter describes an enthralling journey into the world of simulation and optimisation, intricately woven into the fabric of this ambitious residential development. The researcher will navigate through the techniques and methodologies utilised in this endeavour, designed to bolster efficiency, trim costs, mitigate errors, and ultimately orchestrate the triumphant realisation of this expansive residential complex.

By concentrating on this meticulous case study, a spotlight is shone on how cutting-edge simulation and optimisation tools can be wielded to enhance construction projects' effectiveness and resource management. Throughout these pages, the reader will find insights into the methods employed to tackle the complexities of the construction industry in the dynamic landscape of the KSA, and how a meticulous approach to modelling, simulation, and optimisation can dramatically redefine the construction process. In a realm where time is money, Chapter Seven illuminates a path forward through innovation, precision, and resource optimisation.

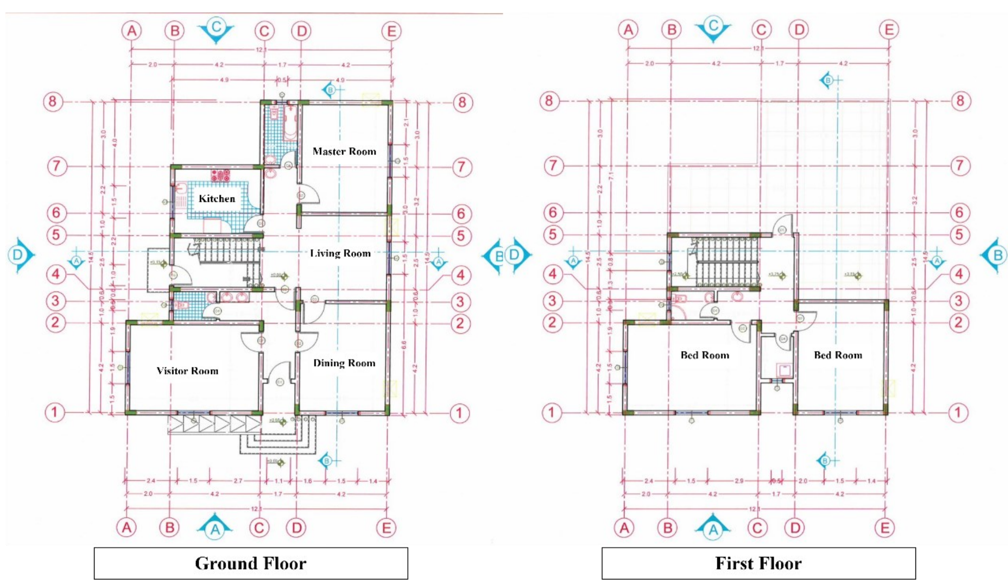


Figure 71: Design of a residential unit with a ground floor and first floor

The project was initially scheduled to be completed in 2012; however, two separate extensions resulted in a three-year delay. An increase in the project scope resulted in higher costs, prompting the owner to grant a 16-month extension, which resulted in an increase of $7,019,257.98 in the budget. As a result of changes in contract terms for items that were not initially covered, an additional 18-month extension was granted, increasing the cost further by $1,635,840.50 to become $8,672,721.81. As a result, the project was completed in 2015 after an extension of 1003 days, resulting in an increase of 92.87% from the original contract period and a 9.89% increase in costs. The need for comprehensive analysis and project study contributed significantly to the delay in project completion, which led to numerous changes and additions throughout the entire process (see Table 30).

Table 30: Detailed information regarding the implementation of the project

Information of project			
Project Contract Value	**Contract Period**	**Final Project Value**	**Increase of Cost**
$86,740,933.6	1080 Days	$95,327,964.06	9.89%
Consultant Contract Value	**Area**	**Type of Contract**	**Level of BIM Used**
$5,426,034	1,185,000 m²	Unit Price	2D
Contract Signing Date	**First Receipt of Project according to Contract**	**Final Receipt of Project**	**Extra Time of Contract Period**
26/07/2009	17/07/2012	16/04/2015	1003 Days

There are several factors attributed to the delay identified in this case study including inadequate planning by the project owner and the lack of as-built drawings during the study and design phases. As a result, project element costs increased and Building Information Modelling (BIM) was not implemented to rectify the problem. Moreover, the project procurement through a public competition placed a considerable emphasis on bid costs, overlooking the impact of technical data on the project and bidders. During the implementation of the project, this oversight led to frequent changes in project orders.

7.3 The Method of Simulation and Optimisation

Analysis of LCC/LCA in residential projects using BIM tools: This study aims to use BIM tools to assist engineers in addressing the rising costs of a residential project and selecting an optimal Scenario for designing the LCC and LCA. For the purpose of determining the technical specifications of the project materials, an existing 3D model of a residential house is modelled with the parent software product, AutoDesk® Revit 2023. This 3D model is then used to prepare the Bill of Quantities (BoQ) of the model and take-off, using Revit to correct the omission of quantities observed at the 2D level in this case, which resulted in higher costs. In addition, 4 alternative design Scenarios will be developed by altering the specifications of the walls and floors, allowing for the assessment of energy costs associated with LCC using Autodesk® Insight. As a result of this comprehensive tool, building energy and environmental performance will be improved, which enables the identification of the best alternative LCC Scenarios. A whole-building analysis software program, AutoDesk® Green Building Studio (GBS), will be used to analyse the four Scenarios. According to actual model data, local energy sources, and weather data, GBS provides results regarding energy consumption, water consumption, costs, natural ventilation potential, and carbon emissions.

Finally, the model will transfer to One Click LCA (https://www.oneclicklca.com/), a web-based analysis service integrated with AutoDesk® Revit, to analyse Scenario 1 in the actual design unit of the case and Scenario 4 after enhancing the specifications of the unit. Moreover, analysis of BREEAM and the building circularity of LCC/LCA, which is the world's leading science-based verification and certification system for sustainable built environments, were compared between the two Scenarios as part of the comparison process (see Figure 72).

Utilising these software tools has the following advantages:

1. 3D modelling in AutoDesk® Revit 2023 enhances the accuracy of determining project materials' technical specifications.
2. Through the use of Revit, the omission of quantities can be rectified and increased costs can be addressed.
3. In order to determine the best LCC Scenario, alternative design Scenarios are developed and energy costs are measured using Autodesk® Insight.
4. A comprehensive whole-building analysis is performed using AutoDesk® Green Building Studio, resulting in crucial information on energy consumption, water consumption, natural ventilation potential, and carbon dioxide emissions.
5. A comparison of LCC/LCA, building circularity results and BREEAM sustainable standards between design Scenarios using One Click LCA enables informed decisions to be made for optimal project outcomes.

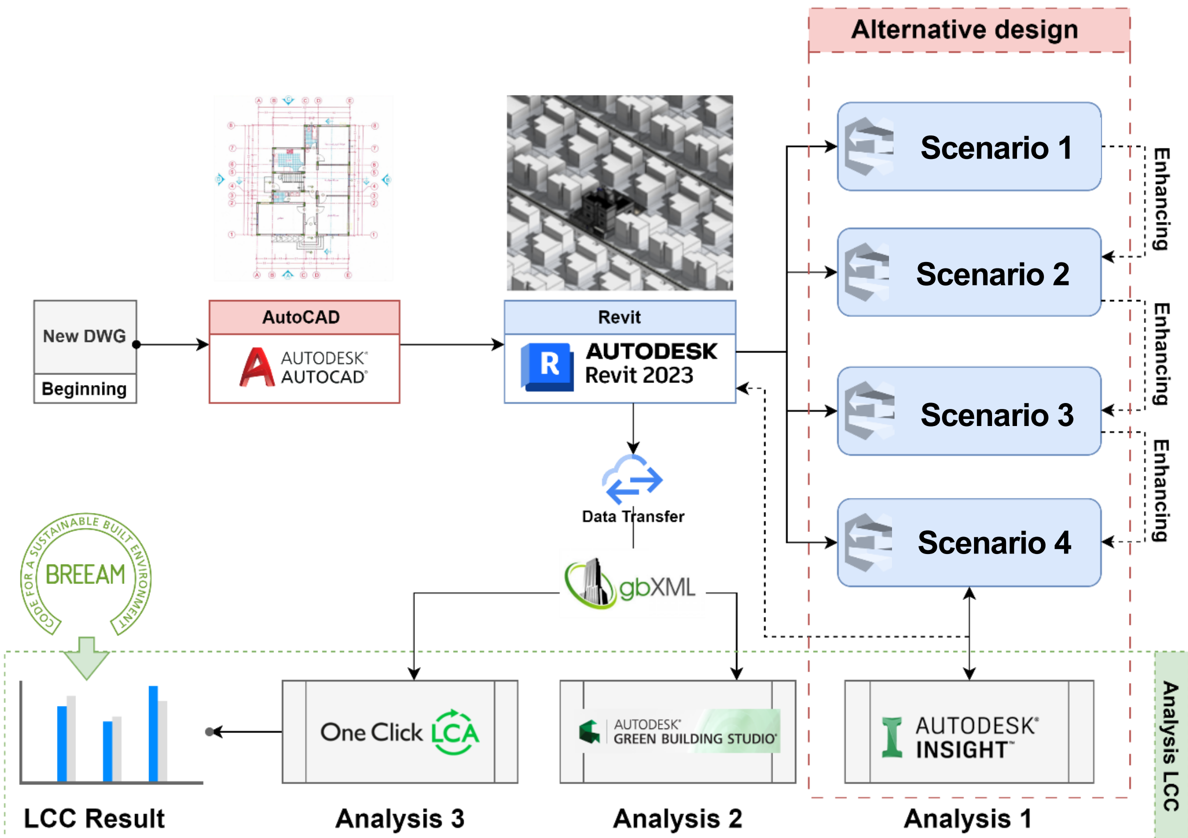


Figure 72: Workflow of LCC analysis

Therefore, the incorporation of BIM tools and different software applications into the process of planning and designing residential projects can have a significant impact on cost management, energy efficiency, and environmental performance. As a result of utilising tools such as AutoDesk® Revit 2023, AutoDesk® Insight, AutoDesk® Green Building Studio, and One Click LCA, engineers and project managers are able to evaluate alternative design alternatives based on LCC and LCA metrics, as well as BREEAM sustainability criteria and building circularity.

In addition to enhancing the accuracy of project material specifications and cost estimates, these tools also contribute to the development of a comprehensive whole-building analysis, including factors such as energy use, water consumption, natural ventilation potential, and carbon emissions. As a result, this holistic approach and triangulation method for analysis of residential project planning and design facilitates the selection of environmentally-friendly, cost-effective, and sustainable solutions, contributing to the advancement of the construction industry and the pursuit of sustainable development worldwide.

This methodology advances the use of BIM to optimise LCC in Saudi residential construction, supporting the sustainability objectives of Saudi Vision 2030. It prioritises LCC analysis during the initial design phase, challenging traditional post-construction evaluations. A hybrid simulation model merges data from Autodesk® Insight 360 and Autodesk® Green Building Studio on energy performance with environmental impact assessments from One Click LCA. This innovative model stands out by effectively integrating diverse datasets, enhancing decision-making in construction design with its comprehensive evaluation of costs, energy, and environmental impacts.

The method employs a sophisticated simulation and optimisation strategy using advanced BIM tools tailored for the Saudi construction sector's specific needs. Each step is meticulously designed to align with sustainability and cost-efficiency goals. This approach significantly surpasses traditional methods by incorporating state-of-the-art tools like Autodesk® Insight 360, Autodesk® Green Building Studio, and One Click LCA, which are typically underutilised in the region. These tools facilitate a deep understanding of the environmental and cost implications of building designs, offering a novel solution to the concurrent challenges of rising costs and sustainability in public construction.

The innovation of this method lies in its holistic application of BIM for LCC analysis in large-scale KSA construction projects. It moves beyond previous studies that focused mainly on initial costs and basic environmental impacts, creating a comprehensive model that utilises advanced BIM technologies to enhance cost efficiency and sustainability.

7.4 Information on the Case Study and Building the 3D to 5D model

An analysis of a case of a family house within a large-scale KSA project is also part of this study. The prototypical sample of the residential development consists of 900 units and one-and-a-half floors serve as the focus of this case study. An overview of the building general characteristics can be found in Table 31.

Table 31: General information on case study

Item	Description
Project type	Residential project 900 units
Building type	Villa house
Type of Construction	Concrete
Gross floor area	294 m²

Ground floor area	145 m²
First floor area	80.58 m²
Height	8 m
Width	12.1 m
Depth	14.5 m
Internal floor height	3 m
Maximum column spacing distance	6.2 m
Doors	25 m²
Windows	17 m²
Exterior Wall	348 m²
Interior Floor	55 m²
Interior Wall	168 m²
Raised Floor	246 m²

Simulation and optimisation techniques will be applied to the study design and construction of such a residential unit. The purpose of these methodologies is to gain a deeper understanding of how buildings perform and to identify potential improvement opportunities including energy efficiency, thermal comfort, and structural stability to demonstrate the value of integrating simulation and optimisation methods into the design process to create sustainable, high-performance residential units within a larger megaproject. This project involved developing and simulating a residential building prototype using Autodesk Revit software adapted to the KSA's design principles. The model house was located in Hafar Al-Batin and utilised data from the local weather station for energy analysis. Figure 73 below illustrates the site plan and three-dimensional perspective of the Revit model.

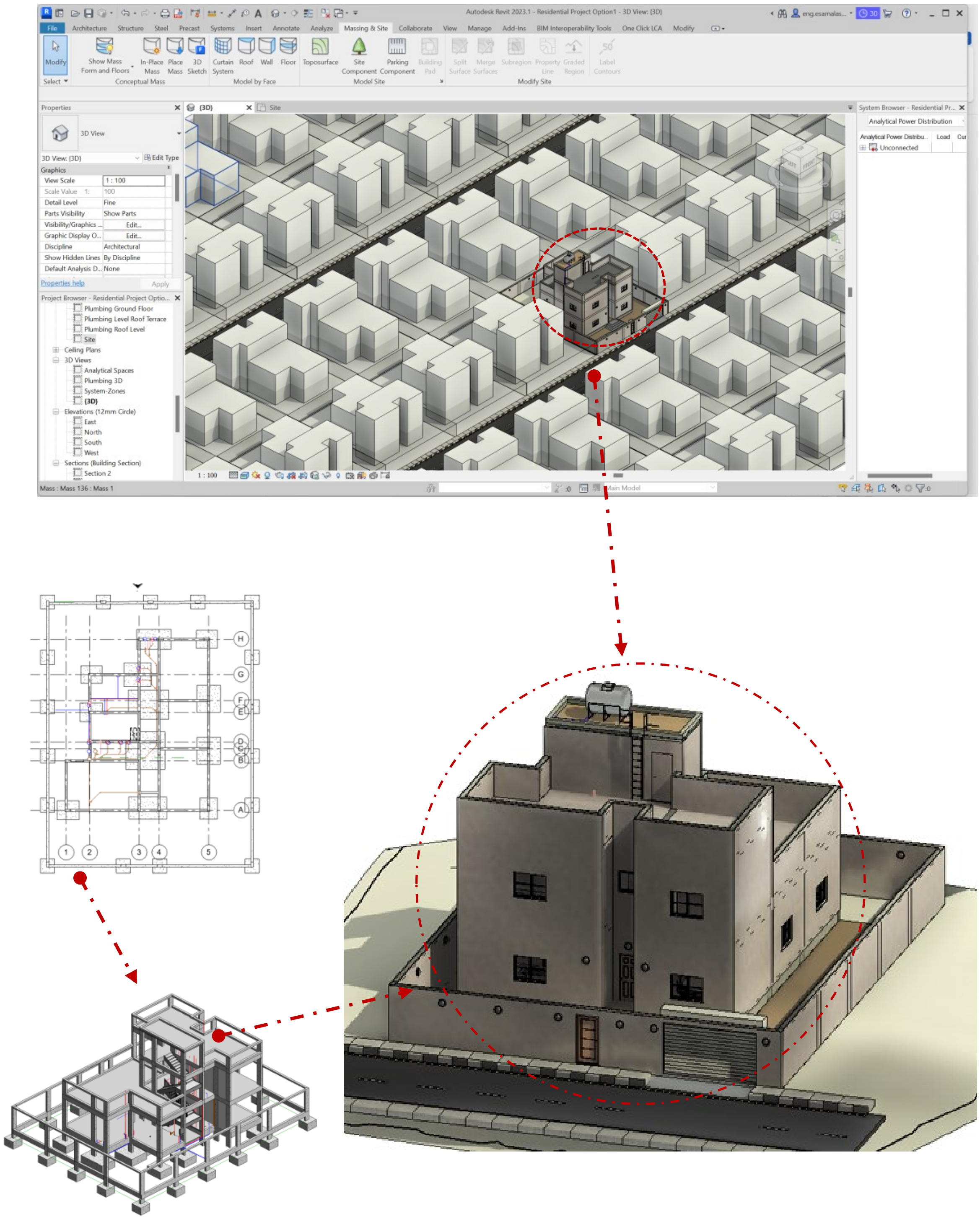


Figure 73: 3D model drawings of site plan and the structure

Autodesk developed an application that enables architects, engineers, and designers to build detailed 3D models of buildings. This includes Detailed Engineering Design (DED) data based on BIM. However, it is essential to note that Revit Autodesk supports structural modelling and creates the house's structural elements including columns, beams, and slabs. To place columns and create beams that connect columns and ensure they are connected to structural elements, the “Column” and “Beam” tools are used. The slabs are also connected to the structural elements using the “Floor” tool. To model stairs, the “Stair” tool is employed to customise the staircase according to the design. To select the appropriate roof type and specify the required slope, the “Roof” tool is used. The “Floor” tool in Revit creates floors; the “Floor” tool also provides a variety of floor types to choose from (see Figure 74).

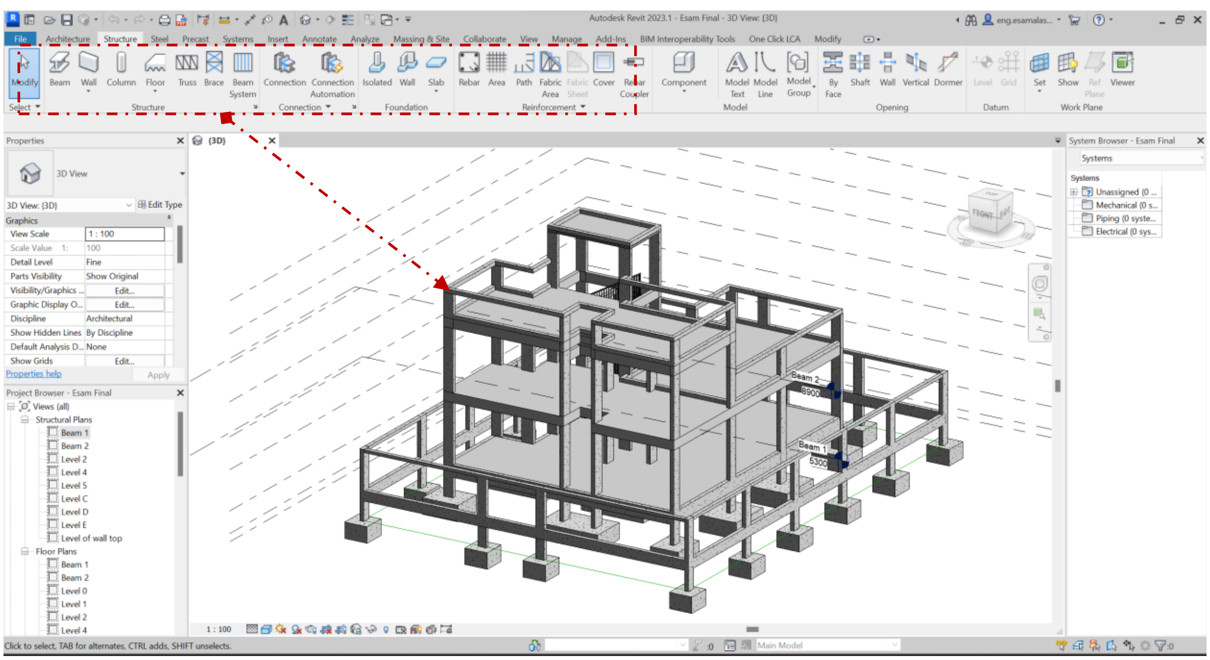


Figure 74: 3D model drawings of site plan and building structures using Autodesk® Revit

In Revit Autodesk software, architectural modelling involves creating a house's basic structure and layout including walls, doors, windows, and other architectural details (see Figure 75).

Additionally, mechanical, electrical, and plumbing (MEP) modelling involves creating and placing the house's mechanical, electrical, and plumbing systems. HVAC tools should be used to design heating, ventilation, and air conditioning systems, while plumbing tools should be used to design plumbing systems. "Electrical" tools can be used to design electrical systems including power distribution, lighting, and communication systems.

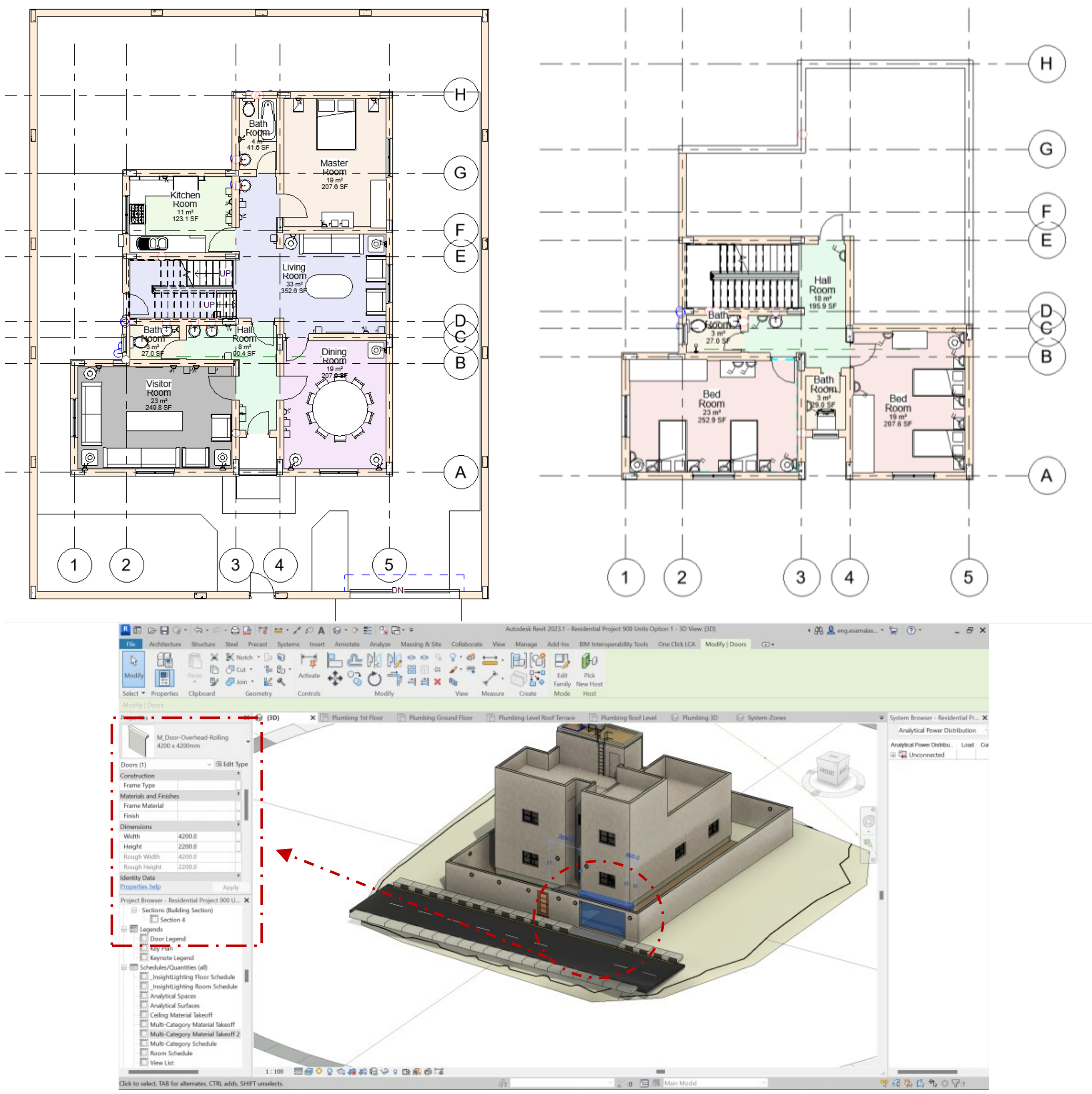


Figure 75: Architectural modelling using Autodesk® Revit

After the modelling process is complete, it is possible to add detailed information to your model.

This includes material specifications, schedules, annotations, and bills of quantities. Furthermore, it may be used to coordinate and detect clashes between different building systems, such as structural, MEP, and architectural elements, by using the "Interference Check" feature (see Figures 76 and 77).

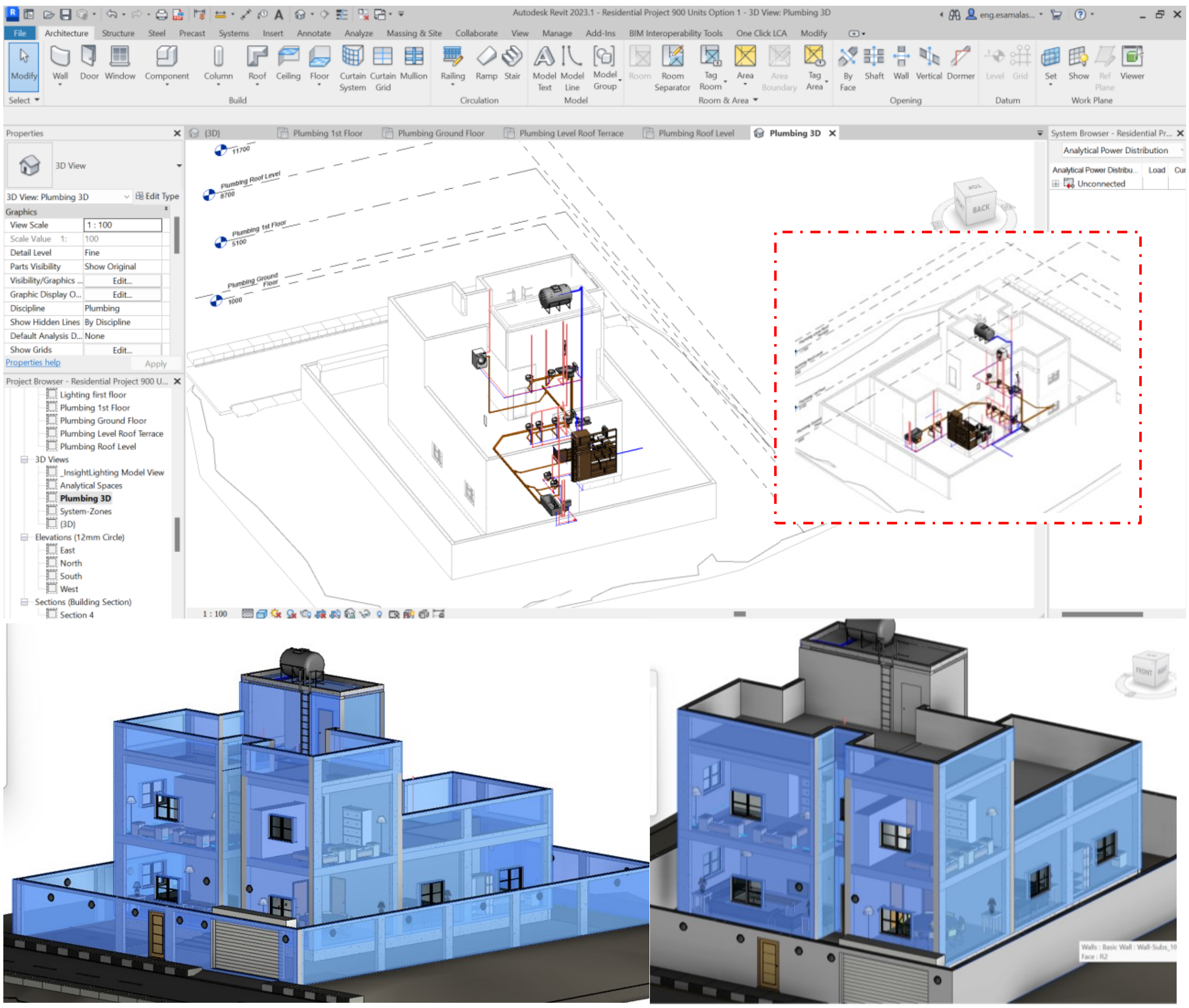


Figure 76: MEP modelling using Autodesk® Revit

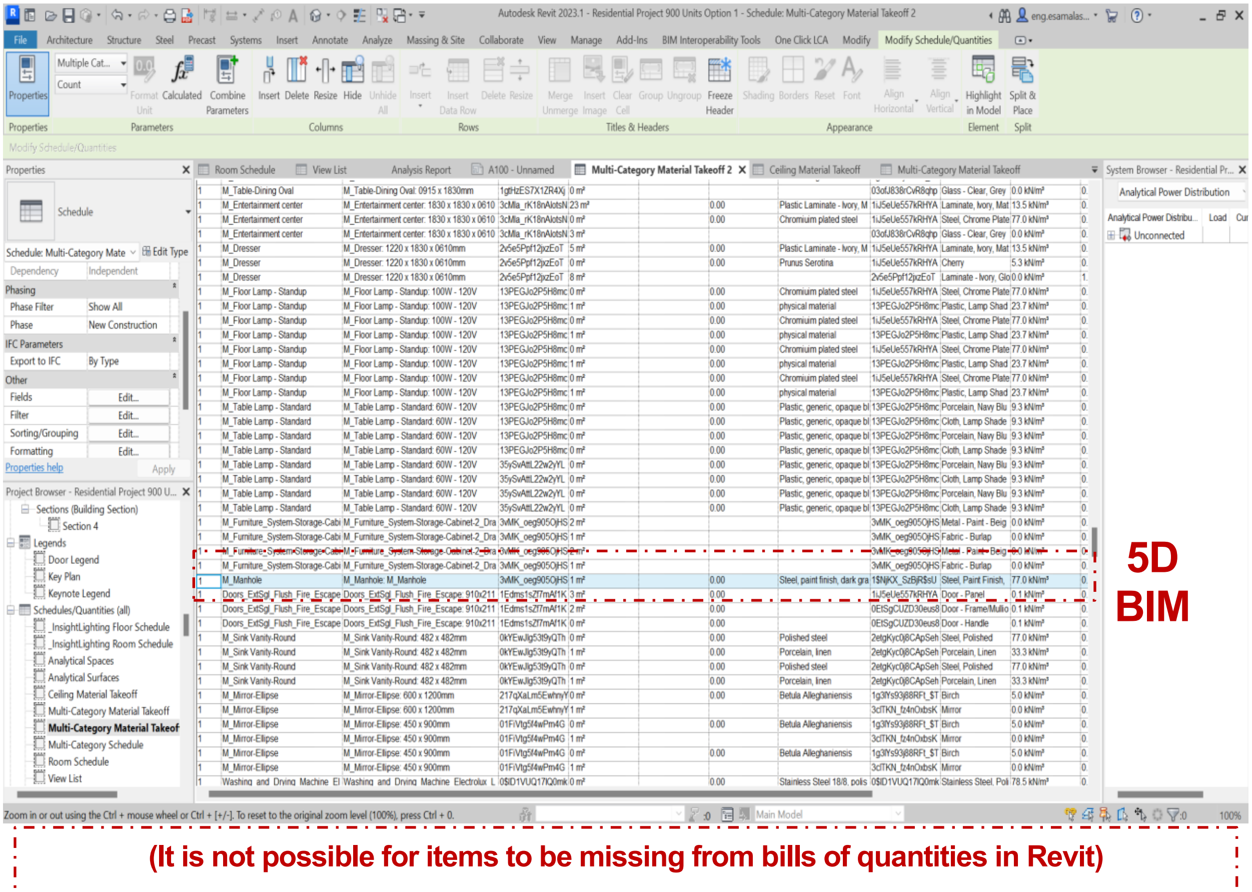


Figure 77: BoQ using Autodesk® Revit

Revit can update project location details using either the default city list or Internet mapping services via the location settings. Users may also choose the building type, specify the building purpose in the Schedule section, and provide additional details in the Energy and Advanced Energy settings sections in the Analyse panel. Project location information is crucial for the analysis process to determine the nearest weather station and local weather data. The material thermal properties feature in Revit allows the user to select the Scenario to consider the thermal properties of building materials. Some values for specific building elements are predetermined in the Advanced energy settings area (see Figure 78).

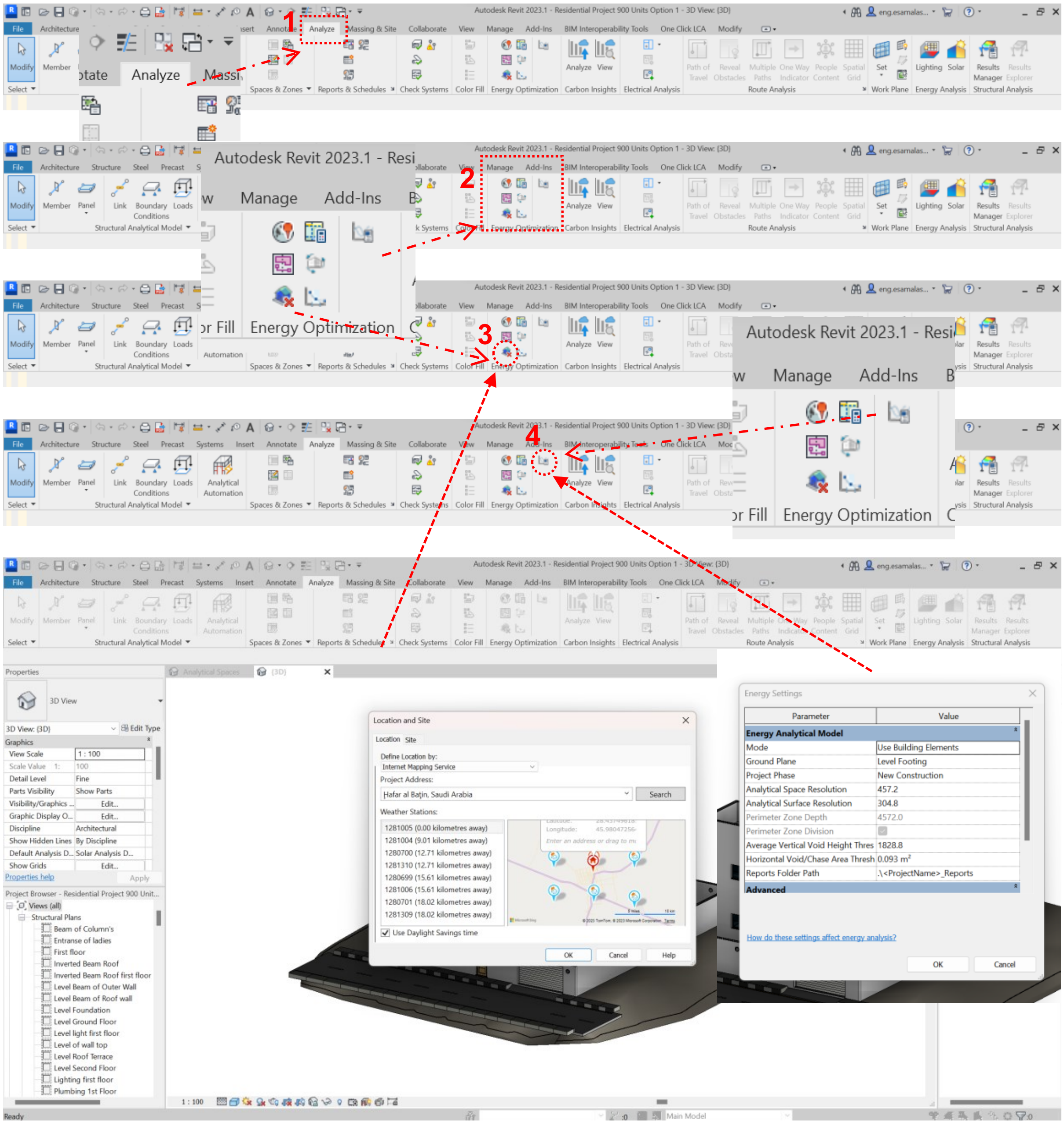


Figure 78: Location and energy settings of the building in Autodesk® Revit

7.5 Building a 6D Model for Alternative Design - Scenario1

Using Revit, a BIM tool, the test cell model is streamlined in its design process. Each element is crafted by incorporating individual layers with physical and thermal properties aligned with the real-world characteristics of the test cell's walls, floors, doors, windows, and roofs. As part of Scenario 1, the physical and thermal properties of the building are inputted and the results are analysed accordingly (see Figure 79).

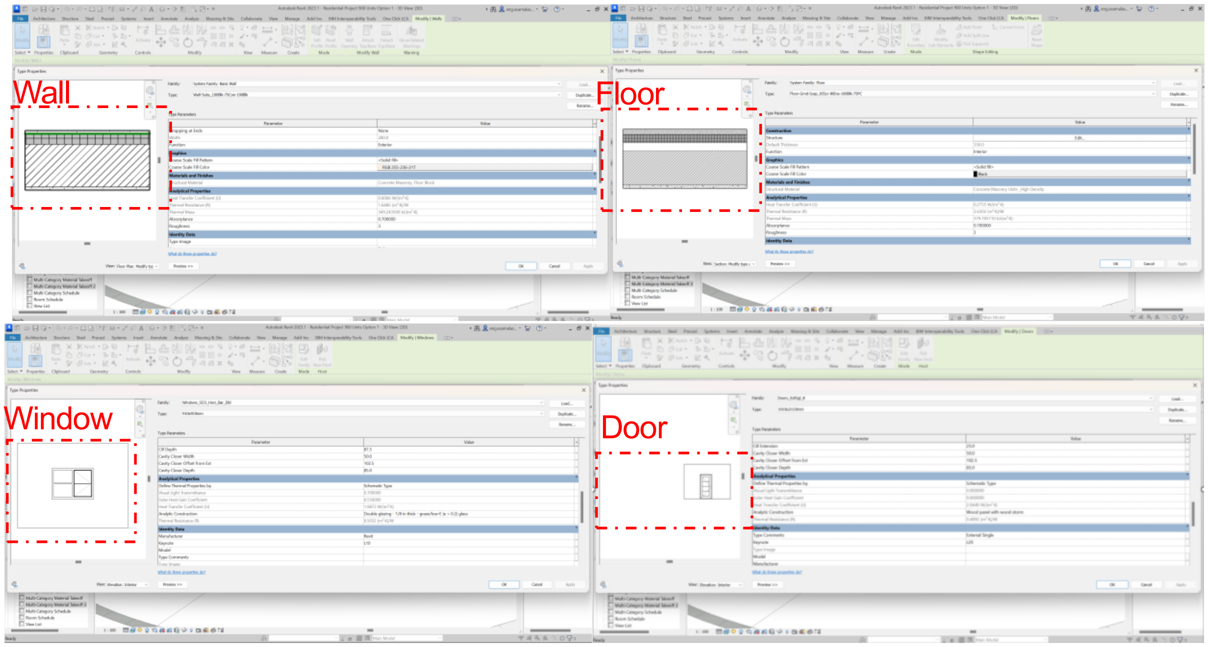


Figure 79: Physical and thermal properties of materials in Autodesk® Revit

A Revit software energy analysis simulation can be significantly enhanced by incorporating individual layers with specific physical and thermal properties for each element including walls, floors, doors, windows, and roofs. Due to the meticulous approach to element design, simulation outcomes are more reliable due to an accurate representation of real-material conditions. Detailed simulations based on the physical properties of the elements can also be used to evaluate the performance of the building envelope. As shown in Table 32, material properties can be compared in relation to heat transfer coefficients, thermal resistances, and thermal masses. This information is crucial for ensuring that simulation results are accurate. By evaluating these properties, designers and engineers will be able to make informed decisions during construction, improving their understanding of how a building thermal performance is affected by different materials.

Table 32: Material properties of Scenario1 alternative design

Elements	Heat Transfer Coefficient (U)	Thermal Resistance (R)	Thermal Masse
Floor	0.2755 W/m². K	3.6302 (m². K) /W	379.71 KJ/ (m². K)
Wall	0.6247 W/m². K	1.6007 (m². K) /W	273.69 KJ/ (m². K)
Window	1.9873 W/m². K	0.5032 (m². K) /W	-
Door	3.701 W/m². K	0.2701 (m². K) /W	-

Autodesk Revit software is used for analysing sun paths (see Figure 80). In order to maximise solar energy production, it is possible to determine the most optimal placement of solar panels, electric water heaters, and other solar equipment within a building or facility based on this analysis. In addition, solar analysis results can help achieve thermal and visual comfort within a building. In Revit, a sun analysis as depicted in Figure 81, typically visualises the impact of solar radiation on a building's surfaces over a certain period. This analysis aids in understanding the building's performance in terms of natural lighting, heat gain, and energy efficiency, which is crucial for sustainable building design and LCC analysis.

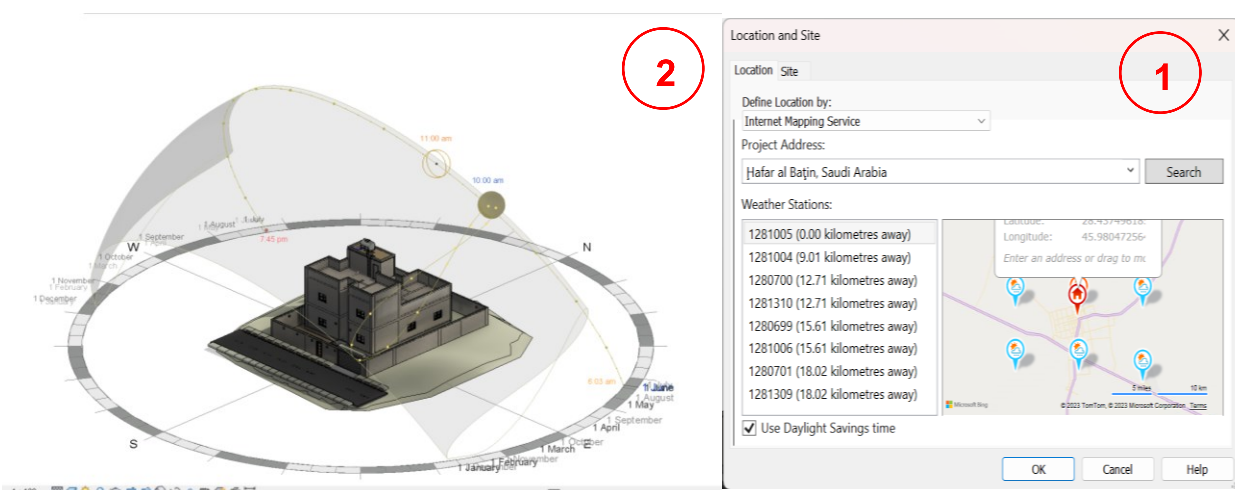


Figure 80: Sun path setting and analysis in Autodesk® Revit

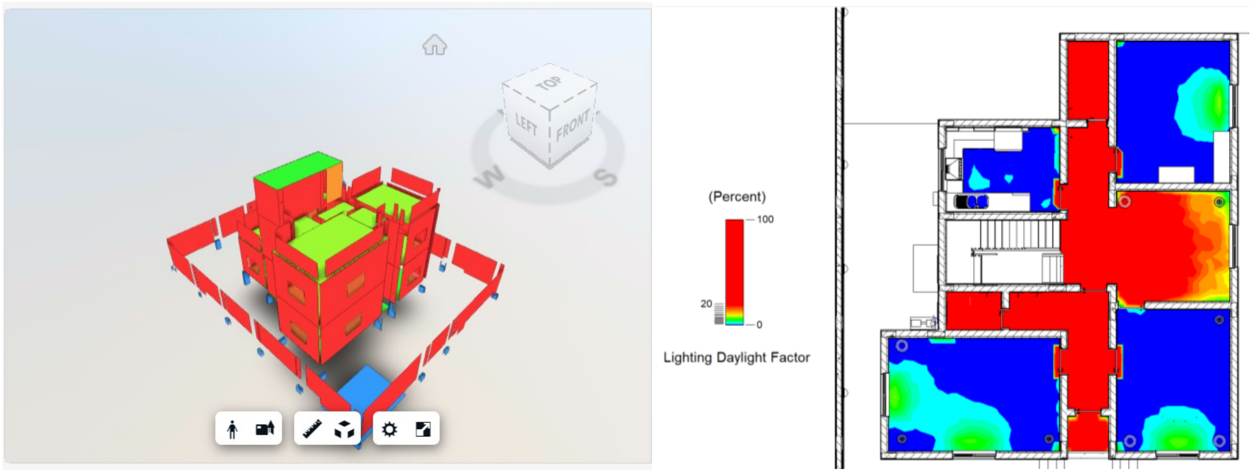


Figure 81: Sun analysis in Autodesk® Revit

It is essential to incorporate DED data into the model to ensure it is accurate and contains all the necessary information for construction. Utilising Revit comprehensive BIM capabilities, architects, engineers, and designers can collaborate more effectively, resulting in more efficient and streamlined construction processes. Moreover, this study makes use of Insight 360 software for the analysis of energy, GBS for the analysis of cost, and One Click LCA for the analysis of sustainability and circular economy.

7.6 Analysis of Energy Cost by Using Autodesk® Insight 360:

Energy analysis can have a significant impact throughout the entire design lifecycle including conceptual massing and complex BIM modelling. Incorporating this approach into their design development process, building owners can significantly lower operational energy costs and reduce operational greenhouse gas emissions. At the same time, engineers can identify performance improvement opportunities throughout the design process. Revit and Insight are part of the Autodesk AEC Collection that allows engineers to conduct energy analyses in the cloud. Autodesk Insight 360 software for better building energy and environmental performance can use a BIM model to analyse energy usage and design possibilities more accurately. Thus, detailed and visible results can be generated.

7.6.1 Alternative Design Scenario 1

During the initial phase, the Revit Analyse panel provides advanced energy settings and energy settings Options. To simulate the energy model, Revit data, including data from walls, doors, roofs, windows, and floors, are used. Figure 82 illustrates the parameters of the energy analytical model, emphasising its interaction with energy settings. It is important to note that the material characteristics and energy characteristics within the Revit model are not determined by these settings alone. All components of the building, such as walls, roofs, ceilings, slabs, floors, and glass, have an influence on the heating and cooling loads. As shown in Table 33, Revit data, including location, weather, and thermal properties, are utilised to construct the energy model. As a result, the energy analytical model can be validated and examined in advance of conducting an energy simulation. Depending on the energy settings dialogue, the energy analytical model may take the form of rooms, spaces, masses or building elements.

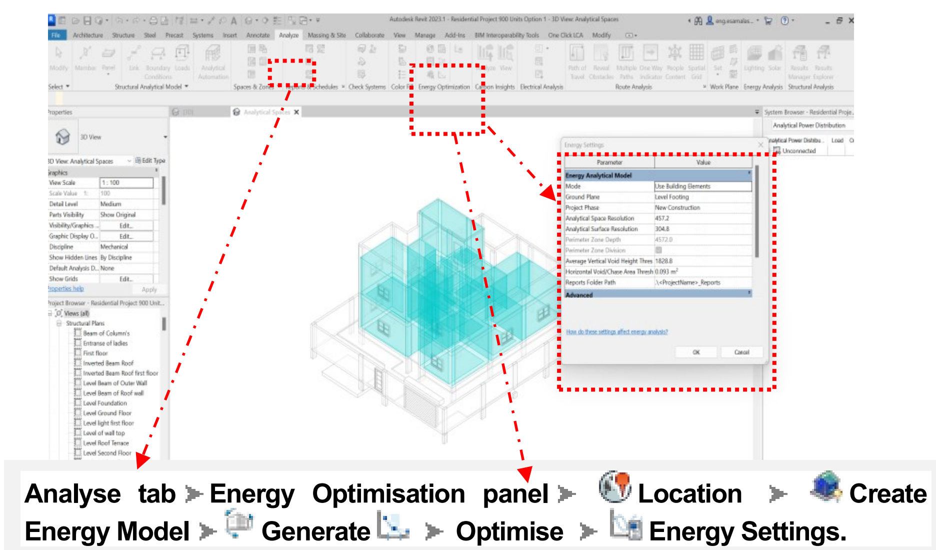


Figure 82: Autodesk® Revit model created for building energy modelling

Table 33: Information on weather station for the case study in Revit

Weather Station: GBS_06M12_18_206161			
Distance to project 0.9 mi (1.5 km)			
Latitude = 28.4500, Longitude = 45.9833			
Cooling Degree Day		**Heating Degree Day**	
Threshold	**Value**	**Threshold**	**Value**
18.3 °C	3175	18.3 °C	607
21.1 °C	2486	15.6 °C	339
23.9 °C	1869	12.8 °C	142
26.7 °C	1308	10 °C	33

Annual Design Conditions				
Threshold	**Cooling**		**Heating**	
	Dry Bulb (°C)	**MCWB (°C)**	**Dry Bulb (°C)**	**MCWB (°C)**
0.1 %	47.6	21.5	0.5	-1.7
0.2 %	47.2	21.0	2.1	0.2
0.4 %	46.8	20.6	3.0	1.5
0.5 %	46.7	20.5	3.3	1.6
1 %	46.2	20.4	4.0	1.9
2 %	45.5	20.0	5.2	2.7
2.5 %	45.1	20.0	5.7	3.0
5 %	43.7	19.7	7.7	4.9

7.6.2 Energy Analysis of Scenario1

After the energy analysis model has been completed, the Generate Insight command in Revit can be activated and the results of the analysis can be accessed through the provided URL (https://insight360.autodesk.com/oneenergy). In Figure 83, a red circle represents the energy cost, which appears immediately in the upper left corner of a project in Insight 360. Additionally, a location map and historical weather data graph can be viewed.

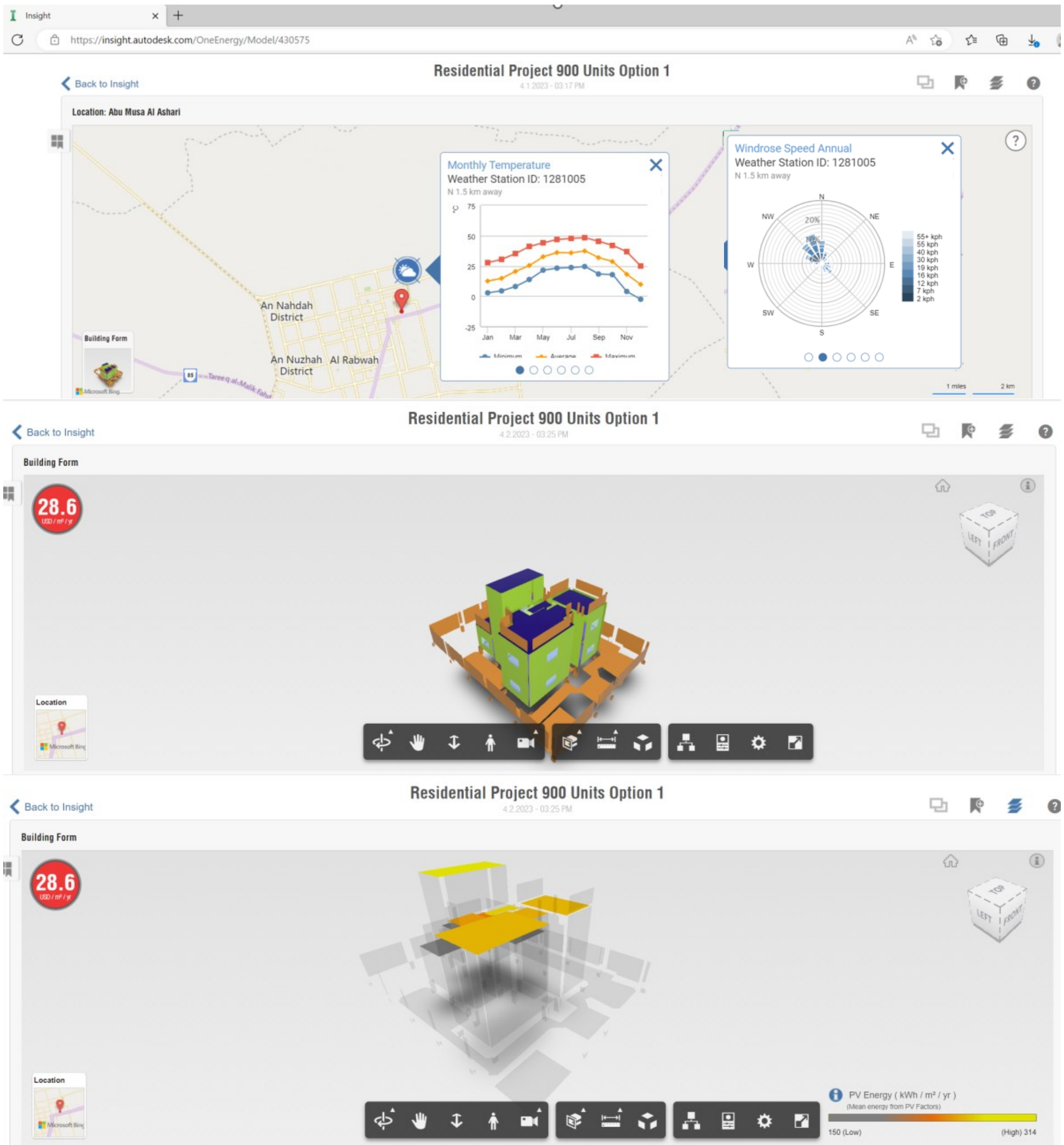


Figure 83: Model created by Insight 360 for energy consumption for Scenario 1

Modifying specific design elements, including orientation and location, does not significantly impact the overall performance (see Figure 83). It is important to note that the “BIM” position corresponds to the current orientation of the Revit model. As illustrated in Figure 84, comparing Building Orientation to another metric, such as Wall Construction, reveals a greater opportunity for influencing the building overall performance. Implementing a super-insulated wall illustrates the possibility of modifying only the walls in this case.

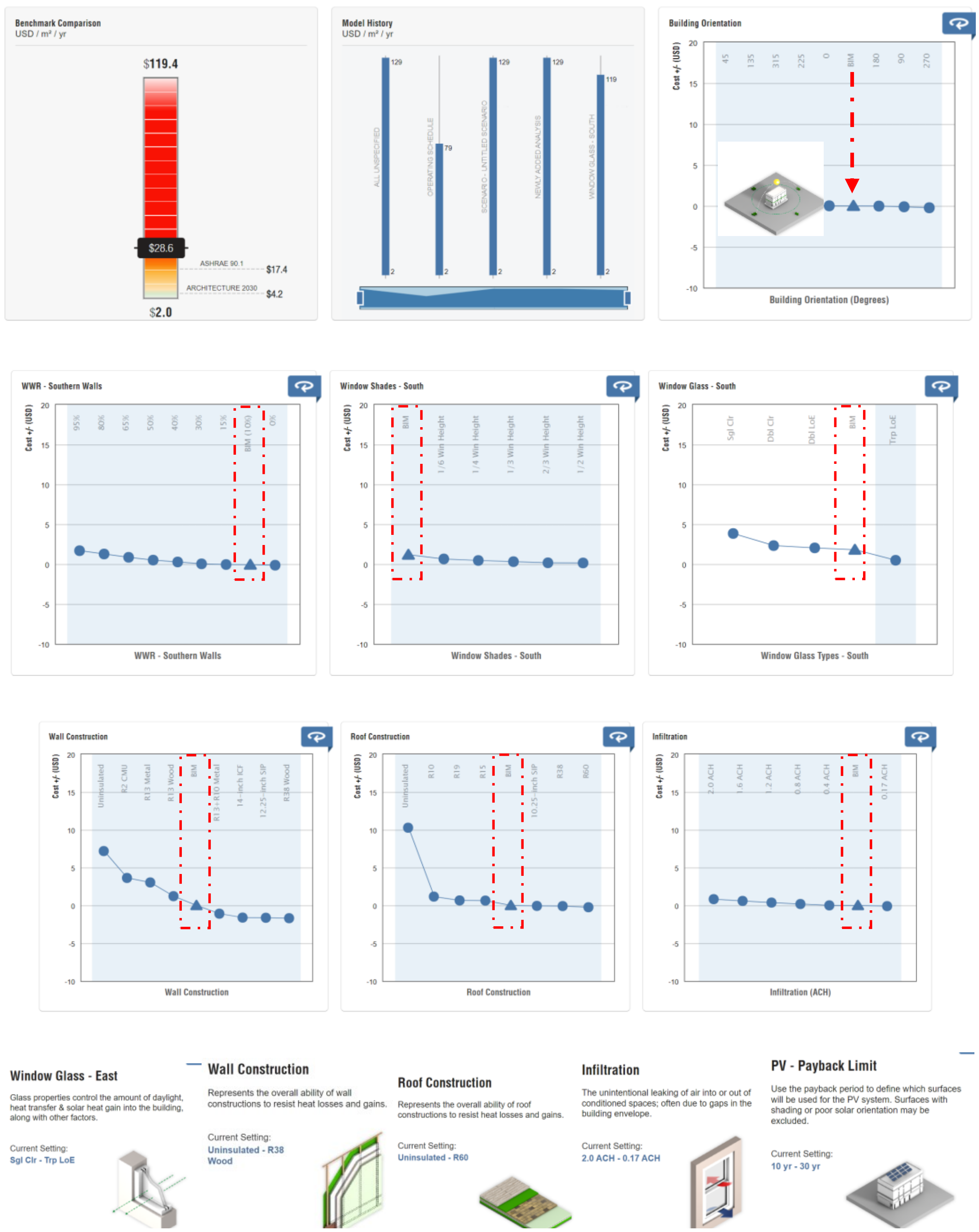


Figure 84: Energy analysis for Scenario1

Energy efficiency and thermal comfort of existing and new buildings can be evaluated using BIM-based simulations such as Autodesk Revit or Insight. Retrofitting the building will reduce the building dependence on mechanical systems. As well as promoting the design of energy-efficient buildings, BIM technologies allow designers to explore all viable design alternatives prior to implementing the final design. Moreover, the study results investigate 16 factors within the building that influence energy consumption in order to determine the impact of energy consumption on environmental sustainability.

These factors include Benchmark Comparison, Model History, Building Orientation, Wall-to-Window Ratio Value, Window Shades, and Window Glass Properties based on the direction, and Wall Construction Heat Gain/Loss Values, Roof Construction Heat Gain/Loss Values, and Infiltration Values based on model gaps, Lighting Efficiency based on heat gain and power consumption, Daylighting and Occupancy based on space settings, Plug Load Efficiency based on equipment loads per space, HVAC System Efficiency and Operating Schedule based on project settings, Photovoltaic Power Panel Efficiency based on the surface area, and Photovoltaic Payback Limit based on shading and orientation.

As a result, energy analysis of buildings is primarily influenced by these factors, providing designers and other stakeholders with information about energy-efficient solutions. According to the findings from Scenario 1, the construction of walls and roofs significantly contributes to reducing energy consumption and costs associated with the building. Therefore, 4 design alternatives are made by Revit (see Figure 85). As shown in Table 34, at first, the wall is equipped with minimal insulation to facilitate the exploration of alternative Scenarios in search of an optimal solution throw calculating Heat Transfer Coefficient (U), Thermal Resistance (R), and Thermal Masse for all material that is changed in the models. The table presents several

Scenarios for different building elements, their corresponding alternative designs, and some thermal properties. Four alternative floor designs are presented, each with a different alternative design. Each Scenario includes U and R values, allowing a calculation of the floor's thermal mass. Furthermore, this table summarises the thermal properties of various building elements in different Scenarios, which can be used to analyse energy efficiency and thermal performance.

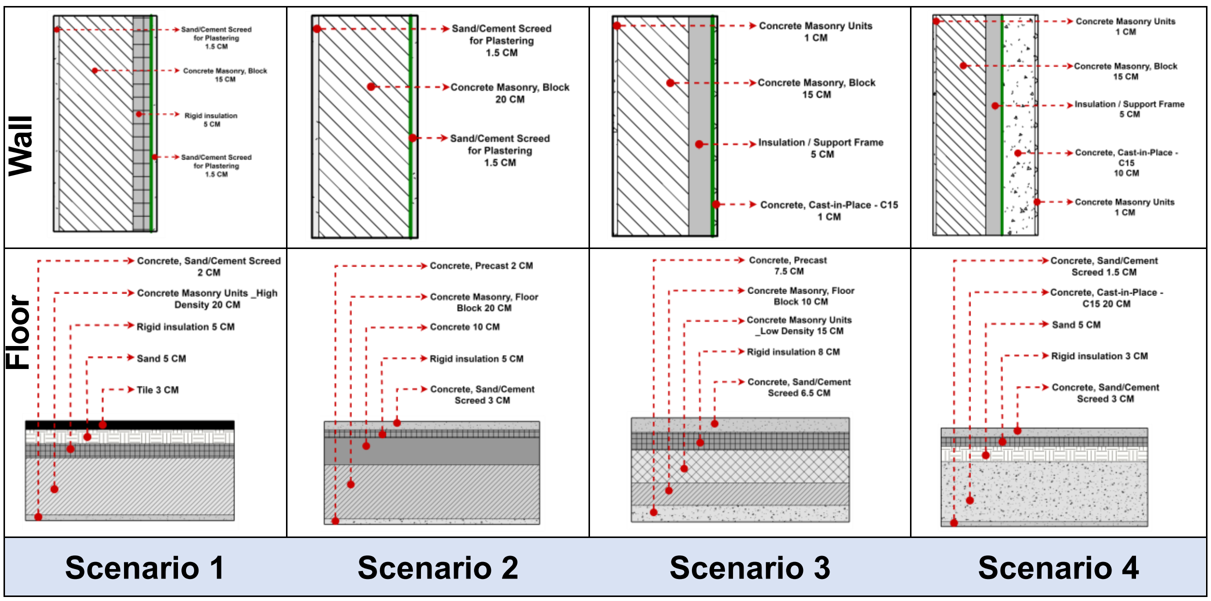


Figure 85: Alternative design Scenarios

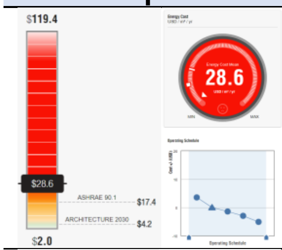
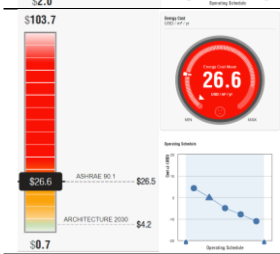
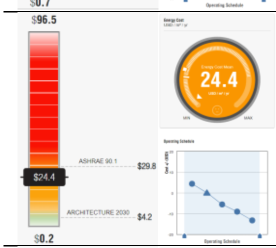
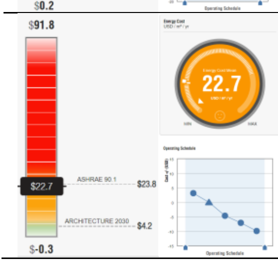
Table 34: Heat transfer coefficient and thermal resistance for several building Scenarios

Elements	Alternative design	Heat Transfer Coefficient (U)	Thermal Resistance (R)	Thermal Masse
Floor	Scenario 1	0.2755 W/m². K	3.6302 (m². K) /W	379.71 KJ/ (m². K)
	Scenario 2	0.1962 W/m². K	5.0961 (m². K) /W	378.91 KJ/ (m². K)
	Scenario 3	0.3801 W/m². K	2.6305 (m². K) /W	592.17 KJ/ (m². K)
	Scenario 4	0.8060 W/m². K	1.2406 (m². K) /W	379.23 KJ/ (m². K)

Wall	**Scenario 1**	0.6247 W/m². K	1.6007 (m². K) /W	273.69 KJ/ (m². K)
	Scenario 2	4.5478 W/m². K	0.2199 (m². K) /W	347.55 KJ/ (m². K)
	Scenario 3	6.2245 W/m². K	0.1607 (m². K) /W	256.89 KJ/ (m². K)
	Scenario 4	3.9310 W/m². K	0.2544 (m². K) /W	408.02 KJ/ (m². K)
Window	**Scenario 1**	1.9873 W/m². K	0.5032 (m². K) /W	-
	Scenario 2 **Scenario 3** **Scenario 4**	3.6886 W/m². K	0.2711 (m². K) /W	-
Door	**Scenario 1** **Scenario 2** **Scenario 3** **Scenario 4**	3.7021 W/m². K	0.2701 (m². K) /W	-

According to the analysis result, the Energy Use Intensity (EUI) for Scenario 1 before changes were made to the wall, roof, window, and door design was 368 kWh/m²/year. After varying the various design criteria, as well as using materials recommended by Autodesk Insight, Scenario 4 reduced the Energy Use Intensity by 289 kWh/m²/year. Approximately 21% of the same amount of energy is saved in Scenario 4 as compared to Scenario 1 (see Table 35). Further, the energy use intensity values decrease in moving from Scenario 1 to Scenario 4, indicating that Scenario 4 is the most energy efficient. Changing the ranges of each design Scenario can reduce the building energy consumption. Modifying the design criteria in the Insight analysis, the Energy Use Intensity (EUI) and the Energy Cost can be lowered to achieve the desired result. It is necessary to consider energy efficiency and costs when evaluating different building operations and design Scenarios.

Table 35: Cost of energy for 4 different Scenarios

Benchmark Comparison	Alternative design	EUI Mean (kWh / m² / yr)	Cost Mean (USD / m² / yr)	Cost Min (USD / m² / yr)
	**Scenario 1**	$378	$28.6	$2
	**Scenario 2**	$342	$26.6	$0.7
	**Scenario 3**	$315	$24.4	$0.2
	**Scenario 4**	$289	$22.7	$-0.3

7.7 Analysis of LCC by using AutoDesk® Green Building Studio

The AutoDesk® Green Building Studio (GBS) provides tools and features to help designers evaluate and optimise the long-term financial and environmental performance of their projects. The GBS provides an integrated view of a project sustainability and financial performance by analysing its LCC in conjunction with its energy and environmental assessment. Through the application of this integrated approach, design strategies and building components can be evaluated for their long-term cost implications. Incorporating LCC into the design process can help to build professionals and contribute to sustainable, cost-effective, and high-performance buildings.

7.7.1 LCC Analysis of Scenarios 1 to 4

A data analysis model was created using the Analysis tab in Autodesk Revit, after calibrating and modifying the necessary parameters. This model was then transmitted to receive data analysis results via an Autodesk account. Concurrently, the energy model will be transferred from Autodesk Revit to both Autodesk Insight and Autodesk Green Building Studio. Climate data, which constitutes the primary environmental aspect surrounding the building, was obtained automatically upon transmission of the energy model by consulting the nearest weather station database. Figure 86 illustrates the average daily minimum and maximum temperatures.

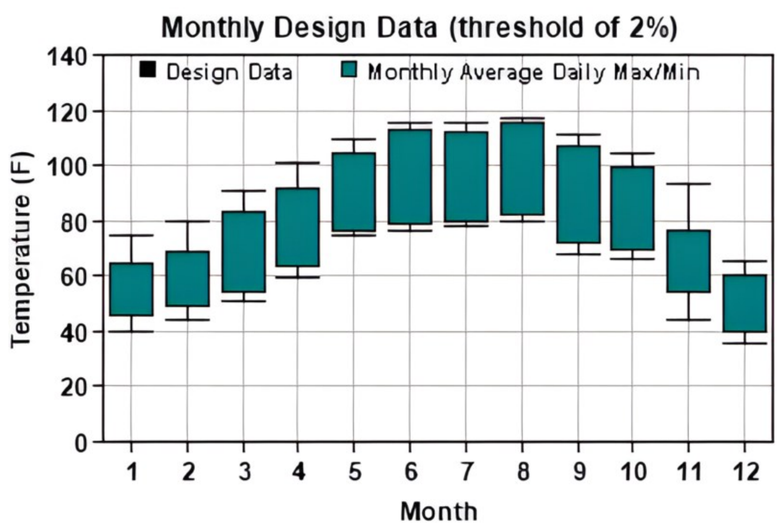


Figure 86: Monthly averages of maximum and minimum temperatures in GBS.

In Figure 87, the climate data are based on annual data and the information is transmitted to the cloud-based GBS engine using the GBXML format, which consists of the data for the year as given.

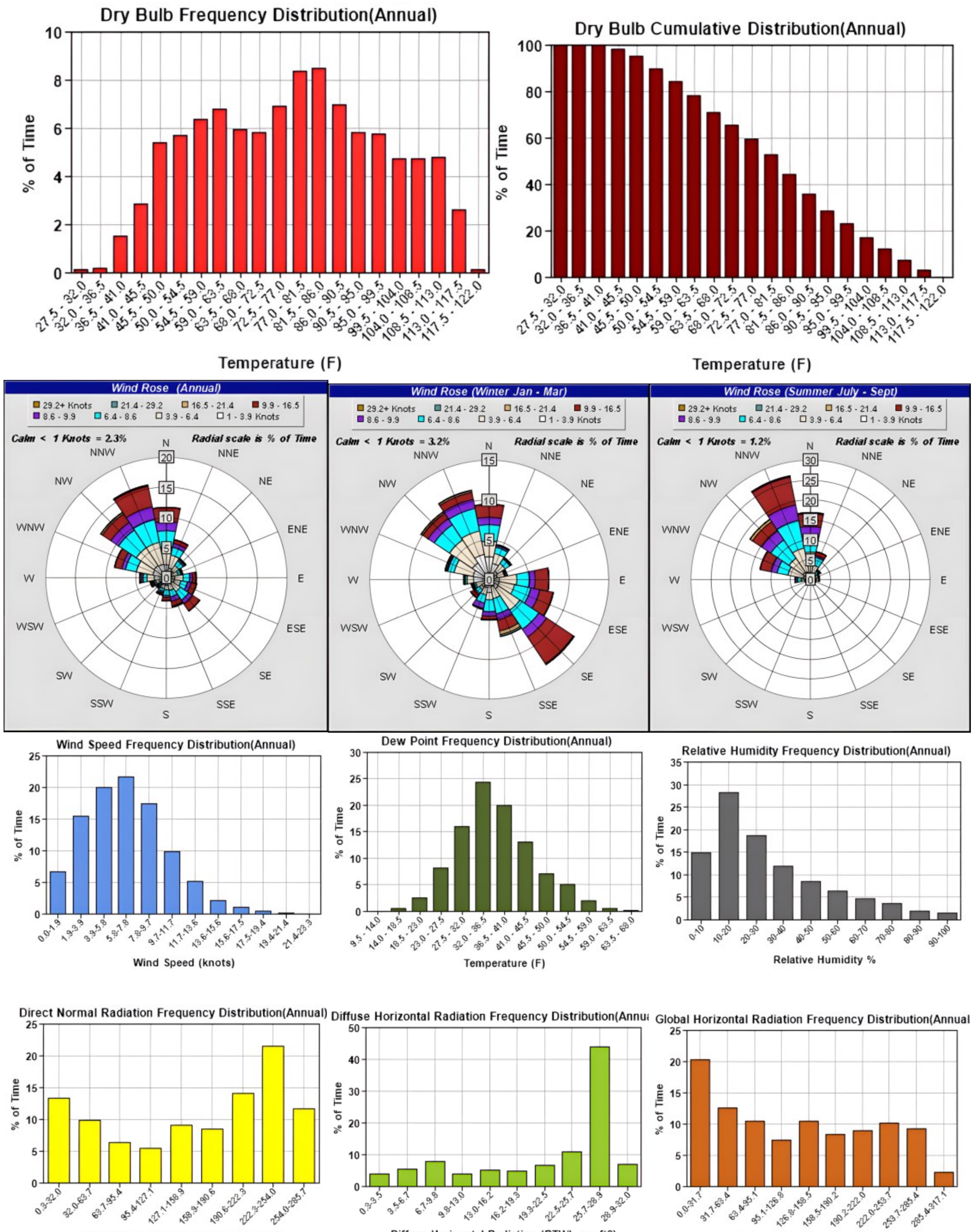


Figure 87: Annual data on climate for the case study in GBS

7.7.2 Result of Analysis of LCC by GBS

According to the simulation results, Scenario 1 exhibited a total Annual Cost of Energy value of $5,267, which was notably higher than the $3,196 value in Scenario 4 after enhancing the alternative design (see Table 36). Moreover, Table 34 demonstrates that the total Annual Cost of Energy in Scenario 1 amounts to $5,267, while it is $4,589 in Scenario 2, $4,005 in Scenario 3, and $3,196 in Scenario 4. Furthermore, the Energy Use Intensity in Scenario 1 stands at 1,715.2 MJ/m²/year, in Scenario 2 at 1,520 MJ/m²/year, in Scenario 3 at 1,237.6 MJ/m²/year, and in Scenario 4 at 908.3 MJ/m²/year.

Nevertheless, total savings amounted to $2,071, representing an approximate 39.31% reduction in energy costs from Scenario 1 to Scenario 4. Additionally, the Energy Use Intensity decreased by approximately 806.9 MJ/m²/year when comparing Scenario 1 with Scenario 4. As a result of the enhancements made to Scenario 4's alternative design, the total annual energy costs and energy intensity have been substantially reduced when compared with Scenario 1. Thus, Scenario 4 has the highest energy efficiency and most cost-effective design among the four Scenarios.

Table 36: Total annual cost and total annual energy

	Energy Use Intensity (MJ/m²/year) *	**Electric Cost (/kWh)**	**Fuel Cost (/MJ)**	**Total Annual Cost**			**Total Annual Energy**	
				Electric	Fuel	Energy	Electric (kWh)	Fuel (MJ)
Scenario 1	1,715.2	$0.09	$0.007	$4,619	$648	$5,267	49,195	87,189
Scenario 2	1,520	$0.09	$0.007	$3,985	$604	$4,589	42,441	81,275
Scenario 3	1,237.6	$0.09	$0.007	$3,366	$640	$4,005	35,842	86,136
Scenario 4	908.3	$0.09	$0.007	$2,850	$346	$3,196	30,347	46,618

* A calculation of the total annual energy consumption, including both electricity and fuel, for the project, expressed per square meter. In this metric, electricity usage is converted from kilowatt-hours (kWh) to megajoules (MJ) according to the international system of units, with 1 kWh equivalent to 3.6 MJ.

As an indicator of building elements insulation performance, the U-value, or thermal transmittance, plays a vital role. In addition to enhancing a building energy efficiency, a lower U-value signifies better insulation and diminished heat transfer. Engineers can refine alternative designs and reduce energy consumption across the entire building life cycle by optimising the U-values of these components (see Table 37). Further, optimising U-values in roofs, walls, doors, and windows with alternative designs can result in significant energy savings and reduced life cycle costs.

Table 37: U-Value of building elements of alternative designs

	U-Value						
	Roofs		Walls		Doors	Windows	
	Floor 1 (129) m²	Floor 2 (156) m²	Wall 1 (554) m²	Wall 2 (5) m²	R2 (25) m²	1/8 in Pilkington (15) m²	Large windows (2) m²
Scenario 1	0.24	0.12	6.22	3.11	2.39	3.69 W / (m²-K) SHGC: 0.86 Vlt: 0.90	5.56 W / (m²-K) SHGC: 0.86 Vlt: 0.90
Scenario 2	0.24	0.20	4.55	2.27	2.39	3.69 W / (m²-K) SHGC: 0.86 Vlt: 0.90	5.56 W / (m²-K) SHGC: 0.86 Vlt: 0.90
Scenario 3	0.24	0.12	3.90	2.35	2.39	3.69 W / (m²-K) SHGC: 0.86 Vlt: 0.90	5.56 W / (m²-K) SHGC: 0.86 Vlt: 0.90
Scenario 4	0.24	0.28	.61	.30	2.39	1.99 W / (m²-K) SHGC: 0.55 Vlt: 0.70	5.56 W / (m²-K) SHGC: 0.86 Vlt: 0.90

Based on a 30-year life expectancy and a discount rate of 6.1% for GBS costs, Table 38 below presents a comparison of LCC and Annual CO_2 Emissions between the four Scenarios. LCC and Annual CO_2 Emissions are significantly different between Scenarios 1 and 4, demonstrating the importance of enhancing alternative designs. In Scenario 1, the total LCC value was $71,739, a significant increase over the $43,529 value observed in Scenario 4. Additionally, the percentage decrease in LCC between Scenarios 1 and 4 was significant. The annual CO_2 emissions in Scenario 1 were approximately 4.3 million tons, whereas in Scenario

4 these emissions decreased to 2.3 million tons. Compared to Scenario 1, Scenario 4 has resulted in significant reductions in both LCC and annual CO_2 emissions as a result of the enhancement of the alternative design. Thus, the LCC of Scenario 4 has been reduced by 39.34%, whereas CO_2 emissions have been reduced by 46.51%, making it the most cost-effective and environmentally-friendly Scenario among the four.

Table 38: Life Cycle Cost (LCC) and annual CO2 emissions

	Life Cycle Cost (LCC) *	Annual CO_2 Emissions (Onsite Fuel)	Energy Use Intensity (EUI)	Life Cycle Energy	
				Electric	Fuel
Scenario 1	$71,739	4.3 Mg	1,715 MJ / m² / year	1,475,854 kW	2,615,669 MJ
Scenario 2	$62,503	4.1 Mg	1,520 MJ / m² / year	1,273,236 kW	2,438,254 MJ
Scenario 3	$54,555	3.6 Mg	1,238 MJ / m² / year	1,241,911 kW	2,156,455 MJ
Scenario 4	$43,529	2.3 Mg	908 MJ / m² / year	910,409 kW	1,398,549 MJ

* The calculation assumes a 30-year life expectancy and a discount rate of 6.1% for costs. Transmission losses as well as renewable and natural ventilation potentials are not considered.

It is evident from these results that energy-efficient design strategies, such as optimising U-values, are essential for reducing life cycle costs and environmental impacts. The pie chart in Figure 88 illustrates the total amount of energy and fuel used annually for all Scenarios. In the world of electricity consumption, the amount of electricity used for cooling equipment, fans, lights, and other miscellaneous equipment is referred to as electricity consumption, while in the world of fuel consumption, the amount of energy used for heating and cooling is known as fuel.

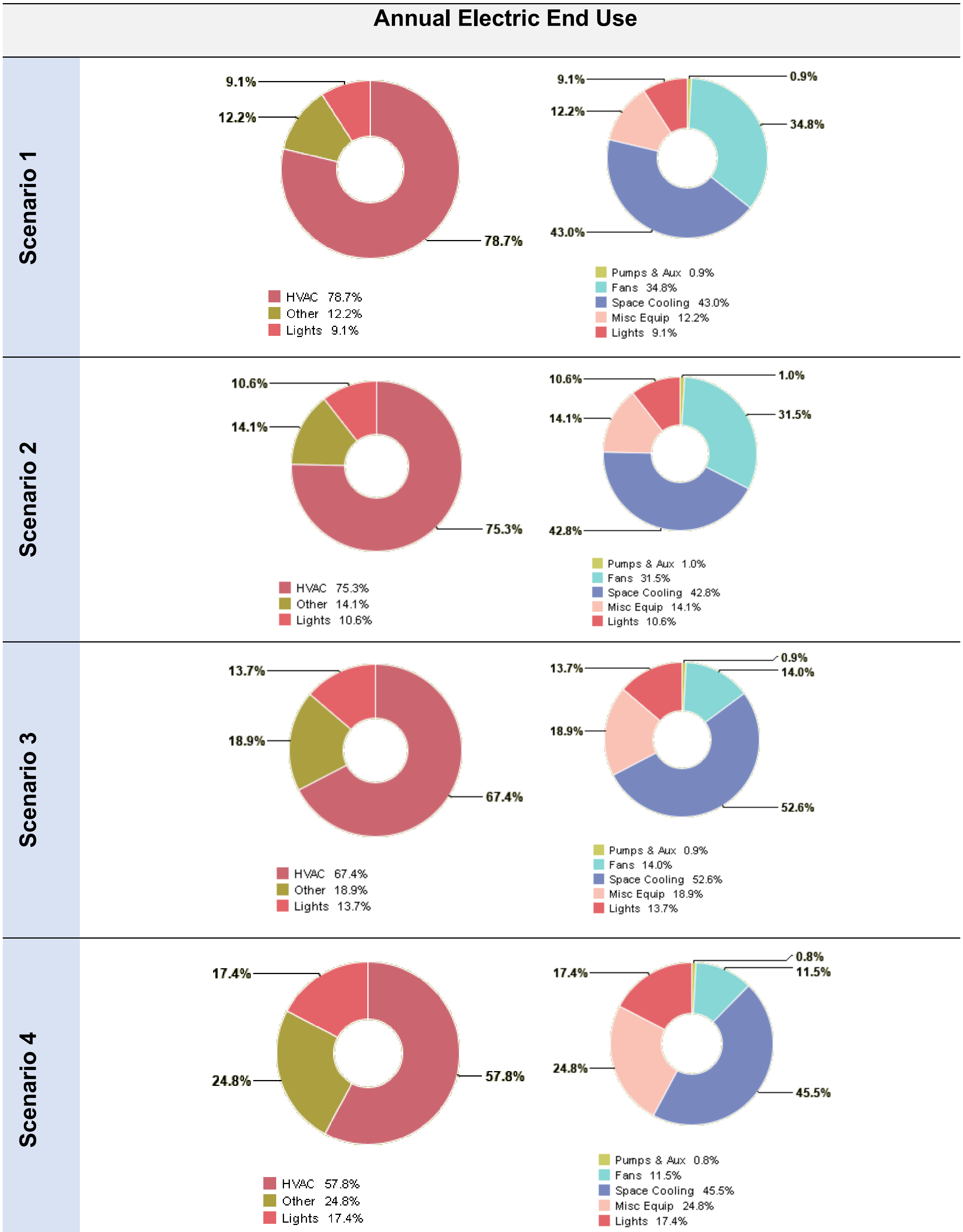


Figure 88: Analysis of annual electric and fuel end use in GBS

As shown in Figure 89, the analysis primarily provides an analysis of the annual energy consumption, which measures the amount of electricity and fuel that the project can consume during a typical annual period as well as the lifecycle energy consumption for a Scenario of 30 years. Furthermore, GBS can alternate that Scenario and enhance it to the best option for reducing costs; as shown in Figure 90, step 2 for the design alternative compared with the base run. The results indicate a 6.7% reduction in Annual Energy Costs and LCC for the design alternative as compared with the base case in Scenario 4.

1 Base Run

Energy, Carbon and Cost Summary		
	Annual Energy Cost	$3,196
	Lifecycle Cost	$43,529
Annual CO_2 Emissions		
	Electric	0.0 Mg
	Onsite Fuel	2.3 Mg
	Large SUV Equivalent	0.2 SUVs / Year
Annual Energy		
	Energy Use Intensity (EUI)	922 MJ / m² / year
	Electric	30,347 kWh
	Fuel	46,618 MJ
	Annual Peak Demand	7.9 kW
Lifecycle Energy		
	Electric	910,409 kW
	Fuel	1,398,549 MJ
Assumptions (i)		

Figure 89: Results of base run design for LCC in GBS

2 Design Alternative

Estimated Energy & Cost Summary	
Annual Energy Cost	$2,982
Lifecycle Cost	$40,616
Annual CO_2 Emissions	
Electric	0.0 Mg
Onsite Fuel	3.1 Mg
Large SUV Equivalent	0.3 SUVs / Year
Annual Energy	
Energy Use Intensity (EUI)	922 MJ / m² / year
Electric	26,893 kWh
Fuel	61,491 MJ
Annual Peak Demand	7.6 kW
Lifecycle Energy	
Electric	806,777 kW
Fuel	1,844,718 MJ
Assumptions	

Figure 90: Results of alternative design for LCC in GBS

In the provided dataset, four distinct scenarios are evaluated for a building project using various metrics indicative of sustainability and efficiency. These metrics include LCC, Annual CO2 Emissions (attributable to onsite fuel consumption), Energy Use Intensity (EUI), and Life Cycle Energy, with the latter being bifurcated into electrical and fuel-based energy. The LCC, a crucial metric, encapsulates the comprehensive cost of building ownership across a 30-year horison, factoring in a discount rate of 6.1%. A preliminary analysis reveals a noticeable trend across the scenarios: as one progresses from

Scenario 1 through to Scenario 4, there is a marked decrease in LCC, CO_2 emissions, EUI, and total life cycle energy. This pattern ostensibly points towards enhanced efficiency and sustainability in the latter scenarios.

To extend the LCC analysis to a 50-year period, it becomes necessary to recalibrate the existing LCC figures, which are initially predicated on a 30-year lifecycle. The original computation employs a discount rate of 6.1%, a parameter that remains unchanged in the extended analysis. The core of this calculation lies in determining the present value of future costs, a task achieved through the formula:

$$PV = \frac{C}{(1+r)t}$$

PV = The present value.
C = The future cost.
r = The discount rates.
t = The time in years.

This formula is instrumental in recalculating the LCC for a 50-year duration, maintaining the foundational assumptions of the initial analysis. The calculated LCC for each scenario over a 50-year period, considering a constant annual cost and a 6.1% discount rate, are as follows: (Scenario 1: $76,343.84, Scenario 2: $66,514.99, Scenario 3: $58,056.82, and Scenario 4: $46,323.08). This extension from a 30-year to a 50-year period demonstrates a moderate increase in the LCC for each scenario. Consequently, Figure 91 shows the annual cost for each scenario from the first year to the 50th year, calculated at a 6.1% discount rate. It provides the present value of the costs for each year, reflecting the time value of money for scenarios.

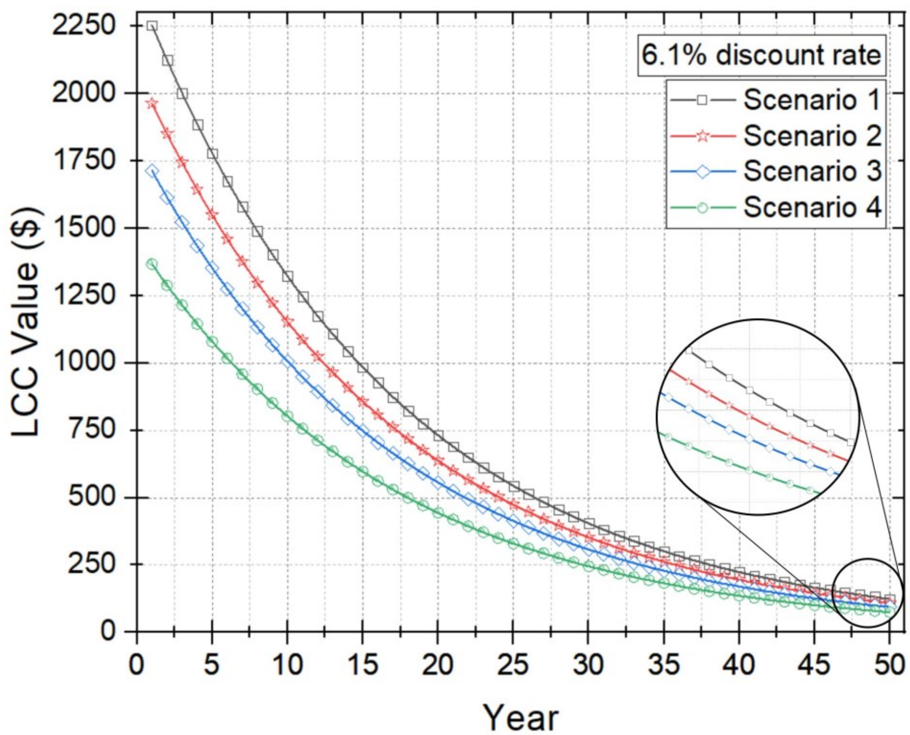


Figure 91: The Cost of LCC for 4 scenarios over 50 years

7.8 Sustainability and Building Circularity Analysis by One Click LCA

The One Click LCA standardised platform is a BIM tool for analysing sustainability and developing circularity. The One Click LCA integrates BIM data, construction drawings, and material specifications into one seamless analysis process. Furthermore, the database provides information on the environmental impact of various materials and processes. One Click LCA offers high-cost and environmental benefits through integrated LCC and LCA. In addition, the software considers these factors during the building construction and use. A comprehensive LCA can be calculated quickly using One Click LCA and BREEAM sustainability criteria and circularity can be analysed. Moreover, users can modify and select materials to simulate carbon emission reductions. Through this flexibility, professionals can make more informed decisions about sustainable design options and optimise their projects to achieve the most effective results.

7.8.1 Data Collection from Revit to One Click LCA

In Revit, the One Click LCA plugin facilitates automatic data import. Upon activating the LCA from the Revit button, the plugin prompts users to choose the desired materials and categories. After an in-depth evaluation, filtering, and assignment of the necessary categories and materials, the plugin enables rapid data synchronisation from Revit to One Click LCA by activating the LCA in the cloud button (see Figure 92).

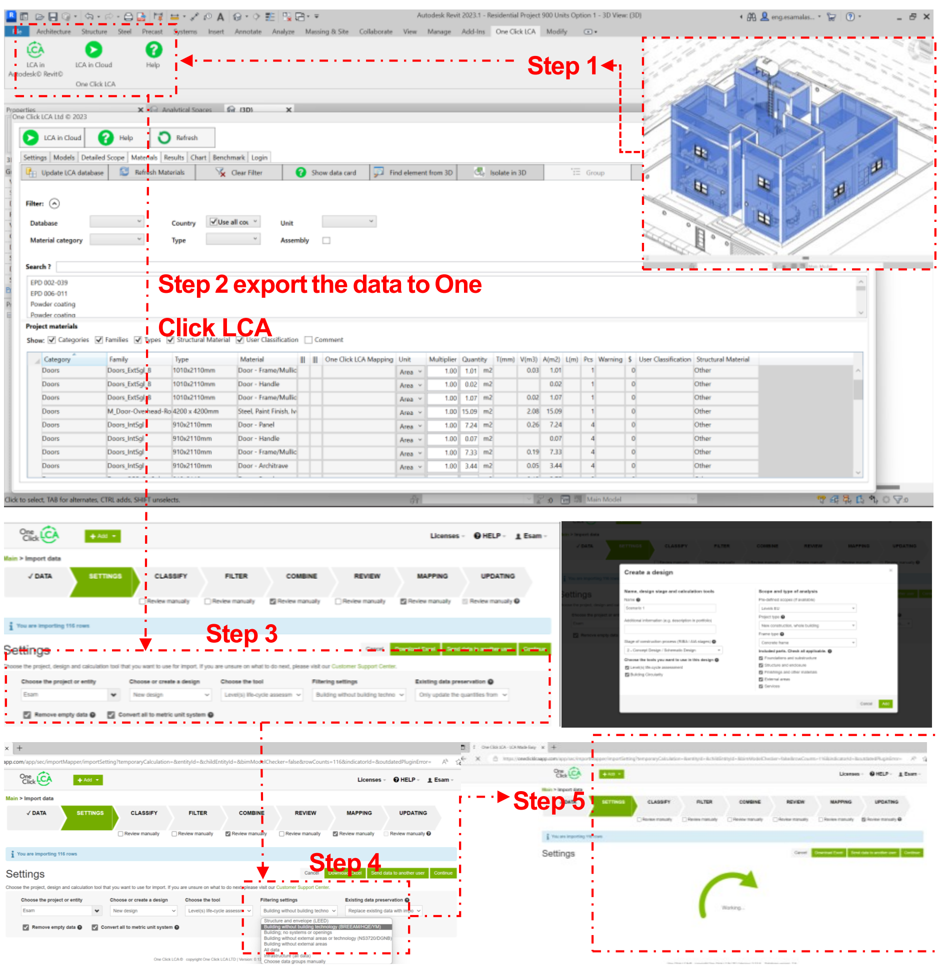


Figure 92: Data export from Revit to One Click LCA

In the order shown in Figure 93, these actions include setting, categorising, filtering, combining, reviewing, mapping, and updating. In this analysis, 50 years of building service life were assumed as part of the classification and filtering process. After selecting the appropriate options in earlier steps, the software automatically performs these tasks until the updating step is completed. On the Results tab, the platform displays the building LCC/LCA based on BREEAM sustainability criteria, circular economy, and carbon footprint.

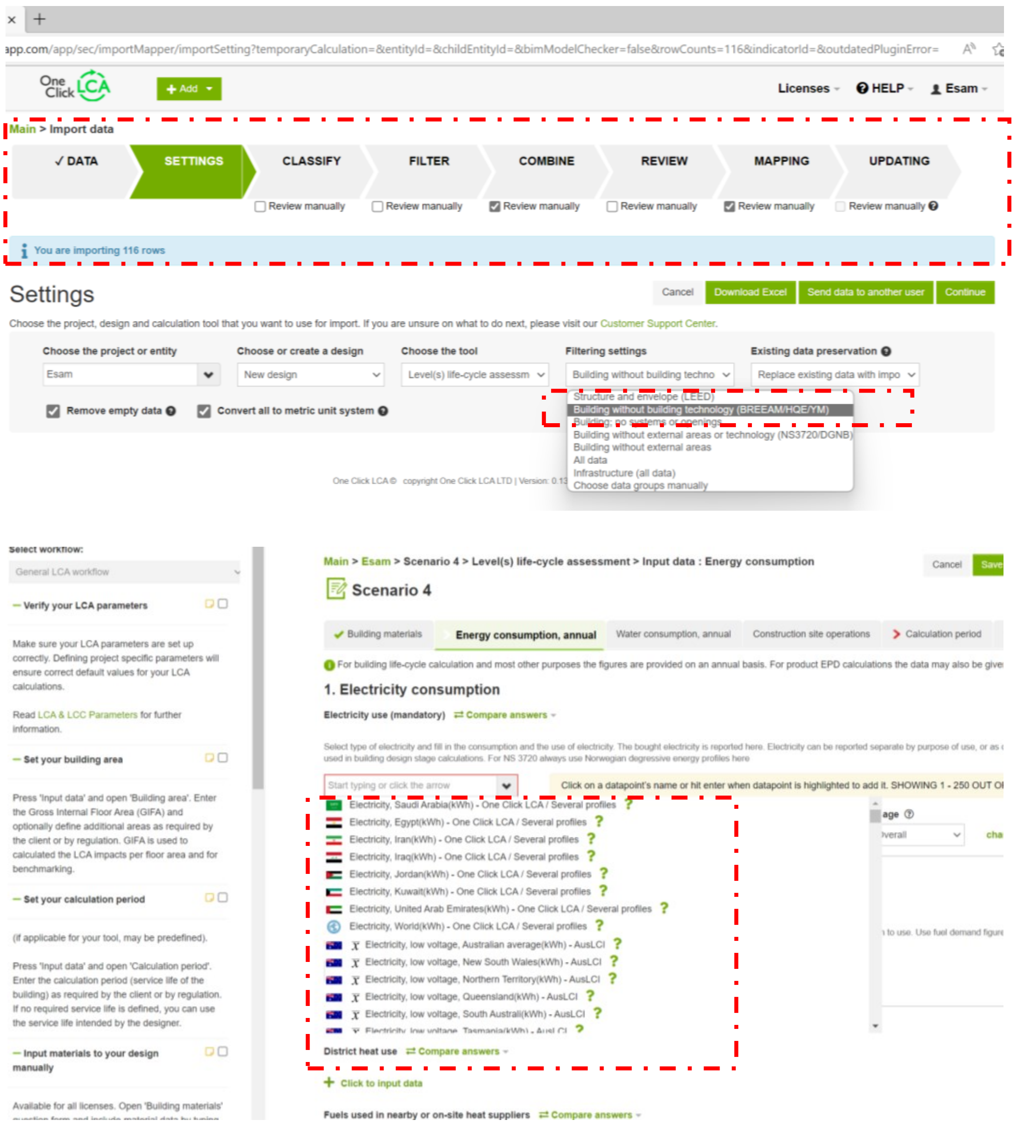


Figure 93: Step-by-step guide for the evaluation of a building and choosing its elements

7.8.2 Result of Data Evaluation for a Case Study in One Click LCA

In this analysis, the primary objective is to evaluate the impact of building materials on the environment using One Click LCA. As shown in Table 39, the materials contributing the most across various environmental impact categories were identified from the production stage through the entire building lifecycle including replacement and maintenance. As shown in the following table, the life cycle assessment of both Scenarios was conducted in accordance with EN15978 life cycle stages.

Table 39: One Click LCA assessment of life cycle stages.

Preconstruction stage	**Product Stage**			**Construction Process Stage**		**Use Stage**							**End-of-Life Stage**				**Benefits and loads beyond the system boundary**		
Activity carried out before a development site is selected	Raw material supply	Transport	Manufacturing	Transport to building site	Installation into building	Use/application	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	Deconstruction/demolition	Transport	Waste processing	Disposal	Reuse	Recovery	Recycling
A0	**A1**	**A2**	**A3**	**A4**	**A5**	**B1**	**B2**	**B3**	**B4**	**B5**	**B6**	**B7**	**C1**	**C2**	**C3**	**C4**	**D**	**D**	**D**

7.8.3 Results of Scenario 1 and Scenario 4:

As shown in Figure 94, the carbon footprint for analysis Scenario 1 is the quantity of carbon dioxide released into the atmosphere as a result of a combination of greenhouse gases. According to the One Click LCA software, building elements include foundations, substructures, vertical structures, façades, and horizontal structures. During the study period of 50 years, the cumulative impact of all life-cycle stages results in approximately 369 tons of

CO_2e emissions, which is equivalent to 25.09 kg of CO_2e per square meter annually. In addition, the social cost of carbon is estimated to be €18,455. Figure 98illustrates that vertical structures and facades make up 49% of the entire embodied carbon distribution from stage A1 to A3. There is a significant difference between the distribution of embodied carbon on the foundation and substructure, which accounts for 24%, the distribution of embodied carbon on horizontal structures like beams, floors, and roofs, which accounts for 18%, and the distribution of embodied carbon on other structures and materials accounting for 15%.

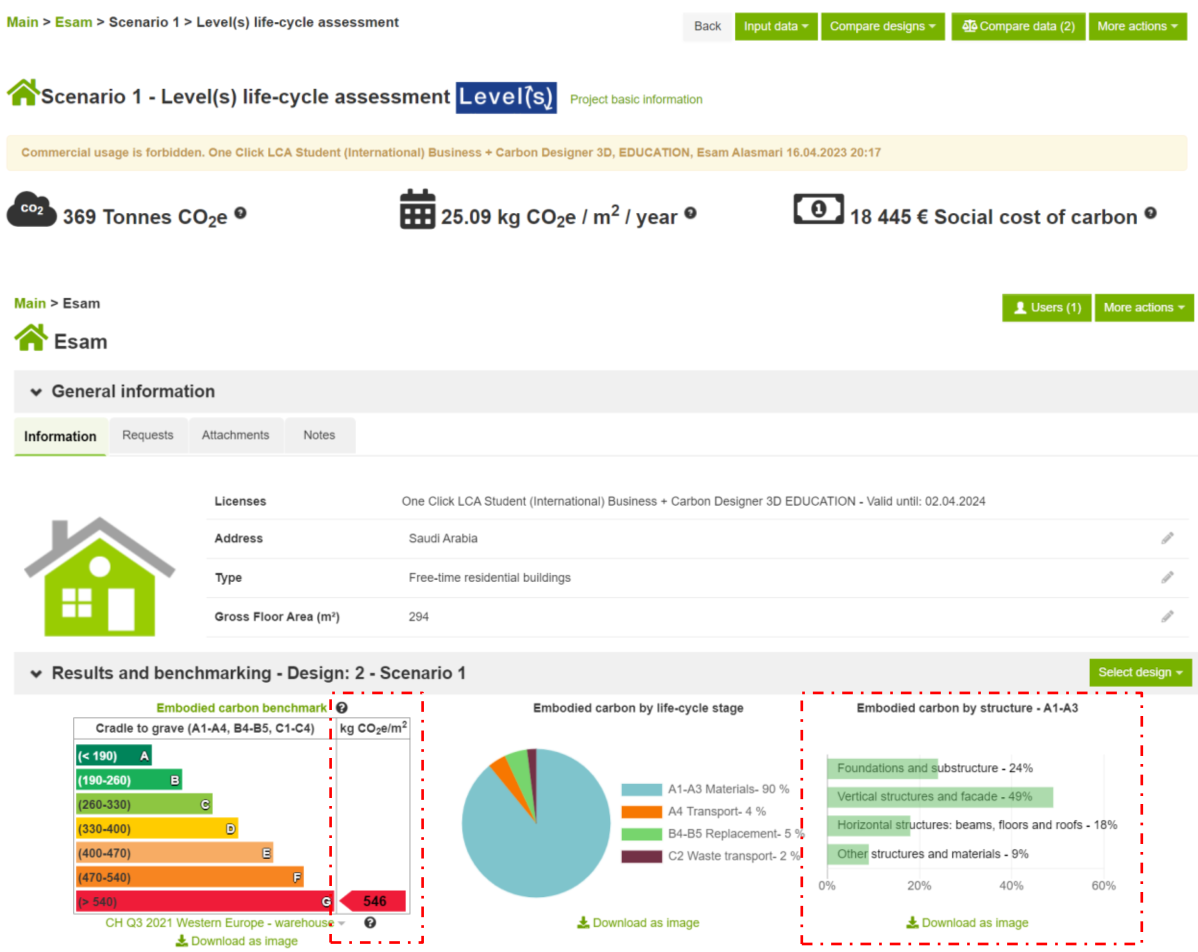


Figure 94: Results of the LCA calculation and the carbon benchmark for Scenario 1

Figure 95 shows how One Click LCA software can be used to conduct a Life Cycle Assessment (LCA) for Level(s), as per the European standard EN15978. In order to improve the environmental performance of buildings throughout their entire life cycle, Level(s) serves as a European framework for sustainable building evaluation. LCAs on buildings are conducted in a consistent, comparable, and credible manner in accordance with EN 15978. One Click LCA software is designed to provide Life-Cycle Assessment for Level(s)' compliance, including Construction Materials (A1-A3), Transport to the site and construction and installation processes (A4-A5), the use stage (B1-B7), the end-of-life stage (C1-C4), as well as potential benefits and loads outside the system boundary (D).

Life-Cycle Assessment for Level(s) in compliancy with EN 15978 Download Results Summary

	Result category	Global warming kg CO_2e	Biogenic carbon storage kg CO_2e bio	Ozone Depletion kg CFC11e	Acidification kg SO_2e	Eutrophication kg PO_4e	Formation of ozone of lower atmosphere kg Ethenee	Abiotic depletion potential (ADP-elements) for non fossil resources kg Sbe	Abiotic depletion potential (ADP-fossil fuels) for fossil resources MJ	
A1-A3	Construction Materials	1,44E5	6,72E2	7,79E-3	3,84E2	6,3E1	2,86E1	1,92E0	1,27E6	Details
A4	Transportation to site	6,69E3		1,14E-3	1,13E1	2,34E0	9,6E-1	3,55E0	9,56E4	Details
A5	Construction/installation process	9,09E4		4,61E-3	2,34E2	9,76E1	9,86E0	4,02E1	6,77E5	Details
B1	Use phase	1,13E5	1,1E4	0E0	0E0	0E0	0E0	0E0	0E0	Details
B3	Repair	0E0		0E0	0E0	0E0	0E0	0E0	0E0	Details
B4-B5	Material replacement and refurbishment	7,5E3		1,89E-3	4,08E1	6,97E0	2,33E0	2,95E0	2,51E5	Details
B6	Energy consumption	3,39E3		4,35E-4	1,75E1	1,43E0	6,97E-1	1,02E2	4,8E4	Details
B7	Water use	3,56E0		2,55E-7	2,43E-2	5,66E-3	8,55E-4	1,07E-5	5,18E1	Details
C1-C4	End of life	3,29E3		6,26E-4	1,32E1	2,83E0	2,74E-1	1,88E1	8,39E4	Details
D	External impacts (not included in totals)	-2,61E4		3,71E-4	1,44E1	4,55E0	2,2E-1	4,2E-1	1,23E4	Details
	Total	**3,69E5**	**1,17E4**	**1,65E-2**	**7,01E2**	**1,74E2**	**4,27E1**	**1,69E2**	**2,43E6**	
	Results per denominator									
	Per gross internal floor area m2 / year	2,51E1	7,97E-1	1,12E-6	4,77E-2	1,18E-2	2,9E-3	1,15E-2	1,65E2	
	Per gross internal floor area m2	1,25E3	3,98E1	5,61E-5	2,39E0	5,92E-1	1,45E-1	5,76E-1	8,25E3	

Figure 95: Results of evaluation of LCA for Level(s) in compliancy with EN15978 for Scenario 1

Through One Click LCA software, users can identify the materials that contribute most to Global Warming Potential (GWP) throughout a building life cycle. Climate change is measured by the amount of carbon dioxide equivalent (CO_2e) emitted by greenhouse gas emissions. The ability to identify materials that contribute the most to GWP can help professionals make informed decisions regarding material selection and design strategies to minimise the carbon footprint of their projects (see Table 40).

Table 40: Global warming is primarily caused by materials

Most contributing materials (Global warming)			
No	**Resource**	**Cradle to gate impacts (A1-A3)**	
1	Ready-mix concrete, normal-strength, generic, C30/37 (4400/5400 PSI), 10% (typical) recycled binders in cement (300 kg/m3 / 18.72 lbs/ft3)	**52 tonnes CO_2e**	**36.0 %**
2	Ready-mix concrete, normal-strength, generic, C40/50 (5800/7300 PSI), 10% (typical) recycled binders in cement (400 kg/m3 / 24.97 lbs/ft3)	**29 tonnes CO_2e**	**20.1 %**
3	Cementitious finishing and repair screed, 0-5 mm, 1.3 kg/m2/mm, 1.6-1.8 kg/l_2	**21 tonnes CO_2e**	**14.9 %**
4	Ready-mix concrete, normal strength, generic, C35/45 (5000/6500 PSI) with CEM I, 0% recycled binders (340 kg/m3; 21.2 lbs/ft3 total cement)	**8,8 tonnes CO_2e**	**6.1 %**
5	Ready-mix concrete, C30/37 (B30 M60 D16 STD FA), synk 220, (16mm max gravel fraction used) **CO_2**	**6,6 tonnes CO_2e**	**4.6 %**
6	Ready-mix concrete, normal strength, generic, C25/30 (3600/4400 PSI) with CEM III/A, 60% GGBS content (280 kg/m3; 18.7 lbs/ft3 total cement)	**5,1 tonnes CO_2e**	**3.5 %**
7	Rock wool insulation panels, unfaced, generic, L = 0.035 W/mK, R = 2.89 m2K/W (16 ft2°Fh/BTU), 50 kg/m3 (3.12 lbs/ft3) (applicable for densities: 25-50 kg/m3 (1.56-3.12 lbs/ft3)), Lambda=0.0346 W/(m.K) **CO_2**	**3,8 tonnes CO_2e**	**2.7 %**
8	Aluminium mullion-transom system with triple glasing, 36.7 kg/m2	**3,6 tonnes CO_2e**	**2.5 %**
9	Asphalt, generic, compacted, 5/95% bitumen-aggregate ratio, 2350 kg/m3	**3 tonnes CO_2e**	**2.1 %**
10	Ready-mix concrete, high strength, generic, C55/67 (7977/9717 PSI) with CEM II/A-S, 20% GGBS in cement (466 kg/m3; 29.1 lbs/ft3 total cement)	**2,6 tonnes CO_2e**	**1.8 %**
11	Window, skylight, insulating glass, 1.2 x 1.2 m, 72.06 kg/m2	**2,1 tonnes CO_2e**	**1.5 %**
12	Window, double glased, PVC-U frame, tilt and turn, per square meter, 1.3 W/m2K, 1.23x1.48 m/piece	**1,5 tonnes CO_2e**	**1.0 %**
13	Industrial and garage sectional door with electric drive, 19.53 kg/m2, std dim.: 3800 x 3500 mm, Lambda=0.168 W/(m.K)	**1,3 tonnes CO_2e**	**0.9 %**
14	Ready-mix concrete, normal strength, generic, C30/37 (4400/5400 PSI) with CEM III/A, 50% GGBS content in cement (300 kg/m3; 18.7 lbs/ft3 total cement)	**0,89 tonnes CO_2e**	**0.6 %**

15	Precast concrete wall elements (solid, uninsulated), generic, C30/37 (4400/5400 PSI), 0% (typical) recycled binders in cement (300 kg/m3 / 18.72 lbs/ft3), incl. reinforcement **CO_2**	**0,65 tonnes CO_2e**	**0.5 %**
16	Plastic film for damp proofing, 12 / 15 / 20 mm	**0,69 tonnes CO_2e**	**0.5 %**
17	Ready-mix concrete, low-strength, generic, C12/15 (1700/2200 PSI), 0% recycled binders in cement (220 kg/m3 / 13.73 lbs/ft3)	**0,47 tonnes CO_2e**	**0.3 %**
18	Doors with wooden frame, interior	**0,38 tonnes CO_2e**	**0.3 %**
19	Mirror glass, 4 mm, 10.78 kg/m2	**76 kg CO_2e**	**0.1 %**
20	Polypropylene vapour membrane, French average, 0.18 kg/m2	**0,17 tonnes CO_2e**	**0.1 %**
21	Removable/mobile partitions with aluminium frame, glased, 38.02 kg/m2	**36 kg CO_2e**	**0.0 %**
22	Softwood timber from spruce and pine, planed, 50 mm x 125 mm, 480 kg/m3, 16-20% moisture content **CO_2**	**0 kg CO_2e**	**0.0 %**

As a result of using primary energy across various stages of its lifecycle, Table 41 provides a detailed overview. Each stage represents a percentage of energy consumption, which allows understanding of the environmental impact and identifying potential improvements. 49.1% (1,200,000 MJ) of the total energy consumed by materials (A1-A3) constitutes 49.1% (1,200,000 MJ) of primary energy consumption. On the other hand, the Waste Processing stage (C3) consumes the least energy, representing only 0.01 per cent (190 MJ) of total energy use. It has been determined that some lifecycle stages, such as those associated with materials and construction, significantly affect primary energy consumption. Focusing on these high-impact areas and considering improvements across all stages makes it possible to identify opportunities to optimise energy consumption and reduce a product's or a process's overall environmental footprint. Nevertheless, its sustainability can still be enhanced.

Table 41: Total use of primary energy ex. raw materials MJ - Life-cycle stages

Item	Value	Percentage
A1-A3 Materials	1 200 000 MJ	49.1 %

A4 Transport	110 000 MJ	4.53 %
A5 Construction	760 000 MJ	31.83 %
B4-B5 Replacement	210 000 MJ	8.89 %
B6 Energy	48 000 MJ	2.02 %
B7 Water	58 MJ	0.0 %
C1 Deconstruction/demolition	12 000 MJ	0.5 %
C2 Waste transport	75 000 MJ	3.11 %
C3 Waste processing	190 MJ	0.01 %

The One Click LCA software incorporates charts as one of its key components, enabling users to visualise data, compare alternatives, monitor progress, target improvements, and communicate effectively with stakeholders to enhance sustainability. Using Figure 96 and Figure 97, the user can compare alternative materials, products or processes regarding environmental performance. The chart can also be used to compare alternatives to the life cycle of global warming. A comparison of alternative options can assist users in making more informed decisions about options with a lower environmental impact.

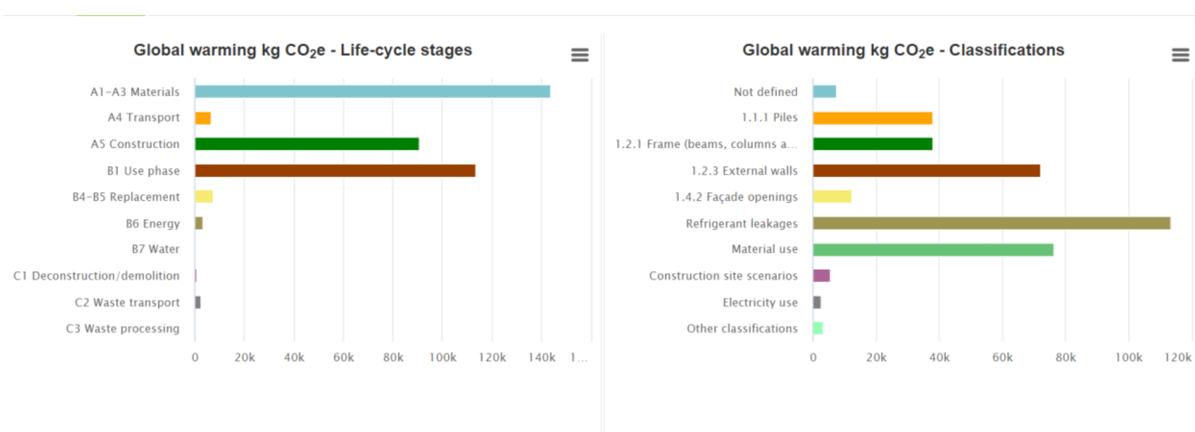


Figure 96: Overview of global warming's life cycle for Scenario 1

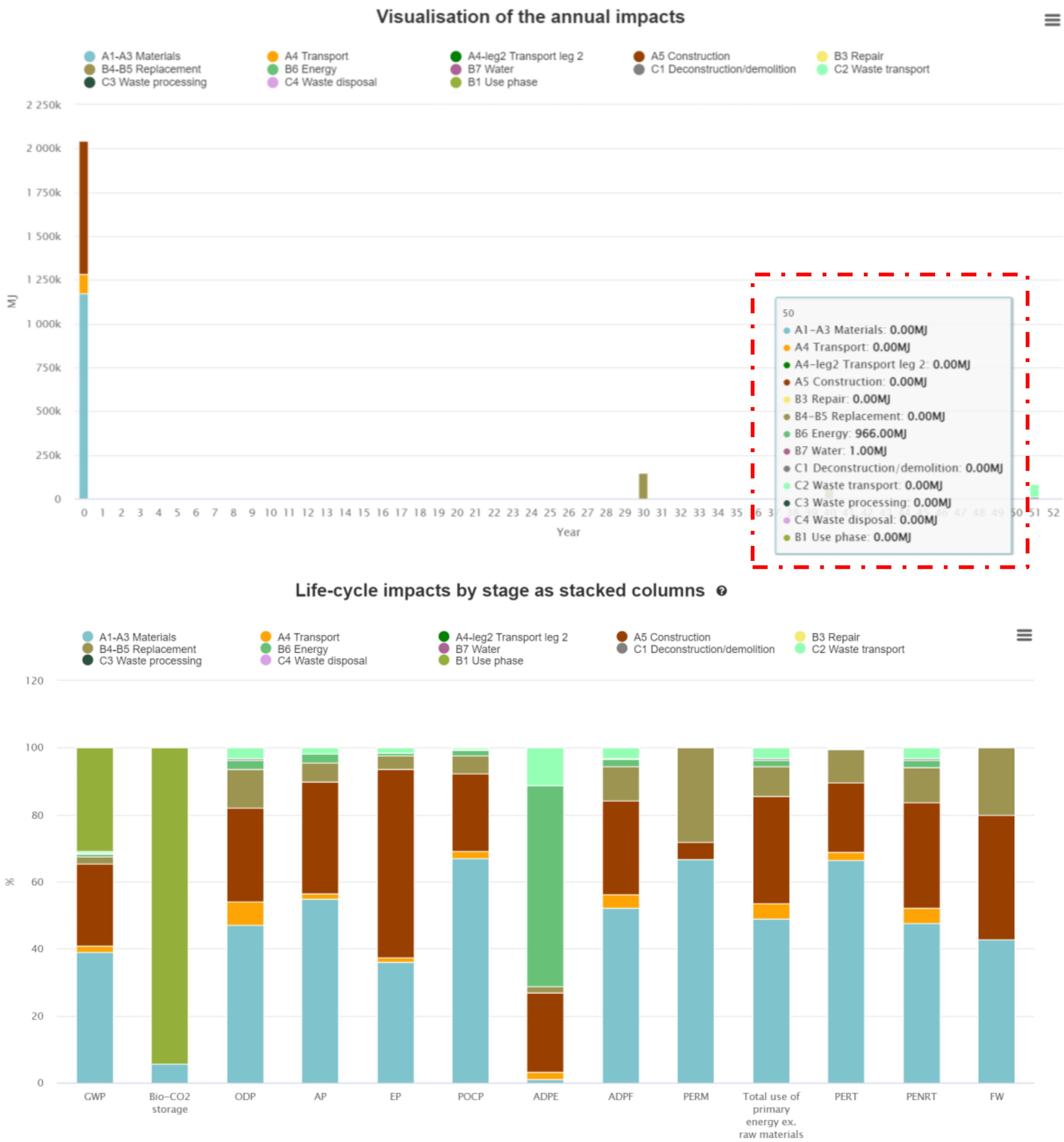


Figure 97: Life cycle and annual impacts for 50 years for Scenario 1

As a result of enhancing the alternative design in Scenario 4, Figure 98 shows that, during the 50-year study period, the cumulative impact of the lifecycle stages results in approximately 189 tons of CO_2e emissions or 12.68 kilograms per square meter. Through optimisation enhancement, CO_2e emissions were decreased by 48.8%, and the social cost of carbon decreased to €9,453. Additionally, Figure 97 indicates that from stage A1 to stage A3, vertical structures and façades account for 36% of embodied carbon. Based on embodied carbon distribution, foundations and substructures account for 22%, horizontal structures like beams, floors, and roofs are responsible for 29%, and other structures and materials are responsible for 13% of carbon emissions.

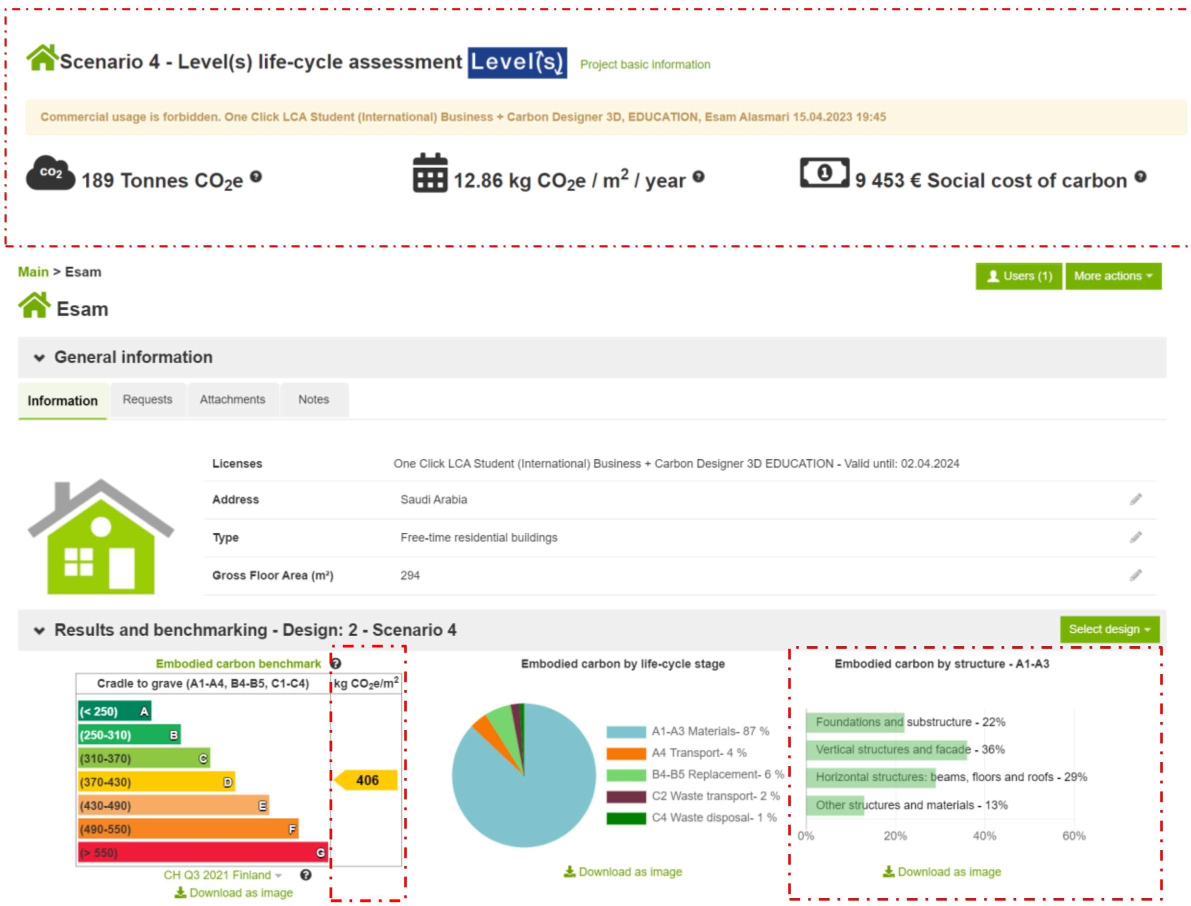


Figure 98: Results of the LCA calculation and the Carbon Benchmark for Scenario 4

7.8.4 Comparison of the Results of Scenario 1 and Scenario 4

According to Figure 103 and the Level(s) lifecycle assessment, the low energy/carbon building (Scenario 4) has a significantly reduced environmental impact across all impact categories in comparison with the baseline building. The most significant emissions reduction occurs during the A1-A3 materials stage, according to global warming lifecycle assessments. As estimated at 143,687.72 kg CO_2e in Scenario 1, the A1-A3 Materials stage contributes to the environment, whereas that contribution decreases to 103,258.82 kg CO_2e in Scenario 4. By analysing the lifecycle assessments of specific elements, the potential benefits are able to demonstrate the low-energy/carbon-building strategies. During Scenario 1, the external walls produce 72,058.26 kg CO_2e, whereas in Scenario 4 they emit 35,425.81 kg CO_2e. Moreover, the decrease in emissions from Scenario 1 to Scenario 4 for the A1-A3 Materials stage is approximately 28.13%, while the decrease in emissions for the external walls is approximately 50.87%.

	Result category	Global warming kg CO_2e	Biogenic carbon storage kg CO_2e bio	Ozone Depletion kg CFC11e	Acidification kg SO_2e	Eutrophication kg PO_4e	Formation of ozone of lower atmosphere kg Ethenee	Abiotic depletion potential (ADP-elements) for non fossil resources kg Sbe	Abiotic depletion potential (ADP-fossil fuels) for fossil resources MJ	
A1-A3	Construction Materials	1,03E5 | -28 %	6,72E2 | 0 %	5,95E-3 | -24 %	2,75E2 | -29 %	5,07E1 | -20 %	2,15E1 | -25 %	2,5E0 | +30 %	8,94E5 | -30 %	Details
A4	Transportation to site	5,3E3 | -21 %		9,04E-4 | -21 %	8,96E0 | -21 %	1,85E0 | -21 %	7,6E-1 | -21 %	2,85E0 | -20 %	7,58E4 | -21 %	Details
A5	Construction/installation process	5,54E4 | -39 %		3,84E-3 | -17 %	2,11E2 | -9,8 %	6,14E1 | -37 %	8,01E0 | -19 %	3,2E1 | -20 %	5,29E5 | -22 %	Details
B1	Use phase	1,18E4 | -90 %	5,52E3 | -50 %							Details
B3	Repair									Details
B4-B5	Material replacement and refurbishment	6,94E3 | -7,5 %		1,87E-3 | -1,4 %	3,86E1 | -5,2 %	6,78E0 | -2,7 %	2,23E0 | -4,3 %	2,93E0 | -0,7 %	2,38E5 | -5,2 %	Details
B6	Energy consumption	1,96E3 | -42 %		2,43E-4 | -44 %	9,59E0 | -45 %	8,35E-1 | -41 %	3,9E-1 | -44 %	1,02E2 | -0 %	2,79E4 | -42 %	Details
B7	Water use	3,56E0 | 0 %		2,55E-7 | 0 %	2,43E-2 | 0 %	5,66E-3 | 0 %	8,55E-4 | 0 %	1,07E-5 | 0 %	5,18E1 | 0 %	Details
C1-C4	End of life	4,45E3 | +35 %		8,23E-4 | +32 %	2,32E1 | +76 %	4,97E0 | +76 %	5,81E-1 | +110 %	1,48E1 | -21 %	9,24E4 | +10 %	Details
D	External impacts (not included in totals)	-2,19E4 | -16 %		3,78E-4 | +1,8 %	1,43E1 | -0,6 %	3,99E0 | -12 %	1,9E-1 | -14 %	3,54E-1 | -16 %	1,66E4 | +35 %	Details
	Total	**1,89E5**	**6,19E3**	**1,36E-2**	**5,66E2**	**1,26E2**	**3,34E1**	**1,57E2**	**1,86E6**	
	Comparing total results with: 2 - Scenario 1									
	2 - Scenario 1 Total	3,69E5	1,17E4	1,65E-2	7,01E2	1,74E2	4,27E1	1,69E2	2,43E6	
	2 - Scenario 4 compared with 2 - Scenario 1	-49 %	-47 %	-17 %	-19 %	-27 %	-22 %	-7,3 %	-23 %	
	Results per denominator									
	Per gross internal floor area m2 / year	1,29E1	4,21E-1	9,27E-7	3,85E-2	8,61E-3	2,28E-3	1,07E-2	1,26E2	
	Per gross internal floor area m2	6,43E2	2,11E1	4,63E-5	1,93E0	4,3E-1	1,14E-1	5,34E-1	6,32E3	

Figure 99: Comparison of the results of the LCA calculation between Scenario 1 and Scenario 4

Circularity in a building refers to the use of resources throughout the entire lifecycle of a structure including design, construction, operation, and end of life. Encouraging the repurposing, recycling, and salvaging of materials, circularity reduces waste generation, decreases non-renewable resource use, and promotes a circular economy. One Click LCA evaluates material use optimisation, design for disassembly, material circularity indicators, and end-of-life Scenarios. The analysis is according to material efficiency and circular economy - for BREEAM MAT 06 and GRI G4 reporting. Figure 100 indicates that 51.6% of the total quantity of materials can be recovered in Scenario 1 as is (recycled content at stage A 3.1%) and 7.8% can be reused for other purposes. The results of Scenario 4 were similar; however, they differed in the fact that 9.9% of the total quantities were returned.

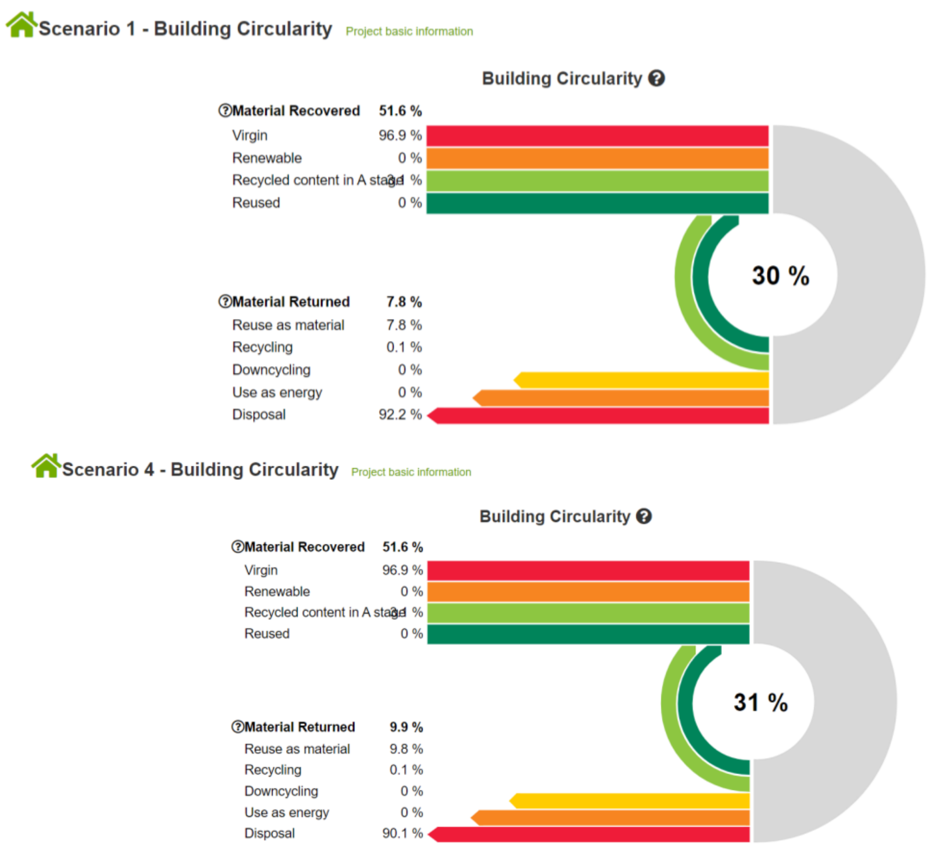
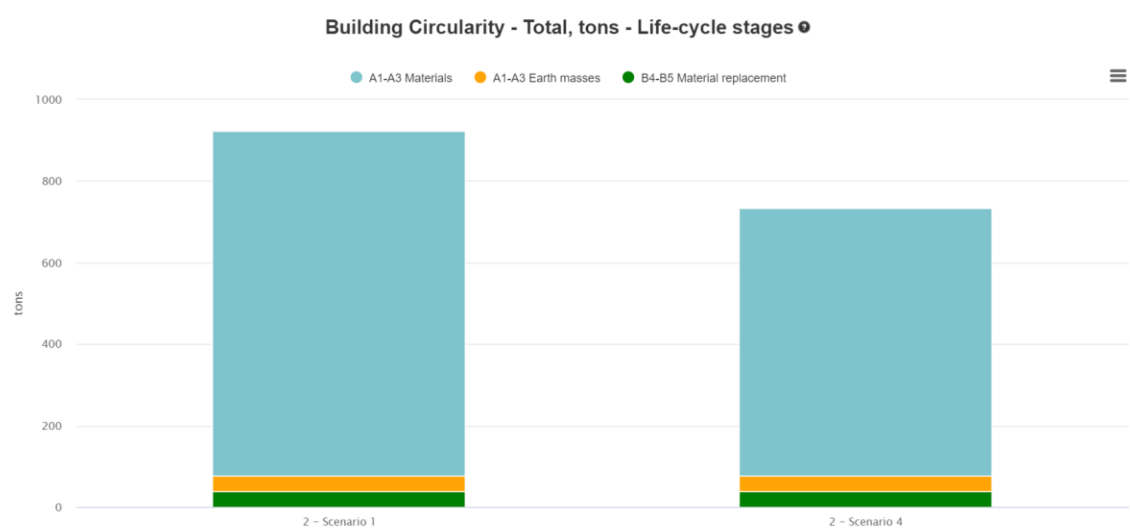


Figure 100: Results of building circularity in Scenario 1 and Scenario 4

For Scenario 1 and Scenario 4, a Building Circularity analysis is presented in Figure 101, with a total material use of 847.47 tons for A1-A3 Materials in Scenario 1. The improvement in resource efficiency in Scenario 4 results in a material usage reduction of approximately 22.40% to 657.60 tons. Additionally, comparing A1-A3 Earth masses has not revealed any differences between Scenario 1 and Scenario 4, with both Scenarios having 37.29 tons. Likewise, the material replacement in Scenario 1 is 38.85 tons, while the material replacement in Scenario 4 is 38.70 tons, an approximately 0.39% reduction. Scenario 4 exhibits better results regarding material consumption (A1-A3) and material replacement (B4-B5) using more sustainable and circular design principles, demonstrating the benefits of adopting such principles. In addition to reducing waste and non-renewable resources, the built environment becomes more environmentally responsible.



Chart

Category	A1-A3 Materials	A1-A3 Earth masses	B4-B5 Material replacement
2 - Scenario 1	847.4741844625001	37.2945	38.855341062499996
2 - Scenario 4	657.6056164625002	37.2945	38.7015780625

Figure 101: Results of building circularity in life cycle stages

A circular arrangement of building elements can be determined based on the tonnage of various building elements, as illustrated in Figure 102. In comparing these Scenarios, we gain an understanding of the materials used in the different building designs and the possibility of circularity. Regarding floor slabs, ceilings, beams, and roofs, Scenario 1 is more resource-efficient than Scenario 2. Scenario 1 includes a foundation, subsurface, basement, and retaining wall weighing 247.99 tons, while Scenario 4 involves a foundation, subsurface, basement, and retaining wall weighing 153.93 tons. However, Scenario 4 uses 94.06 tons less material, making it more circular and environmentally friendly. There are 55.15 tons of load-bearing columns in Scenario 1, while 55.27 tons are used in Scenario 4. Both Scenarios have a minimal difference in column weight and load-bearing vertical structures, which makes their impact on circularity relatively equal. It is estimated that windows and doors in Scenario 1 weigh approximately 4.35 tons, while those in Scenario 4 weigh approximately 4.50 tons. Scenario 4 uses 0.15 tons more material for windows and doors than Scenario 1, making Scenario 1 slightly more circular. As a result, Scenario 4 demonstrates improved circularity and sustainability regarding external walls, façades, foundations, subsurfaces, basements, and retaining walls.

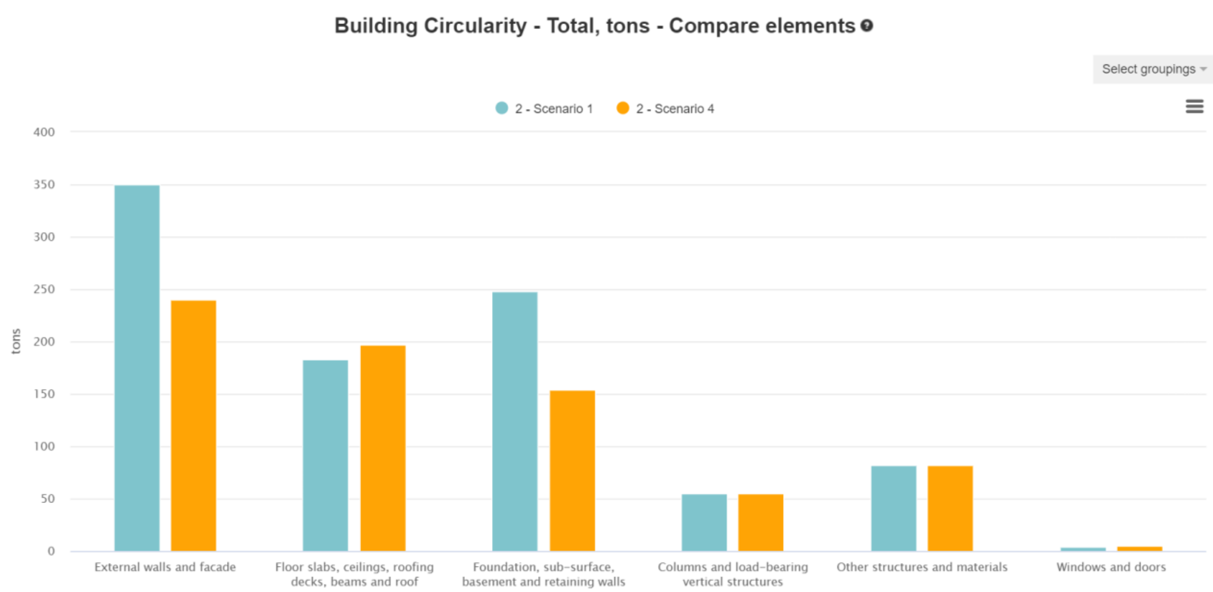


Figure 102: Results of building circularity of elements in Scenario 1 and Scenario 4

7.9 Outcome

Based on analysing LCC in residential projects using BIM tools, an existing 3D model of a residence was modelled using AutoDesk® Revit 2023 to determine the technical specifications of the project materials. As a result of the omission of quantities observed at the 2D level of this case, this 3D model was utilised in the preparation of the Bill of Quantities (BoQ). Through the use of BIM, time and cost savings have been realised by approximately $8,672,721.81. The AutoDesk® Revit 2023 software enhances the accuracy of determining the technical specifications of project materials by utilising 3D modelling. BIM does not only stimulate design, but also provides 3D concept design, physical simulation, and monitoring of building performance.

As a result of altering the specifications of the walls and floors, Autodesk® Insight was utilised to estimate the energy costs associated with LCC. By using this comprehensive tool, building energy and environmental performance can be improved, allowing alternative LCC scenarios to be identified. The Autodesk Insight analysis result indicates that Scenario 1 has an Energy Use Intensity of 368 kWh/m²/year. In addition, Scenario 4 reduced the Energy Use Intensity by 289 kWh/m²/year by varying the design criteria and using materials recommended by Autodesk Insight. Compared to Scenario 1, Scenario 4 saved approximately 21% of energy. However, this saving represents only one unit in the project so the estimated annual energy saving for 900 units, in this case, would be 71100 kWh/m²/year.

An analysis of the four scenarios was conducted using AutoDesk® Green Building Studio (GBS), a whole-building analysis program. Based on actual model data, local energy sources, and weather data, GBS determined energy consumption, water consumption, costs, natural ventilation potential, and carbon emissions results. Thus, Scenario 4 has a 39.34% reduced

LCC, while its CO_2 emissions have decreased by 46.51 per cent. This makes the scenario the most environmentally-friendly and cost-effective option available. In addition, it can save about $25,389,000 on LCC for the 900 units in the project over the next 30 years.

In One Click LCA software, users can make informed decisions regarding building circularity and adopt strategies promoting sustainable and resource-efficient built environments by analysing these aspects of building circularity. In addition to reducing environmental impacts, reducing costs, and improving resilience, this can have long-term benefits. The cumulative impact of the lifecycle stages of Scenario 4 using One Click LCA results in approximately 189 tons of greenhouse gas emissions, or 12.68 kilograms per square meter, as a result of enhancing the alternative design. By enhancing the product's carbon footprint, CO_2 emissions were reduced 48.8%, while the social cost of carbon decreased to €9,453.

Several software applications and BIM tools have been proven highly effective in enhancing the efficiency, cost management, and environmental performance of residential projects in the planning and design phases. AutoDesk® Revit 2023, AutoDesk® Insight, and AutoDesk® Green Building Studio provide tools that make it possible to make informed decisions about alternative design scenarios. In One Click LCA, metrics such as LCC, LCA, BREEAM sustainability criteria, and circular design are used to assess sustainability. This analysis is based on AutoDesk® Insight and One Click LCA. By adopting energy-efficient design strategies, significant benefits can be realised through reduced energy consumption, cost, and environmental impact. It is imperative that BIM tools and energy-efficient design strategies are incorporated into construction projects so that future generations can benefit from a sustainable and environmentally-responsible built environment.

7.10 Framework to Adopting BIM in the KSA

In the KSA construction sector, utilising BIM for life cycle cost optimisation faces considerable impediments. Among these, a salient issue is the deficiency in BIM literacy across critical stakeholders such as contractors, architects, and owners. This knowledge gap acts as a barrier to the widespread institutionalisation of BIM methodologies, thereby undermining their potential for enhancing economic efficiency throughout a building life cycle. In the KSA construction landscape, the sector's fragmented nature significantly hampers the seamless integration of BIM throughout the project lifecycle. Comprising a multiplicity of isolated stakeholders—from government bodies to contractors and consultants—this fragmentation engenders collaborative deficiencies that obstruct the effective deployment of BIM. Such a compartmentalised environment not only creates inefficiencies, but also cultivates resistance to standardisation and innovation, thereby impeding the utilisation of BIM as a tool for optimising life cycle costs.

7.10.1 Lack of Standardisation of BIM in the KSA

The lack of standardised implementation practices and protocols for BIM adds complexity to its adoption and integration in the construction industry in the KSA. With multiple stakeholders involved, each with their own processes and procedures, achieving a consistent and streamlined approach to implementing BIM becomes challenging. The absence of clear standards and guidelines for BIM implementation creates uncertainty and inconsistency across different projects. This can result in interoperability issues, data inconsistencies, and difficulties in exchanging information between project participants, ultimately impacting the optimisation of life cycle costs.

7.10.2 Shortage of Skilled Manpower

Another significant challenge facing the construction industry in the KSA is the shortage of skilled manpower qualified to work with BIM. The successful implementation of BIM requires individuals with a deep understanding of its principles, processes, and tools. However, there is currently a gap in the availability of professionals who possess the necessary BIM skills and expertise. To overcome this challenge, it is crucial to invest in training and education programmes that offer comprehensive BIM courses and certifications. By nurturing a skilled workforce proficient in BIM, the industry can effectively harness the potential of BIM for life cycle cost optimisation.

7.10.3 Regulatory and Legal Challenges

The construction industry in the KSA operates within a complex regulatory and legal framework that can present challenges for the implementation of BIM. Adapting existing regulations and codes to incorporate BIM requirements and processes can be a lengthy and challenging process. Additionally, clarifying ownership rights, liability, and intellectual property rights related to BIM models and data poses legal challenges. Addressing these regulatory and legal challenges is vital to provide a supportive environment for the implementation of BIM and the optimisation of life cycle costs.

7.10.4 Process to Adopting BIM on LCC in the KSA

Before implementing BIM for LCC optimisation in the KSA, it is crucial to adequately prepare for the framework process. The successful implementation of BIM requires careful planning and consideration of various factors. This section will discuss the key steps and considerations for preparing for BIM implementation in the KSA. As BIM continues to evolve and be adopted in various industries, including the construction sector in the KSA, there are several future trends and developments that can be expected in BIM and its application for LCC optimisation. These trends and developments aim to further enhance the benefits and effectiveness of BIM in optimising LCC in the KSA. These future trends include:

7.10.4.1 Enhanced BIM Platforms and Technologies

One of the major future trends in BIM and LCC optimisation is the advancement and enhancement of BIM platforms and technologies. As technology continues to evolve, BIM platforms will become more sophisticated and user-friendly, offering improved functionalities for better cost estimation, analysis, and management. This will allow for more accurate and detailed LCC calculations, leading to better decision making during the planning and design stages of construction projects in the KSA.

7.10.4.2 Data Management and Integration in BIM

Data management and integration are critical components of BIM implementation for LCC optimisation in the KSA. Efficient data management and integration facilitate seamless collaboration, enhance decision-making processes, and enable effective maintenance and facilities management throughout the building life cycle. This section explores the importance of data management and integration in BIM, the challenges involved, and the strategies for successful implementation in the KSA context.

7.10.4.3 Collaborative and Integrated Project Delivery

Collaboration and integration are fundamental principles of BIM and their importance will continue to be emphasised in the future. BIM enables multidisciplinary teams to work collaboratively on a construction project, sharing information and making real-time decisions.

In the future, collaborative and integrated project delivery methods are expected to become even more prevalent in the KSA, enabling stakeholders to effectively optimise LCC through enhanced communication, coordination, and shared knowledge.

7.10.4.4 Government Support and Regulations

The KSA government has been actively promoting the adoption of BIM in the construction industry. As the government continues to prioritise sustainable development and efficient resource utilisation, it is likely to further support BIM implementation for LCC optimisation. This support may include the development of BIM standards, regulations, and guidelines that require the use of BIM in public and private sector projects. Such initiatives will help drive the future adoption of BIM and ensure that LCC optimisation becomes an integral part of the construction industry in the KSA.

7.10.4.5 Increased Awareness and Training

As BIM adoption increases, so does the need for skilled professionals who are proficient in BIM methodologies and technologies. In the future, there will be an increased emphasis on training and education programmes to equip construction industry professionals in the KSA with the necessary BIM skills. This will include both technical training in BIM software and tools as well as the development of BIM-related standards and best practices. Fostering a culture of continuous learning and professional development, the construction industry in the KSA can effectively harness the benefits of BIM for LCC optimisation.

7.10.4.6 Standardisation and Interoperability

The future of BIM and LCC optimisation will also involve standardisation and interoperability. Standardisation efforts aim to ensure consistency and compatibility between different BIM software platforms and tools, allowing for seamless data exchange and collaboration among project stakeholders. Establishing industry-wide standards and protocols, the KSA's construction industry can unlock the full potential of BIM for LCC optimisation, as information flows seamlessly between different stages of a building lifecycle. See Figure 103.

7.11 Chapter Summary

Chapter Seven focuses on the simulation and optimisation aspects of a significant residential project in Saudi Arabia consisting of 900 units. It provides an overview of the case study's background, simulation, and optimisation methods employed. It discusses the creation of 3D to 5D models and explores the development of a 6D model for alternative design scenarios. The chapter also covers energy cost analyses using Autodesk® Insight 360, particularly in Alternative Design Scenario 1, and life cycle cost analyses with Autodesk® Green Building Studio, shedding light on different design scenarios' economic aspects. Furthermore, it investigates sustainability and building circularity analyses through One Click LCA, involving data collection, evaluation, and comparative assessments between Scenario 1 and Scenario 4. In essence, this chapter unravels how simulation and optimisation impact cost management, energy efficiency, life cycle considerations, sustainability, and circularity in large-scale construction projects.

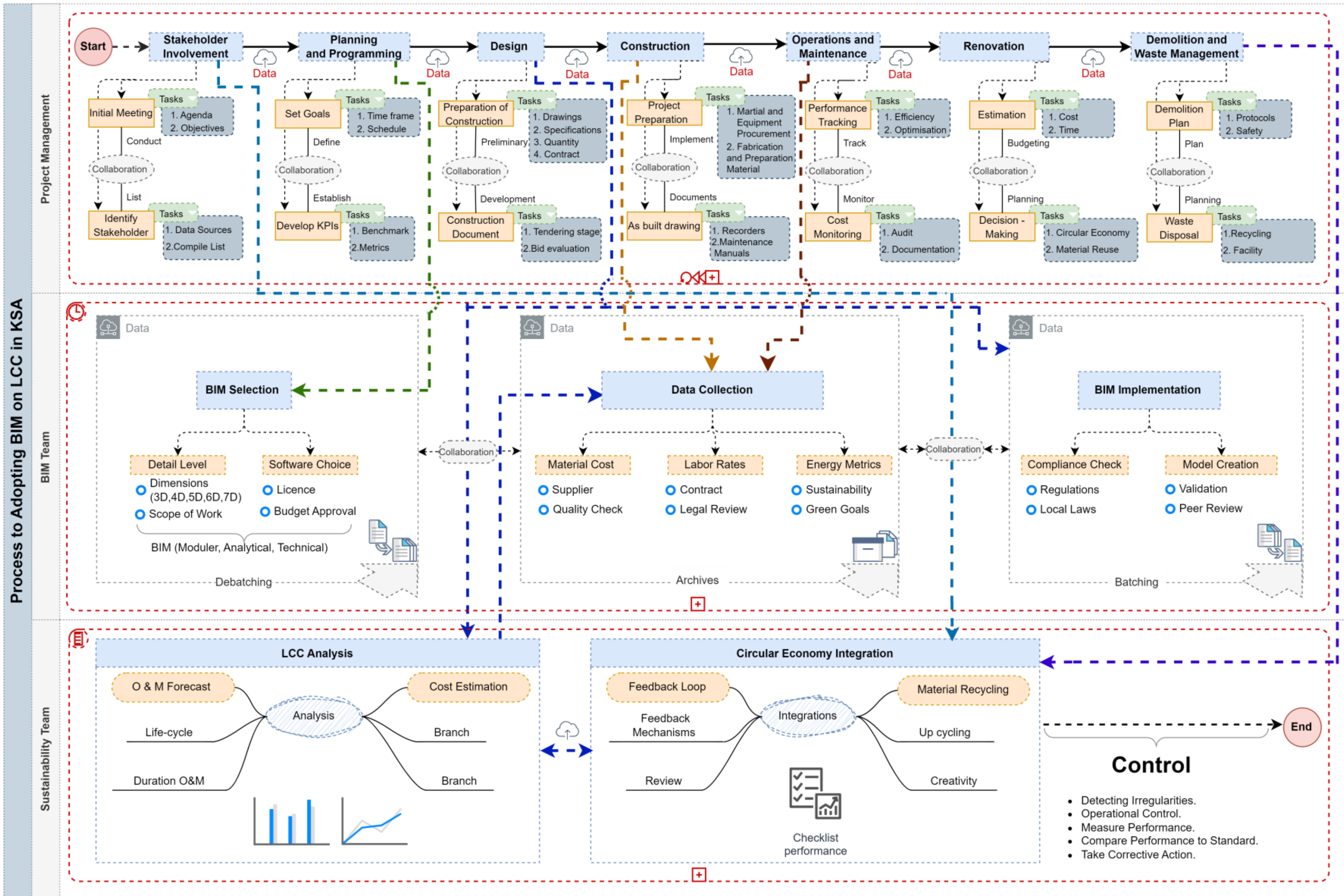


Figure 103: Framework of Standardisation to Adopting BIM in KSA

Chapter 8

Discussion and Conclusions

8 Chapter Eight: Discussion and Conclusions

8.1 Introduction

The purpose of this chapter is to present a comprehensive discussion of the study's findings and then draw conclusions. Use of BIM on the LCC of sustainable building in relation to the Saudi Arabian construction sector was extensively explored in the previous chapters. The chapter will therefore start with a discussion of how each and every objective was achieved, starting with the first objective that aimed to comprehensively review the literature. This initial objective was very important because it helped in identifying gaps in knowledge specific to BIM in Saudi Arabia. The chapter will then review each research objective, outlining the methodologies and the findings. The chapter will finally present the conclusion and the limitations of the study as well as the proposed recommendations.

8.2 Discussion

8.2.1 Achievement of the Objectives

Objective 1: To conduct a review of research literature to identify the research gap in knowledge on BIM in Saudi Arabia.

Extensive literature searches were conducted in reliable databases, including Web of Science, Google Scholar, Scopus, ScienceDirect, and relevant journals in the field of construction. Keywords such as "BIM," "Saudi Arabia," "construction industry," "Life Cycle Cost," and related terms were employed to ensure a thorough search. Inclusion and exclusion criteria were established to filter articles, focusing on relevance to the Saudi Arabian context and BIM implementation in the construction industry. The review revealed a limited number of studies specifically addressing BIM in the context of Saudi Arabia, indicating a research gap in localised literature.

Existing global literature provided information regarding BIM technologies, processes, and benefits. However, they lacked specificity to the socio-economic and regulatory conditions unique to Saudi Arabia. This resulted in the need for targeted research to address the specific challenges and opportunities of BIM implementation in the Saudi Arabian construction industry. The findings highlighted an opportunity for future research endeavours to contribute context-specific knowledge, facilitating more effective BIM adoption strategies in the region.

Objective 2: To determine the enablers and constraints associated with the use of BIM technology in governmental projects in Saudi Arabia.

Surveys and interviews were conducted with key stakeholders including government officials, project managers, and BIM experts involved in governmental projects. Questions focused on identifying factors facilitating (enablers) or hindering (constraints) the successful implementation of BIM in governmental projects.

Enablers included strong government initiatives promoting digital transformation, awareness programs, and training opportunities. Constraints encompassed a lack of standardised protocols, resistance to change among stakeholders, and a need for more robust regulatory frameworks supporting BIM implementation. Policymakers can leverage identified enablers to strengthen government support for BIM adoption. Recommendations include addressing constraints, emphasising the importance of regulatory updates, stakeholder engagement, and change management strategies.

Objective 3: To quantify the extent to which BIM technology is used in Saudi Arabia.

To gauge the prevalence and depth of BIM technology utilisation in Saudi Arabia, a combination of quantitative surveys and project case studies was employed. A structured survey instrument was distributed among professionals involved in the construction industry across various roles. The survey comprised questions regarding the frequency and extent of BIM use including software proficiency and project integration levels. In-depth case studies were also conducted on a representative sample of construction projects in Saudi Arabia. They involved interviews with project teams, scrutiny of project documentation, and onsite evaluations to assess the actual implementation and benefits derived from BIM. Usage Frequency: The survey revealed varying degrees of BIM adoption, with a spectrum ranging from sporadic use to fully integrated project management. Software Proficiency: Disparities in software proficiency were observed, emphasising the need for standardised training programs. Project Integration Levels: Case studies provided a detailed understanding of how BIM was integrated into different phases of construction projects, highlighting areas of strength and potential improvement.

The findings suggest a diverse landscape of BIM implementation in Saudi Arabian construction projects. While some projects showcase advanced integration, others operate at initial levels. This signals the need for targeted interventions to standardise and enhance BIM usage across the industry. Policymakers and industry leaders can develop strategies that encourage widespread and consistent BIM adoption, ensuring its benefits are realised across diverse construction projects in the region.

Objective 4: To explore the programs currently used during the design phase of construction projects in Saudi Arabia and their compatibility with BIM programs.

This objective aimed to understand the common software programs used during the design phase of construction projects in Saudi Arabia. A targeted survey was administered to professionals involved in the design phase of construction projects. The survey sought to understand the software tools commonly used and the extent to which they align with BIM principles. Detailed assessments were then conducted on select design programs to evaluate their interoperability with BIM platforms. This involved examining data exchange capabilities, file format compatibility, and collaborative features.

The findings conclude a diversity of software usage; there are many design programs in use, indicating a lack of standardisation in the industry. The responses also highlighted varying levels of awareness regarding the compatibility of design programs with BIM. Some professionals capitalise on BIM-integrated tools and others rely on standalone software.

Interoperability Challenges: The compatibility assessments revealed challenges in interoperability between certain design programs and BIM platforms, potentially hindering seamless collaboration. Collaboration is a key factor to the success of any construction project. There is the need to promote industry-wide education and standardisation. This is a conclusion from the diversity in software usage and varying levels of awareness about BIM compatibility in the Saudi Arabian construction industry. Recommendations for enhancing compatibility and streamlining workflows can be formulated to guide professionals and organisations towards more effective and integrated BIM adoption during the design phase of construction projects in Saudi Arabia.

Objective 5: To study projects in Saudi Arabia that used BIM and impact identification to reduce LCC and enhance sustainability.

A selection of construction projects in Saudi Arabia were studied in depth through case studies. Projects were chosen based on their explicit use of BIM for LCC reduction and sustainability considerations. For the identified projects, quantitative analyses were conducted to assess the realised reduction in Life Cycle Costs and the positive impact on sustainability indicators. Data sources included project reports, financial documents, and environmental impact assessments. The case studies comprised a variety of project types, including commercial, residential, and infrastructure projects, showcasing their versatility. They demonstrated a notable reduction in LCC with BIM contributing to efficient design, construction, and maintenance phases. The utilisation of BIM facilitated the identification of sustainability benefits such as optimised resource utilisation, energy efficiency, and reduced environmental impact.

From the positive outcomes, BIM has the potential of achieving both economic and environmental objectives. Recommendations can be made for the broader adoption of BIM in projects across the Saudi Arabian construction industry, emphasising its role in enhancing both financial viability and environmental sustainability.

Objective 6: To understand the types of contracts and building technologies utilised in the Saudi Arabian construction industry and their influence on the implementation of BIM.

A comprehensive analysis of construction contracts prevalent in Saudi Arabia was conducted, focusing on their compatibility with BIM requirements. Contracts ranged from traditional to collaborative models. The prevalent building technologies in use were identified and their compatibility with BIM systems was assessed. This included an examination of software, hardware, and communication technologies.

Certain traditional contracts posed challenges to the effective implementation of BIM due to limited collaboration mechanisms and rigid structures. Projects with collaborative and integrated contracts demonstrated a more seamless integration of BIM processes, emphasising the importance of contractual frameworks. On the other side, the compatibility of prevalent software with BIM systems varied. Projects utilising BIM-compatible software reported smoother implementation. Some building technologies required upgrades to align with BIM standards, highlighting the importance of continuous technological advancement.

The findings emphasise the interdependence of contractual frameworks and building technologies with the successful implementation of BIM. Recommendations can be made for adopting collaborative contracts and ensuring technological alignment for optimal BIM integration in the Saudi Arabian construction industry.

Objective 7: To define a strategic framework within which BIM can be applied to government projects.

A thorough examination of existing policies and regulations related to government projects and BIM implementation was conducted. This included an assessment of legal frameworks and compliance requirements. Key stakeholders involved in government projects, including government officials, project managers, and industry experts, were consulted to understand their perspectives on BIM integration. International best practices for BIM implementation in government projects were also researched and analysed to identify relevant strategies for adaptation in the Saudi Arabian context.

The analysis identified gaps in existing policies regarding BIM application in government projects. This suggested a need for specific guidelines tailored to the Saudi Arabian context. Stakeholders exhibited varying levels of awareness regarding BIM benefits. Education and awareness programmes were identified as crucial components for successful BIM adoption. Successful BIM implementation models from other countries were identified, providing information on the strategies that could be adapted to the Saudi Arabian government project context.

The strategic framework proposed involves a comprehensive approach, considering policy enhancements, stakeholder education, and the incorporation of successful international models. Policy refinements and educational initiatives are also integral to promoting a conducive environment for BIM adoption in Saudi Arabian government projects.

8.2.2 Impact of BIM Tools

The incorporation of BIM tools, AutoDesk® Revit 2023, AutoDesk® Insight, and AutoDesk® Green Building Studio, profoundly influenced the outcomes of this research. They left a notable impact on the efficiency and precision of the study. These tools have emerged as critical instruments, enabling various aspects of the investigation, and their contributions are discussed in detail below.

AutoDesk® Revit 2023

Utilising Revit 2023 significantly enhanced the 3D modelling capabilities of the study. This allowed for the creation of intricate and accurate representations of construction projects, offering a comprehensive view of the spatial relationships and geometry. The tool proved indispensable in visualising design concepts, streamlining collaboration among project stakeholders, and minimising errors in the planning phase.

AutoDesk® Insight

The inclusion of AutoDesk® Insight facilitated in-depth energy analysis, a critical component in ensuring the sustainability of residential projects. This tool enabled the assessment of energy performance, aiding in the identification of optimisation opportunities and the integration of energy-efficient solutions. The information gained helped in making informed decisions aimed at reducing energy consumption and environmental impact.

AutoDesk® Green Building Studio

The integration of AutoDesk® Green Building Studio extended the study's scope to life cycle assessments. This tool enabled a comprehensive evaluation of the environmental impact of construction projects throughout their life cycle. By considering factors such as material choices, energy consumption, and operational efficiency, the tool contributed to a comprehensive understanding of sustainability implications.

8.2.3 Building a Circular Economy

The exploration of circular design principles within the construction industry, facilitated by the analysis using One Click LCA, unravelled a range of conclusions into the transformative potential of embracing circularity. The focus on Scenario 4, specifically tailored to emphasise circular principles, engendered a paradigm shift in our understanding of construction practices, manifesting in tangible reductions in greenhouse gas emissions and material utilisation. The detailed breakdown of this analysis is as discussed below.

One Click LCA Analysis

The One Click LCA tool served as a comprehensives platform for quantifying and evaluating the environmental impact of various construction scenarios. By employing LCA methodologies, it provided a comprehensive overview of the ecological footprint associated with each scenario, with Scenario 4 emerging as a standout exemplar of circular economy integration.

One Click LCA facilitated a comprehensive evaluation of the environmental impact associated with each construction scenario. It surpassed various assessments by considering various factors such as raw material extraction and manufacturing to construction, operation, maintenance, and eventual end-of-life considerations. This broad analysis allowed for a comprehensive understanding of the sustainability implications at every stage of the project.

The One Click LCA analysis provided a detailed overview of the ecological footprint associated with each scenario. This comprised the quantification of environmental impacts in terms of carbon footprint, embodied energy, and other relevant metrics. Scenario 4 emerged as a standout exemplar, showcasing a reduced ecological footprint attributed to the integration of circular economy principles.

The analysis revealed a significant optimisation of material usage in Scenario 4. By incorporating circular economy principles, such as material recovery and reuse, the scenario showcased a departure from the linear 'take-make-dispose' model, exhibiting a more regenerative approach to construction. This not only minimised the demand for new raw materials, but also alleviated the environmental burdens associated with extraction and processing.

8.3 Limitations of the Study

Assumptions and Generalisability

The study's findings are anchored in specific assumptions including a 50-year life expectancy and a 6.1% discount rate. While these assumptions provide a structured framework for analysis, it is crucial to acknowledge their influence on the results. Variations in regional factors, construction practices, and material availability across different geographical contexts might introduce variations that impact the generalisability of the study's outcomes. Recognising the study's limitations in this regard is critical for interpreting results in diverse settings.

Regional Disparities

The construction industry operates within a diverse landscape of regional disparities. Localised factors, such as regulatory frameworks, climate conditions, and cultural practices, were considered to the best extent possible. However, the inherent variability in these factors across regions may introduce uncertainties in arriving at universal findings. Stakeholders and researchers should exercise caution in applying the study's outcomes directly to contexts with distinct regional characteristics.

Omitted Variables

The study focused on specific variables crucial to the identified objectives. Nevertheless, certain variables that could influence the sustainability outcomes were omitted. Transmission losses, renewable energy potentials, and natural ventilation, for instance, were not included in the analysis. The exclusion of these variables introduces potential bias in the assessment and it is essential to acknowledge the limitations derived from these omissions.

Biases in Analysis

The absence of considerations for transmission losses and renewable energy potentials might introduce bias in the overall analysis. These aspects are integral to a comprehensive understanding of the environmental impact of construction scenarios. The study's limitations, therefore, emphasise the need for future research endeavours to comprise a broader range of variables for a more comprehensive sustainability assessment.

Temporal Considerations

The study adopted a snapshot perspective within a specific timeframe. Changes in technology, regulations, or market dynamics beyond this timeframe could influence the long-term sustainability of construction scenarios. Recognising the temporal constraints is essential for understanding the study's implications in the context of evolving trends and advancements in the construction and sustainable design sectors.

Scope of Impact Assessment

The environmental impact assessment primarily focused on selected dimensions such as carbon footprint and embodied energy. While these metrics provide important information, a more extensive assessment, including social and economic dimensions, would provide a more comprehensive understanding of the overall sustainability implications. The study's limitations, therefore, signal an avenue for future research to embrace a broader scope of impact assessment. While the research provides valuable insights into the adoption of BIM in Saudi Arabia’s new construction sector, its limitations must be noted. The study is geographically limited to Saudi Arabia, which may affect the generalizability of the findings to other regions with different economic, cultural, and regulatory environments. Additionally, the focus on new construction projects means the results may not be directly applicable to renovation projects, which could be significantly impacted by legacy building practices and existing structures.

8.4 Conclusions

This thesis aimed to address the “Use of Building Information Modelling on the Life Cycle Cost of the Sustainable Building: The Case of Saudi Arabia”. This research has looked into Building Information Modelling (BIM) implementation in the context of the Saudi Arabian construction industry. The study systematically addressed a series of research objectives aimed at comprehensively understanding the current state of BIM usage and, ultimately, that of the LCC. The research has specifically addressed enablers and constraints and explored the implications for sustainability and LCC considerations. The findings show how BIM technology can enhance efficiency not just in design, but also in building, operation, and even demolition phases, impacting the overall trajectory of life cycle costs.

The first objective, a review of the research literature, helped to derive some significant research gaps specific to Saudi Arabia. The gaps mostly emphasise the need for context-specific studies in this unique socio-economic and regulatory environment. The subsequent objectives provided a detailed exploration of BIM adoption, programs employed in the design phase, project impacts, contract types, and the formulation of a strategic framework.

The integration of BIM tools, as discussed in Objective 2, demonstrated an important role in enhancing efficiency and accuracy in planning and design. The detailed analysis of building circular economy principles, as outlined in Objective 3, underscored the potential benefits of circular design, emphasising resource recovery and sustainability.

Scenario 4, which is carefully integrated with circular design principles, stands out as a model of ecological and economical building among the kaleidoscope of scenarios. The effectiveness of the circular economy in maximising the life cycle of residential constructions is supported by statistics that show a notable decrease in greenhouse gas emissions and material use. This situation is more than just a design decision; it represents an important shift and provides concrete examples of how circular economy principles may be easily incorporated into construction methods. Beyond the numerical revelations, the research fills a critical void in localised literature, offering a contextualised understanding of sustainable construction practices in Saudi Arabia. The statistics illuminate the scarcity of studies specific to this region, emphasising the need for targeted research. The implications extend beyond academic discourse, resonating with policymakers, practitioners, and researchers alike.

This research contributes to the evolving discussion on sustainable construction practices. It establishes a framework for well-informed decision making in the Saudi Arabian construction industry by examining the complexity of BIM adoption and its broader implications. As the industry continues to advance, the findings from this study serve as a foundation for future research endeavours and policy formulations.

8.5 Recommendations for Future Research

8.5.1 Investigation of Regional Variations

Future research endeavours should deal with the challenges of regional variations and their impact on LCA and cost analyses. Considerations should extend beyond geographical boundaries to comprise climate variations, energy cost dynamics, and diverse construction practices. Understanding how these regional variations influence the sustainability outcomes of construction scenarios is critical for developing context-specific strategies and policies.

8.5.2 Exploration of Advanced BIM Applications

As the construction industry continues to evolve, future studies should focus on exploring advanced BIM technologies and applications. This includes an in-depth examination of emerging BIM tools that offer more accurate detail and analyses of building performance and life cycle impacts. By staying up to date with technological advancements, researchers can contribute to the continuous refinement and enhancement of BIM applications for sustainable construction practices.

8.5.3 Integration of Dynamic Simulation Models

To enhance the accuracy and relevance of sustainability assessments, future research should consider the integration of dynamic simulation models. These models can account for temporal variations in occupancy patterns, climate conditions, and energy demand over time. By incorporating dynamic elements into the analysis, researchers can provide a more realistic and comprehensive understanding of the long-term environmental implications of construction scenarios.

8.5.4 In-Depth Studies on Circular Economy Strategies

Circular economy principles play a crucial role in sustainable construction. Future studies should conduct in-depth investigations into circular economic strategies within the construction sector. This includes exploring material recycling, reuse, and repurposing in construction projects. Understanding their practical implications and challenges will help in shaping environmentally-conscious construction practices.

8.5.5 Social and Economic Dimensions of Sustainability

While the present study primarily focused on environmental dimensions, future research should broaden the scope of sustainability assessments to include social and economic dimensions. This includes exploring the social implications of construction scenarios on communities and evaluating the economic feasibility of sustainable practices. This will provide a more comprehensive understanding of the overall impact. Integrating these dimensions into sustainability assessments will be critical in guiding comprehensive decision making.

8.5.6 Longitudinal Studies and Technological Trends

Given the rapid evolution of technology and the construction industry, longitudinal studies are essential to track the sustainability implications of construction scenarios over time. Future research should focus on capturing technological trends and assessing their impact on the long-term sustainability of building projects. This forward-looking approach will facilitate adaptive strategies in response to emerging technologies and market dynamics.

8.5.7 The integration of BIM and Information Technology (IT)

The selection of BIM tools and technologies is critical for aligning with project requirements and objectives in developing a BIM implementation plan. This entails not only choosing appropriate software platforms for design, collaboration, and modelling but also considering hardware requirements. Essential is selecting tools and technologies compatible with existing project infrastructure and facilitating seamless data exchange across various disciplines and stakeholders. Beyond software installation, IT specialists manage networks and resolve problems, playing a pivotal role in the technical aspects of BIM implementation. Their responsibilities encompass ensuring the smooth operation of the BIM platform and providing technical support to team members, necessitating a robust understanding of database management, computer networks, and BIM software.

As technology progresses, BIM technology and tools are poised for evolution, promising enhanced collaboration, data analysis, and visualisation capabilities within the expanding construction industry. The revolutionary impact of BIM in construction will be further amplified by integrating emerging technologies such as virtual and augmented reality, the Internet of Things (IoT), and artificial intelligence. These advancements are expected to aid stakeholders in making well-informed decisions, streamlining processes, and enhancing productivity. Furthermore, Artificial Intelligence (AI) integration in BIM assists in design optimisation, cost estimating, and scheduling by automating repetitive tasks and providing insights for better operational strategies.

For the construction industry in the KSA, integrating BIM and IT, especially with advances in

AI, and IoT technology, presents a transformative opportunity. With this integration, construction processes will be streamlined, sustainability and efficiency will improve. Nonetheless, implementing the system successfully will require addressing challenges such as data integration, technological infrastructure, skill development, and privacy.

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Appendices

Appendix 1: Application for approval Ethical Review ERN_20-0402

Application for Ethical Review ERN_20-0402

Susan Cottam (Research Support Services)

Mon 17/05/2021 01:57

To: Charalampos Baniotopoulos (Civil Engineering) <C.Baniotopoulos@bham.ac.uk>;

Cc: Pedro Martinez-Vazquez (Civil Engineering) <P.Vazquez@bham.ac.uk>; Esam Alasmari (PhD Dept of Civil Eng FT) <EXA855@student.bham.ac.uk>;

Dear Professor Baniotopoulos

Re: "Use of Building Information Modelling (BIM) on the LCC of the sustainable Building. The Case of Saudi Arabia"
Application for Ethical Review ERN_20-0402

Thank you for your application for ethical review for the above project, which was reviewed by the Science, Technology, Engineering and Mathematics Ethical Review Committee.

On behalf of the Committee, I confirm that this study now has full ethical approval.

I would like to remind you that any substantive changes to the nature of the study as described in the Application for Ethical Review, and/or any adverse events occurring during the study should be promptly brought to the Committee's attention by the Principal Investigator and may necessitate further ethical review.

Please also ensure that the relevant requirements within the University's Code of Practice for Research and the information and guidance provided on the University's ethics webpages (available at https://intranet.birmingham.ac.uk/finance/accounting/Research-Support-Group/Research-Ethics/Links-and-Resources.aspx) are adhered to and referred to in any future applications for ethical review. It is now a requirement on the revised application form (https://intranet.birmingham.ac.uk/finance/accounting/Research-Support-Group/Research-Ethics/Ethical-Review-Forms.aspx) to confirm that this guidance has been consulted and is understood, and that it has been taken into account when completing your application for ethical review.

Please be aware that whilst Health and Safety (H&S) issues may be considered during the ethical review process, you are still required to follow the University's guidance on H&S and to ensure that H&S risk assessments have been carried out as appropriate. For further information about this, please contact your School H&S representative or the University's H&S Unit at healthandsafety@contacts.bham.ac.uk.

Kind regards

Susan Cottam
Research Ethics Manager
Research Support Group

Appendix 2: Application for Questionnaire.

A survey of Engineers awareness of building information modelling (BIM) in Saudi Arabia.

مسح لقياس مدى وعي المهندسين السعوديين بشأن نمذجة معلومات البناء (BIM) في المملكة العربية السعودية.

* Indicates required question

I am a PhD student in the department of civil engineering at the University of Birmingham, UK. I kindly request your participation in a research study I am conducting that aims to measure awareness of the concept of (BIM) in the construction sector in the Kingdom of Saudi Arabia. Kindly this questionnaire takes less than 10 minutes to be filled. So, I hope that the survey will be answered to serve the construction sector in the Kingdom of Saudi Arabia. All information in the questionnaire is confidential and will only be used for the purpose of scientific research. Thank you very much in advance for your time and assistance.

Researcher: Esam Alasmari.
Email: exa855@student.bham.ac.uk

UNIVERSITY OF BIRMINGHAM

أنا طالب دكتوراه في قسم الهندسة المدنية في جامعة برمنغهام ، المملكة المتحده. أرجو التكرم بمشاركتك في دراسة بحثية أجريها تهدف إلى قياس الوعي بمفهوم BIM في قطاع البناء في المملكة العربية السعودية. الرجاء التكرم بملء هذا الاستبيان والذي سيستغرق أقل من 10 دقائق. لذا آمل أن يتم الرد على الاستبيان لخدمة قطاع البناء في المملكة العربية السعودية. جميع المعلومات الوارده في الاستبيان سرية ولن يتم استخدامها إلا لأغراض البحث العلمي فقط. شكرًا جزيلاً على وقتك ومساعدتك.

الباحث: عصام الأسمري.
ايميل: exa855@student.bham.ac.uk

UNIVERSITY OF BIRMINGHAM

1. Do you agree to complete the questionnaire? هل توافق على إستكمال الإستبيان؟ *

Mark only one oval.

- ⬭ Yes نعم
- ⬭ NO لا

Skip to question 2

2. What are you by profession? ماهو تخصصك المهني؟ *

Mark only one oval.

- ⬭ Civil Engineer مهندس مدني
- ⬭ Structural Engineer مهندس إنشائي
- ⬭ Quantity Surveyor مساح الكميات
- ⬭ Architect مهندس معماري
- ⬭ Mechanical Engineer مهندس ميكانيكي
- ⬭ Electrical Engineer مهندس كهربائي
- ⬭ Facilities Manager مدير المرافق
- ⬭ Project management إدارة المشروع
- ⬭ Other: ______________________

3. What is your education level? ماهو مستواك التعليمي؟ *

Mark only one oval.

- ⬭ Bachelor بكالوريوس
- ⬭ Master ماجستير
- ⬭ PhD دكتوراة
- ⬭ Other: ______________________

4. What kind of organisation are you currently working with? ماهو تصنيف المنظمة التي تعمل بها حالياً؟ *

Mark only one oval.

- ◯ Government sector القطاع الحكومي
- ◯ Contractor sector قطاع المقاولات
- ◯ Consultant sector قطاع الإستشارات
- ◯ Industrial sector القطاع الصناعي
- ◯ Development sector قطاع التطوير
- ◯ Supply sector قطاع التوريد
- ◯ International company الشركات الدولية
- ◯ Local company (KSA) الشركات المحلية بالسعودية
- ◯ Other: ____________________

5. Where is your organisation located (Country, Region, City)? أين تقع المنظمة التي تتبع لها (الدولة، المنطقة، المدينة)؟ *

____

6. How much experience do you have in the construction industry? كم عدد سنوات الخبرة في قطاع صناعة البناء؟ *

Mark only one oval.

- ◯ No experience لايوجد خبرة
- ◯ Less than 2 years أقل من سنتين
- ◯ 2 to 5 years من سنتين إلى خمس سنوات
- ◯ 5 to 10 years من خمس سنوات إلى عشر سنوات
- ◯ 10 to 20 years من عشرسنوات إلى عشرين سنة
- ◯ More than 20 years أكثر من عشرين سنة
- ◯ Other: ____________________

7. Are you aware of the Building Information Modelling (BIM) approach? هل أنت مدرك بمنهجية نمذجة معلومات البناء؟ *

Mark only one oval.

- ◯ Yes نعم
- ◯ No لا

8. Have you used BIM before? هل سبق وأن استخدمت نمذجة معلومات البناء من قبل؟ *

Mark only one oval.

- ◯ Yes نعم
- ◯ No لا

9. How would you estimate your knowledge of BIM? (Rating 1-5, 5 being highest) كيف تقدر معرفتك بـنمذجة معلومات البناء؟ (التقييم من 1-5 ، 5 أعلى درجة) *

Mark only one oval.

1	2	3	4	5
◯	◯	◯	◯	◯

10. Does your organisation currently use BIM? هل تستخدم منظمتك حالياً نمذجة معلومات البناء؟ *

Mark only one oval.

- ◯ Not use لا تستخدمه
- ◯ No, but we plan to adopt لا، ولكن مخطط لإعتماده مستقبلاً
- ◯ Yes, started using BIM نعم، بدأت بإستخدام نمذجة معلومات البناء *Skip to question 12*
- ◯ Yes, use BIM for small- scale projects نعم، تستخدم نمذجة معلومات البناء في المشاريع الصغيرة *Skip to question 12*
- ◯ Yes, use BIM for every project نعم، تستخدم نمذجة معلومات البناء لكافة المشاريع *Skip to question 12*
- ◯ Other: ____________________

11. If your organization does not use BIM at this time, how likely is your organization to use BIM in the future? إذا كانت مؤسستك لا تستخدم نمذجة معلومات البناء في الوقت الحالي ، فما مدى احتمالية استخدام مؤسستك لنمذجة معلومات البناء في المستقبل؟ *

Mark only one oval.

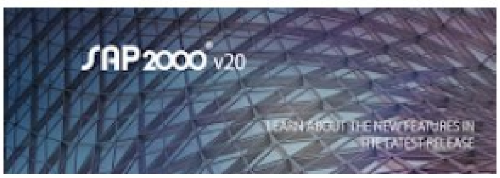
- ( ) Improbable عير محتمل
- ( ) Somewhat likely محتمل نوعاً ما
- ( ) Moderately likely محتمل بشكل معتدل
- ( ) Very likely محتمل جداً
- ( ) Other: ____________________

12. Does your organization use any of these engineering software programs? هل تستخدم منظمتك أي من البرامج الهندسية التالية؟ *

Check all that apply.

- [ ] AutoCAD
- [ ] Autodesk Revit (Architecture, Structure, and MEP)
- [ ] DDS-CAD
- [ ] ArchiCAD
- [ ] VICO Constructor
- [ ] Bentley Systems Architecture

- [ ] Autodesk Robot Structural Analysis
- [ ] Tekla Structures



- [ ] SAP
- [ ] STAAD
- [ ] Other: ____________

- [ ] Allplan

13. Are your regular Consultants / Contractors using BIM? هل يستخدم الاستشاريون/ المقاولون في مشاريعك نمذجة معلومات البناء؟ *

Mark only one oval.

- Yes نعم
- No لا
- Don't Know لا أعلم
- Other: ______________

14. How long has been used BIM in your organisation? منذ متى يتم إستخدام نمذجة معلومات البناء في منظمتك؟ *

Mark only one oval.

- Has not been using BIM لم يتم استخدام نمذجة معلومات البناء
- Less than 1 year أقل من سنة
- 2 to 5 years من سنتين إلى خمس سنوات
- 6 to 9 years من ست سنوات إلى تسع سنوات
- 10 to 13 years من عشر سنوات إلى ثلاثة عشر سنة
- 14 to 20 years من أربعة عشر سنة إلى عشرين سنة
- More than 20 years أكثر من عشرين سنة
- Other: ______________

15. For what types of buildings does your organisation use BIM? ماهو تصنيف المباني الذي استخدمت منظمتك به نمذجة معلومات البناء؟ *

Mark only one oval.

- Government office building مبنى مكتبي حكومي
- Residential سكني
- Education تعليمي
- Healthcare رعاية صحية
- Transportation وسائل النقل
- Infrastructure بنية تحتية
- Industrial صناعي
- Commercial/ Retail تجاري/بيع بالتجزئة
- Other: ______________

16. What are the current BIM applications level used within your organisation? ماهو مستوى تطبيقات نمذجة معلومات المباني المستخدمة في منظمتك؟ *

Check all that apply.

- [ ] CAD (CAD is used for Engineering Drawing). الأوتوكاد ويستخدم للرسم الهندسي
- [ ] 2D modeling (2 Dimension is used for Engineering Drawing 2D Draft) ثنائي الأبعاد، ويستخدم للرسم الهندسي
- [ ] 3D modeling (3 Dimension is used for engineering and can show 3D drawing) ثلاثي الأبعاد، ويستخدم لإظهار الهندسي للرسم الثلاثي الأبعاد
- [ ] 4D modeling (4 Dimension is used for schedule time of construction) رباعي الأبعاد، ويستخدم لجدولة الوقت في المشروع
- [ ] 5D modeling (5 Dimension is used for a cost estimate) خماسي الأبعاد، ويستخدم لتقدير التكلفة
- [ ] 6D modeling (6 Dimension is used for sustainability) سداسي الأبعاد، ويستخدم للإستدامة
- [ ] 7D modeling (7 Dimension is used for facility management) سباعي الأبعاد، ويستخدم لإدارة المرافق

17. How open are you to adopting BIM? مامدى رؤيتك لإعتماد نمذجة معلومات البناء؟ *

Mark only one oval.

- ( ) I liked BIM and I will continue using it. أستحسنت استخدام نمذجة معلومات البناء وسأواصل إستخدامه
- ( ) I didn't like BIM and I think of stopping using it. لم أستحسن استخدام نمذجة معلومات البناء وأفكر في التوقف عن إستخدامه
- ( ) Hesitant متردد
- ( ) Other: ____________________

18. Who should support the adoption and implementation of BIM? من الذي يجب أن يدعم تطبيق وتنفيذ نمذجة معلومات البناء؟ *

Mark only one oval.

- ( ) Government الحكومة
- ( ) Saudi Council of Engineers هيئة المهندسين السعوديين
- ( ) Construction sector companies شركات قطاع البناء
- ( ) Clients العملاء
- ( ) Responsibility is shared between the construction sector and the government المسؤولية مشتركة بين قطاع البناء والحكومة
- ( ) Other: ____________________

19. What is the budget value for projects your organization is currently implementing? ما هي قيمة الميزانية للمشاريع التي تنفذها منظمتك حاليًا؟ *

Mark only one oval.

- $ 100,000-500,000
- $ 500,000-1M
- $ 1 M -10 M
- $ 10 M -30 M
- $ 30 M -50 M
- $ 50 M -80 M
- $ 80 M +
- Other: ________________

20. How much is the project budget for which your organization has applied building information modelling? ما مقدار ميزانية المشروع التي طبقت عليه منظمتك نمذجة معلومات البناء؟ *

Mark only one oval.

- $ 100,000-500,000
- $ 500,000-1M
- $ 1 M -10 M
- $ 10 M -30 M
- $ 30 M -50 M
- $ 50 M +
- Other: ________________

21. Do you consider BIM to be available for application to all scales of a project? هل تعتبر أن نمذجة معلومات البناء يمكن تطبيقها على كافة أحجام المشاريع؟ *

Mark only one oval.

- Yes نعم
- No لا
- Other: ________________

22. How much do you expect the return on investment proportion to increase as a result of applying BIM to projects? كم تتوقع أن تزداد نسبة العائد على الاستثمار نتيجة لتطبيق نمذجة معلومات البناء على المشاريع؟ *

Mark only one oval.

- 1 - 10 %
- 10 - 30 %
- 30 - 50 %
- Above 50 %
- Other: ________________

23. How do you rate the importance of the following benefits of BIM? (on a scale of 1–5, 5 being highest) كيف تقيم أهمية الفوائد التالية لنمذجة معلومات البناء؟ (على مقياس من 1 إلى 5 ، 5 أعلى) *

Mark only one oval per row.

	1	2	3	4	5
Time saving حفظ الوقت	⬭	⬭	⬭	⬭	⬭
Cost estimation تقدير التكلفة	⬭	⬭	⬭	⬭	⬭
Minimising changes الحد من التغييرات	⬭	⬭	⬭	⬭	⬭
Sustainability analyses تحليل الإستدامة	⬭	⬭	⬭	⬭	⬭
Remove any omission تفادي الإغفال	⬭	⬭	⬭	⬭	⬭
Quality management إدارة الجودة	⬭	⬭	⬭	⬭	⬭
Logistics management إدارة الأعمال اللوجستية	⬭	⬭	⬭	⬭	⬭
Established life cycle دورة حياة ثابتة	⬭	⬭	⬭	⬭	⬭
Life cycle cost تكلفة دورة الحياة	⬭	⬭	⬭	⬭	⬭
Operations and maintenance التشغيل والصيانة	⬭	⬭	⬭	⬭	⬭
Efficient use of energy الإستخدام الفعال للطاقة	⬭	⬭	⬭	⬭	⬭
Facility management إدارة المنشأة	⬭	⬭	⬭	⬭	⬭
Daylight analysis تحليل ضوء النهار	⬭	⬭	⬭	⬭	⬭
Thermal design التصميم الحراري	⬭	⬭	⬭	⬭	⬭
Transparency cost تكلفة الشفافية	⬭	⬭	⬭	⬭	⬭

Appendix 3: Application for Interview Questions.

UNIVERSITY OF BIRMINGHAM

Dear Sir,

I am a Ph.D. I kindly request your participation in a research study I am conducting that aims to measure the use of Building Information Modelling (BIM) on the LCC of Sustainable Building in the construction sector in the Kingdom of Saudi Arabia. Kindly this Interview questions take between (35-45) minutes to answer. So, I hope that the Interview questions will be answered to serve the construction sector in Saudi Arabia.

All information in Interview questions is confidential and will only be used for the purpose of scientific research. Thank you very much in advance for your time and assistance.

I would like to begin by asking you a few questions about your experience in the Kingdom of Saudi Arabia construction business. Furthermore, I will then proceed on to something more specific BIM questions.

Date of interview			
Time of start the interview		**Time of end the interview**	
Name of Interviewee			
Name of organisation		**Position of Interviewee**	
1	**Participants Background**		

	Q1	Kindly inform me about your job experience and the number of years you have been working with BIM?
	Q2	Could you please explain how you become involved with BIM?
	Q3	Could you briefly describe your teamwork abilities as they relate to a BIM expert position?
	Q4	Could you please tell me what experience do you have with CAD, 2D, 3D, 4D, 5D, 6D, 7D, and nD BIM?
2	**Building information modelling (BIM)**	
	Q1	What do you think are the significant challenges of adopting BIM in the Saudi Arabia construction industry?
	Q2	From your experience, what are the benefits of implementing BIM?
	Q3	How well do current BIM-related standards foster teamwork and BIM integration with other software?
	Q4	Who is responsible for adopting the BIM application in the Kingdom of Saudi Arabia?
3	**Life Cycle Cost estimation (LCC)**	
	Q1	Do you think that project LCC is important during the design phase of the decision-making process? ☐ YES ☐ NO
	Q2	Have you ever conducted a LCC analysis of a project?

		☐ YES ☐ NO If the answer is yes, specify what mathematical methods are used, and the software programs you used.
	Q3	Do you think there are many Saudi Arabia construction projects with a high LCC?
4	**Impact BIM on LCC**	
	Q1	What type of software did you use to manage LCC data within the BIM environment?
	Q2	What is your perspective on the efficiency of LCC when utilising BIM costing software compared to the classic costing method?
	Q3	How can BIM 5D environment support the estimated cost analysis of LCC better than it is currently practised in Saudi Arabia projects?
	Q4	Through your experience with BIM, what are the costs implications of not using BIM technology on the cost, time, and LCC in Saudi Arabia construction projects?
5	**Impact of the types of contracts on BIM**	
	Q1	Who extent does the contracts signed in the projects allow for the successful use of BIM models?
	Q2	Do you know what it contains ISO 19650 international standard of BIM?

	Q3	Do you think that the type of contract design, implementation, and operation has an actual relationship to influence the final cost of the project? ☐ Agree ☐ Disagree ☐ Don't, Know
	Q4	What are the risks of different types of contracts such as a fixed price contract, a Design and Build, a traditional, or a design-build operation and their impact on the final cost of the project?
	Q5	What are the motivating factors that encourage the use of BIM for the key stakeholders such as the supply chain, contractors, clients, architects, and engineers to build a sustainable design to lower operating costs?
In conclusion, I would like to thank you for your cooperation. Please do not hesitate to talk to me if there is further information.		