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A FRAMEWORK FOR SUSTAINABLE CONSTRUCTION
PROJECT BASED ON BIM ENVIRONMENT

SCHOOL OF AEROSPACE, TRANSPORT AND
MANUFACTURING
PhD in Manufacturing

PhD
Academic Year: 2019 - 2023

Supervisor: Dr. Ahmed Al-Ashaab
Associate Supervisor: Prof. Konstantinos Salonitis
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ABSTRACT

The global construction industry's significant resource consumption and environmental impact underscore the urgency of sustainability. This research emphasizes the intersection of sustainability and construction, focusing on ecological, economic, and social considerations. It highlights Building Information Modelling (BIM) as a key enabler of sustainability within the construction value chain.

Construction, vital to economic and societal development, necessitates sustainability as a core project objective. Efficient resource utilization, compliance with evolving sustainability standards, and effective collaboration among stakeholders are crucial. However, communication challenges often impede shared understanding and data integration. BIM emerges as a digital solution, unifying project phases, facilitating collaboration, and informed decision-making.

In response to the global sustainability mandate, construction projects worldwide are adopting more effective approaches. BIM plays a pivotal role in enhancing efficiency, performance, and productivity. This research addresses a gap by presenting a framework to assess how building materials impact energy consumption within the BIM environment.

The research aims to develop a comprehensive framework for promoting sustainability in construction projects through BIM. This involves investigating sustainable practices, assessing BIM's role in sustainability, selecting optimal engineering calculations, and creating an integrated framework. The framework's effectiveness will be evaluated through a hypothetical case study.

Key research questions include BIM's alignment with sustainability, expected improvements in addressing sustainability issues, and the value of sharing sustainability calculations within the construction value chain. The thesis comprises seven chapters, including a literature review on sustainability and BIM, a detailed research methodology, a hypothetical case study, analysis of conduction heat transfer calculations, the development of a sustainable construction framework, and discussions, conclusions, and future directions. This

research seeks to empower the construction industry with a practical framework for embedding sustainability within the BIM environment, driving efficiency, environmental responsibility, and societal well-being.

Keywords: Sustainability issues in construction, BIM Environment, Revit software, Heat transfer, Embodied carbon footprint, BIM collaborate Pro.

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TABLE OF CONTENTS

ABSTRACT	i
ACKNOWLEDGEMENTS.....	iii
LIST OF FIGURES.....	vii
LIST OF TABLES	viii
LIST OF EQUATIONS.....	x
LIST OF ABBREVIATIONS	xi
1 IDENTIFICATION AND SIGNIFICANCE OF THE RESEARCH PROBLEM....	1
1.1 Research Background	1
1.2 Research Aims and Objectives.....	3
1.3 Research Questions	3
1.4 Thesis Structure.....	3
1.5 Closing Remarks.....	5
2 LITERATURE REVIEW	6
2.1 Introduction	6
2.2 Overview of Sustainability and Sustainable Construction	6
2.2.1 Definition of Sustainability	6
2.2.2 Concept of Sustainability in Construction.	7
2.2.3 Principles of Sustainability in Construction.	8
2.2.4 Construction Sustainable Design	10
2.3 Perception of Sustainability within a Construction Project	11
2.3.1 Implementation of Sustainability in Construction Projects.	11
2.3.2 Construction Sustainability Issues.....	13
2.4 Overview of Building Information Modelling (BIM)	17
2.4.1 BIM Definition	17
2.4.2 BIM Objects.....	20
2.4.3 BIM and Autodesk Revit.....	22
2.4.4 BIM Dimensions	23
2.4.5 BIM Standards	24
2.4.6 BIM Level	27
2.4.7 BIM Libraries	30
2.5 Review of Sustainability Research within the BIM Environment	31
2.5.1 The Benefits and Advantages of Sustainability within BIM.....	33
2.5.2 Construction Value Chain in a BIM Environment	35
2.6 Research Gap.....	37
2.7 Closing Remarks.....	38
3 RESEARCH METHODOLOGY	39
3.1 Introduction	39
3.2 Methodological Approach:	42
3.2.1 Construction Sustainability Practices	43

3.2.2 Sustainability in a BIM Environment.	46
3.2.3 Sustainability Engineering Calculations.....	47
3.2.4 Sustainable Construction Framework Based on BIM.	50
3.2.5 Validation Via Case Study.....	50
3.3 Closing Remarks.....	51
4 THE FORMULATION OF THE CASE STUDY BASED ON ONE-BEDROOM SINGLE STOREY HOUSE	52
4.1 Introduction	52
4.2 Case Study of One-Bedroom House.....	52
4.3 Wall Structure and Quantities of Materials.....	53
4.3.1 Quantity of Bricks	53
4.3.2 Quantity of Cement, Sand and Water for Brickwork.	54
4.3.3 Quantity of Plasterboards.....	59
4.4 The representation of One-bedroom house in BIM.....	60
4.5 Closing Remarks.....	61
5 COMPARATIVE CONDUCTION HEAT TRANSFER IN SIMPLE CONSTRUCTION ELEMENTS	62
5.1 Introduction	62
5.2 Conductive Heat Transfer Calculation for a Wall.	63
5.2.1 Calculation Data for a Brick Wall with Plasterboard.	65
5.2.2 Calculation Data for a Precast Concrete Wall.	66
5.3 Discussion	66
5.4 Closing Remarks.....	68
6 THE DEVELOPMENT OF A SUSTAINABLE CONSTRUCTION FRAMEWORK BASED ON BIM.....	69
6.1 Introduction	69
6.2 Construction Sustainability Framework in a BIM Environment.....	69
6.3 The Application of a Construction Sustainability Framework to the Embodied Carbon Footprint of a One-Bedroom House in a BIM Environment.....	73
6.3.1 Information Management.	73
6.3.2 Start of Construction Value Chain Work.....	77
6.3.3 Embodied Carbon Footprint: Engineering Calculation	79
6.3.4 Embodied Carbon Footprint Results in a BIM Environment (BIM Collaborate Pro Software)	88
6.4 Closing Remarks.....	99
7 DISCUSSIONS, CONTRIBUTION TO KNOWLEDGE, CONCLUSION AND FUTURE WORK.....	100
7.1 Introduction	100
7.2 Discussion	100
7.3 Contributions to Knowledge	104
7.4 Conclusions:	105

7.5 Future Works	106
8 REFERENCES	108

LIST OF FIGURES

Figure 1-1 Thesis Structure	5
Figure 2-1 Triple line principle (Ghaffarianhoseini et al., 2013)	10
Figure 2-2 The Importance of BIM in construction industry (Author).	20
Figure 2-3 Illustration of the BIM object "window" (Author).....	21
Figure 2-4 BIM Dimensions (Charef, 2022; Montiel-Santiago et al., 2020)	23
Figure 2-5 BIM Maturity Levels. PAS1192-2:2013	27
Figure 2-6 Construction Value Chain in a BIM Environment (Author).	36
Figure 3-1 Research onion model	39
Figure 3-2 Bricks description	48
Figure 4-1 Case study design (Author).....	53
Figure 4-2 Wall dimensions 10m x 3m (Author).....	54
Figure 4-3 Brickwork process	56
Figure 4-4 Type of Plasterboard (Sheet, 2021)	59
Figure 4-5: The representation of One-bedroom house in BIM (Author)	61
Figure 5-1 Detailed description of the structure (Author)	63
Figure 5-2 Different wall materials & parameters from Revit (Author)	64
Figure 6-1 Illustration of a framework for managing sustainability issues in a BIM environment (Author).....	71
Figure 6-2 Illustration of the application of the BIM framework on embodied carbon of one-bedroom house (Author).....	75
Figure 6-3 An example of detailed project plan of one-bedroom house (Author).	77
Figure 6-4 The overall design of the one-bedroom house (Author).	78
Figure 6-5 Elevation and floor plan of the one-bedroom house (Author).	78
Figure 6-6 Construction project life cycle information (Gibbons & Orr, 2020b). 80	
Figure 6-7 C3-C4 Waste processing values (RICS, 2017)	83
Figure 6-8 Total embodied carbon of brick walls (Author).	84
Figure 6-9 Total embodied carbon of plasterboard (Author).....	86
Figure 6-10 Embodied carbon benchmark (Pasanen & Castro, 2019)	88

Figure 6-11 (1) TableGen application to Integrate calculation into Revit (Author).	90
Figure 6-12 (2) TableGen application to Integrate calculation into Revit (Author).	91
Figure 6-13 (3) TableGen application to Integrate calculation into Revit (Author).	92
Figure 6-14 (4) TableGen application to Integrate calculation into Revit (Author).	93
Figure 6-15 overview of one-bedroom house project in BIM (Author).	94
Figure 6-16 Project Docs view (Author).	95
Figure 6-17 Project Members (Author).	96
Figure 6-18 3D Model view (Author).	96
Figure 6-19 Object Properties (Author).	97
Figure 6-20: The Side Elevation view (Author).	97
Figure 6-21 A screenshot presenting the embodied carbon result in BIM environment (Author).	98
Figure 6-22 Project Status (Author).	98

LIST OF TABLES

Table 2-1 Different sustainability issues related to an asset.	14
Table 2-2 Sample Governments Requiring Use of BIM (Author).	18
Table 2-3 Various definitions of BIM (Author).	18
Table 2-4 Identifies relevant standards issued by the British Standards Institution (BSI) and International Organisation for Standardization (ISO) (Author).	26
Table 2-5 List of open access BIM object libraries (Author).	30
Table 2-6 Integration of BIM and sustainability benefits (Author).	34
Table 3-1 Research Approach.	42
Table 5-1 Comparison of wall materials (Author).	67
Table 6-1 The owner information requirements (Author).	74
Table 6-2 Default distance values (Gibbons & Orr, 2020a)	82

Table 6-3 Selection of waste rate data (Gibbons & Orr, 2020a)	82
Table 6-4 Default values for module C2 (Gibbons & Orr, 2020a)	83
Table 6-5 Production embodied carbon factors (RICS, 2017).....	85
Table 6-6 Total embodied carbon footprint for one-bedroom house (Author)...	87

LIST OF EQUATIONS

(3-1)..... 49

(3-2)..... 50

(5-1)..... 64

(6-1)..... 81

(6-2)..... 81

LIST OF ABBREVIATIONS

BIM	Building Information Modelling
ISO	International Organization for Standardization
CAD	Computer Aided Design
LCA	Life Cycle Assessment
MEP	Mechanical, Electrical and Plumbing
RVT	Revit Model File
IFC	Industry Foundation Classes
LOD	Level of Development
GIS	Geographic Information System
RTRS	Real-Time Replay System

1 IDENTIFICATION AND SIGNIFICANCE OF THE RESEARCH PROBLEM

1.1 Research Background

The proportion of natural resources consumed by the global construction industry is considerable. For instance, it uses 16% of the water, 25% of the timber and 40 % of the raw materials consumed, and approximately 40% of all the energy generated (Iyer-Raniga, 2019). It is also responsible for 35-40% of CO₂ emissions and produces 30-40 % of waste (Safinia et al., 2017; Tokbolat et al., 2020). Thus, it is not surprising that sustainability in the construction industry is high on the agenda of governments, practitioners, and the academic community. Sustainable construction is considering ecological and environmental, economic (e.g., competition, costs, and construction time) and social (e.g., health and safety, local community needs) factors to be taken into account (Elawi et al., 2016). These last considerations can be grouped as “technical sustainability”, dealing with concepts that are related to the performance, quality, and service life of a building or structure and, typically, sustainability in construction is viewed in terms of the tripartite domains: environment, economy and society (Cruz et al., 2019). It also, of course, requires mechanisms for critically evaluating the success, or otherwise, of sustainability in construction projects.

The construction industry has been considered a dominant factor in the sustainable development of economies and societies, nationally and internationally. This means sustainability generally is directly linked to the sustainability performance of construction related projects, which means sustainability should be a project goal (Cruz et al., 2019). Therefore, sustainability is an important factor in infrastructure projects in terms of durability, cost reduction, and involves multiple stakeholders with varying expectations.

It is a requirement for the construction project manager to use the available resources efficiently to meet new standards and legislation introduced in respect of resource consumption and sustainable standards. Many actors are involved in construction projects, including contractors, clients, designers, architects, and

suppliers (Flores et al., 2018). In a construction project, different organizations are involved at different stages. Each stakeholder has their own perspective and vision for the final asset. The use of different tools, such as software packages and in-house techniques, can create communication challenges between these stakeholders. This can hinder a shared understanding of the project, as well as the integration of data and information. For this intention, Building Information Modelling (BIM) is a digital process that integrates different phases of a construction project into one coordinated working structure. This allows stakeholders to collaborate more effectively and make better decisions throughout the project lifecycle (Ahuja et al., 2020; Kreider & Messner, 2013). BIM uses a shared digital representation of a built asset to capture and manage information about the asset's design, construction, and operation. This information can be used to improve communication, coordination, and decision-making (ISO 19650, 2018). The use of BIM can help construction projects by providing a deeper understanding of the project and its requirements. This can lead to better decision-making throughout the supply chain, as stakeholders have access to more accurate and up-to-date information. BIM can also help to redefine the construction process and the relationships between key stakeholders, saves time and cost and provides the most efficient design with customized tools for the customer to adjust outcomes of the project to their needs.

In response to the growing concern regarding the need for increased sustainability, many construction projects around the world have endorsed the construction sector's use of more effective approaches in projects (Correia, 2019). An increasing awareness exists in the different elements in the construction value chain that embedding good practices regarding sustainability will increase efficiency, performance and productivity. For example, when working toward sustainability during the construction process, BIM can be used to facilitate the selection of material suppliers.

The information that can be incorporated in BIM objects is already specified by existing guidelines and standards (ISO 19650, 2018). However, there is a lack of emphasis on sustainable dimensions and how such information should be

presented based on the level of development of the project. Currently, it is crucial not only to make the project's sustainable information accessible, but also to make that information accessible in a suitable way. This research presents a framework of addressing the sustainability issue of how, within the BIM environment, the materials used in the design of a building affect energy consumption to obtain better performance of the building.

1.2 Research Aims and Objectives

The aim is to develop a framework to enhance the sustainability of a construction project as part of the value chain based on the application of Building Information Modelling (BIM). This aim will be achieved by:

1. Critically investigating the application of good practices in the construction sector regarding sustainability.
2. Understanding how BIM applications are currently addressing sustainability in construction projects.
3. Identifying and selecting the optimum engineering calculations to address the most common sustainability issues.
4. Developing a framework for integrating sustainability good practices in a BIM environment.
5. Evaluating the framework via a hypothetical case study.

1.3 Research Questions

1. How, currently, are BIM and its related dimensions and standards addressing sustainability?
2. How will the applications of BIM improve the manner in which the identified issues regarding sustainability in construction are addressed?
3. The value of sharing sustainability calculation result in BIM among the construction value chain?

1.4 Thesis Structure

The thesis comprises seven chapters as shown in Figure 1-1, with multiple sections and subsections included in each chapter. Chapter Two (Literature

review) presents an overview of sustainability and implementation of sustainable practices in the construction industry. Additionally, the chapter provides an overview of BIM practices throughout the construction value chain, as well as a review of sustainability research conducted within the BIM environment. Chapter Three (Research methodology) outlines the various phases of the study based on the research objective, with each phase containing key tasks and deliverables. Chapter Four (The case study) presents the detailed structure of the hypothetical case study. The results of the experiments are then analysed and discussed. Chapter Five (Conduction heat transfer calculation) concerns the calculation of, and discussion about, the heat transfer rate in the case study. Chapter Six (The development of a sustainable construction framework based on BIM) presents a construction sustainability framework in the BIM environment and validates its application regarding the carbon footprint results for the case study. Finally, Chapter Seven (Discussions, Conclusion & Future work) summarises the findings of the thesis and suggests possible avenues for future work.

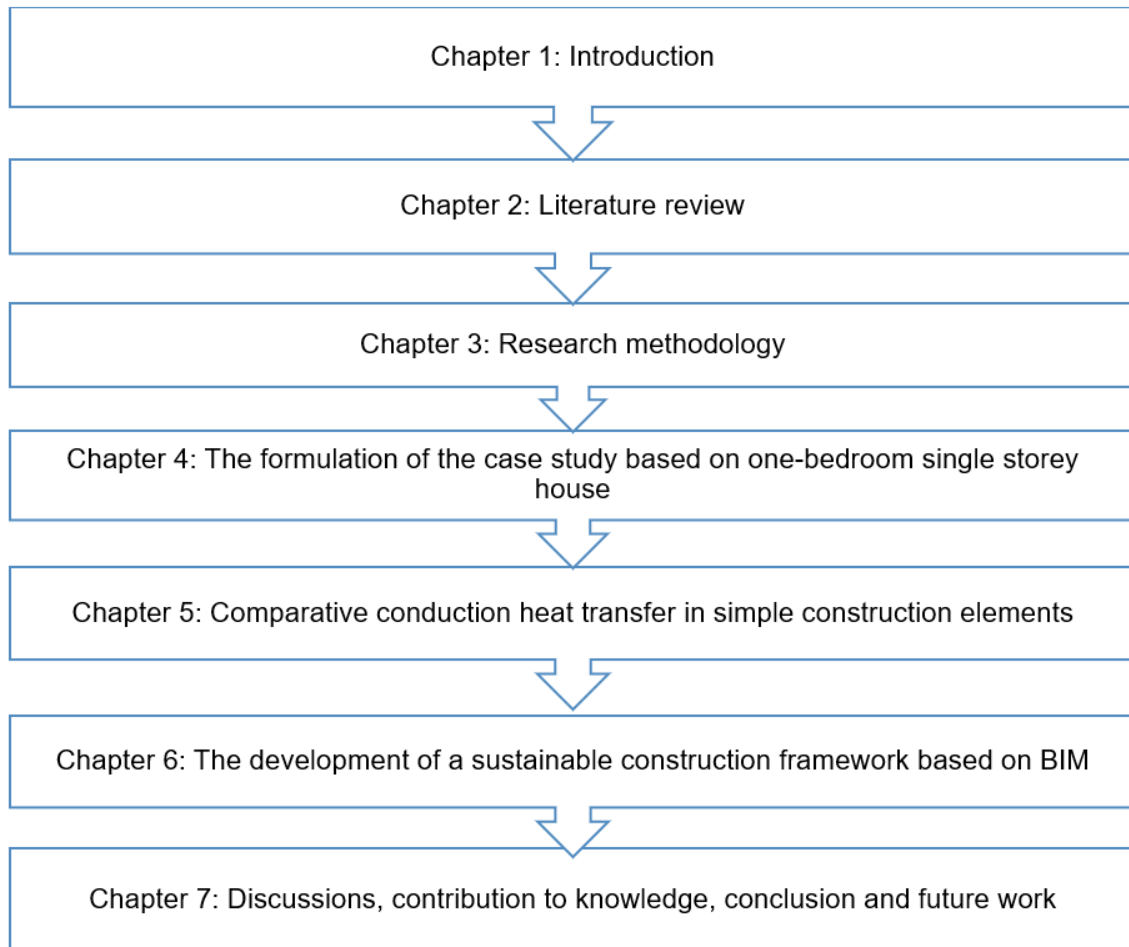


Figure 1-1 Thesis Structure

1.5 Closing Remarks

By laying out the aim and objectives of the research, this chapter has set the stage for the rest of the study. This chapter also identifies the rationale for conducting research into developing a framework to enhance the sustainability of a construction project as part of the value chain based on Building Information Modelling. Moreover, the discussion provides an outline of the methodology used in the current study to attain its objectives. The next chapter looks at the relevant literature to help focus the research topic.

2 LITERATURE REVIEW

2.1 Introduction

This chapter provides an overview of the latest developments in sustainability and BIM research in the construction industry. It covers key aspects such as the implementation of sustainability and common issues encountered in the sector. It also discusses ISO standards and various BIM applications. The chapter highlights the importance of incorporating multiple elements into the management of information across the construction value chain to ensure that best practices are utilized. This approach serves as the foundation for developing an effective sustainable construction framework in BIM for managing construction projects.

2.2 Overview of Sustainability and Sustainable Construction

2.2.1 Definition of Sustainability

The term "sustainability" encompasses various perspectives and definitions, particularly in the context of addressing global environmental challenges. One common interpretation, as articulated by Yates (2013), defines sustainability as economic growth that meets the needs of the present generation without compromising the ability of future generations to meet their own needs. Additionally, sustainability has been employed to promote the concept of the triple bottom line, emphasizing the interconnectedness of social, environmental, and financial aspects in corporate society, as advocated by (Glass, 2012).

In the context of this research, the focus on sustainability aligns with the broader consensus among scholars, including (Awadh, 2017a; Elmqvist et al., 2019; Jum'a et al., 2022; Moore et al., 2017; Virtanen et al., 2020). Sustainable development, as understood within this framework, entails several key elements for achieving a high quality of life for both current and future generations. These elements include the responsible protection of the environment, efficient utilization of natural resources, social progress that meets the diverse needs and desires of all individuals, and the maintenance of robust economic growth. At its core, sustainable development is characterized by a holistic perspective that integrates economic, social, and environmental factors. This encompasses

practices such as cleaner production, pollution prevention, and the design and implementation of environmentally conscious architectural and structural solutions for buildings, as advocated (Virtanen et al., 2020).

2.2.2 Concept of Sustainability in Construction.

To achieve sustainability, responsible construction is required which develops the notion of sustainable construction. This can be defined as the search by those participating in a project for alternative ways of undertaking activities to align with the principles of sustainability, see section 2.2.3. This underscores how important the notion of sustainable development has become in the construction industry. However, there are several different ways in which sustainable construction can be defined. Typically, it is defined as having zero impact which essentially means that construction activities do not exert a negative impact on the environment, society, or the economy (Mavi et al., 2021).

Different ways of examining how sustainability have been addressed in construction projects. For instance, a seminal study by Marcelino-Sádaba et al., (2015) illustrated how such projects are implemented to ensure buildings and infrastructure have a greater level of sustainability. Sustainability is less concerned with accruing profits and more with the possible benefits to society, (Shen et al., 2010). However, this may create tensions between short-term economic goals and long-term benefits to the environment. Therefore, to attain a mutually advantageous equilibrium, a balance must be struck between them. To facilitate this, prior to conducting a project, a feasibility study should be performed that includes elements of sustainability, as this will help determine the overall success of the project (Shen et al., 2010). Sustainability is an undertaking driven by processes that have no single fixed path and can be attained through a variety of activities (Bridson et al., 2020). Developed in 1994, the concept of the triple bottom line indicates that sustainable construction can be achieved by focusing on social, environmental, and economic performance as equally vital dimensions in delivery of a project (Bamgbade et al., 2017). Thus, embedding a sustainability-oriented element when creating a methodical workflow will form the foundation for the processes and practices that follow within a project. This will establish a

sustainable structure through which to deliver sustainable construction outcomes. Awadh, (2017), Chan & Lee, (2008), and Darko & Chan, (2017) have offered the following descriptions of sustainable construction with respect to environmental, social, and economic sustainability:

- Environmental sustainability: This involves reducing energy consumption, and amount of waste produced through the effective and efficient use of natural resources; of managing structures or facilities in such a way as to reduce adverse impacts on the environment.
- Social sustainability: This concerns promoting social harmony and establishing a safe and healthy environment for everyone by taking account of people's needs throughout the duration of the construction process, including the subsequent life of the structure.
- Economic sustainability: This involves creating cost-efficient structures that are fit for the purpose and/or meet users' needs by reducing the operating costs and extending the service life of structures through efficacious, quick repair and maintenance systems. It also concerns elevating profits by best utilisation of construction resources such as labour, and materials such as water.

2.2.3 Principles of Sustainability in Construction.

Djokoto et al. (2014) proposed six principles vital to the success of sustainable construction practices or processes. These are as follows:

- Utilising renewable and recyclable resources or materials.
- Establishing a non-toxic and healthy environment.
- Maximising reuse of resources.
- Minimising consumption of resources.
- Safeguarding the natural environment.
- Ensuring high quality construction processes.

(Harish Raju.P, Krithika, 2016) identified the following reasons why owner or programme managers may decide to practise sustainability:

- Reduced liability.

- Reduced costs.
- Productive and efficacious management and disposal of materials.
- Improved community image.
- Short-term and long-term corporate responsibility.

Figure 2-1 depicts the benefits of sustainable construction offered by the triple principles. The key components of the triple bottom line are the following (Cruz et al., 2019; Goh et al., 2020a):

Fitness for purpose: Each structure or facility that is built should fulfil the needs of users or society.

Encourages the local community: This considers the local communities' needs and ensures that they are fully engaged in the process of development.

Encourage social cohesion: This nurtures social relationships, i.e., ensures equal employment opportunities for ethnic minorities, women, and people with disabilities:

- Quality of life: enhanced for both current and future generations.
- Culture and heritage: improved or existing culture and heritage preserved in a way that takes local styles of architecture into consideration; new projects should align with local, cultural, and historical contexts.
- Whole lifecycle cost: it is essential to consider this when building a structure or facility.
- Training and education: these should be provided to project participants and there ought to be a focus on sustainable construction subjects.
- Land usage: promote the use of the most suitable sites for development and encourage mixed land usage.
- Biodiversity: the long-term effects of construction on biodiversity should be considered. Biodiversity should be protected and improved, whereas threats to sites of special scientific interest, protected species, and local environmentally sensitive sites should be avoided.
- Prevent pollution: reduce air pollution and the risk of water pollution and avoid/lessen the effect of emissions.

- Prevent the reduction of natural resources: limit their use, utilise them more efficiently, use renewable and sustainably sourced materials, avoiding those that have a negative impact on either people or the environment.
- Reduce the effect of waste: limit the amount sent to landfill, reuse and recycle materials.

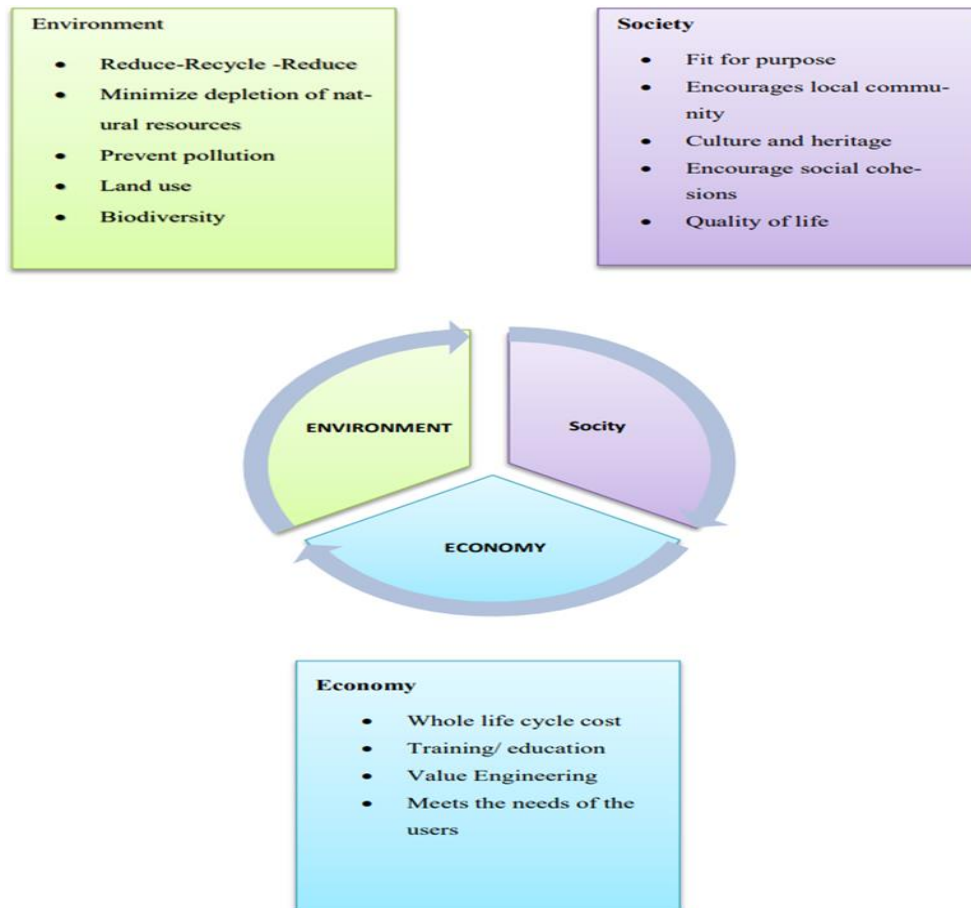


Figure 2-1 Triple line principle (Ghaffarianhoseini et al., 2013)

2.2.4 Construction Sustainable Design

Sustainable design is a system that takes into account the life cycle of a project and its effect on energy resources and the environment. Thus, a core objective of sustainable design is to reduce the consumption of resources and materials, principally through sustainable construction (Kivilä et al., 2017). Sustainable design has a substantial role to play in lessening or at least preventing any increase in the effects of climate change and in controlling risks via the process

of adaptation. This is the first step on the path to attaining sustainable construction (Reading et al., 2012). In summary, to attain the best environmental, social, and economic outcomes, the principles of sustainable construction and sustainability must be enacted in a cohesive manner while addressing regional variation.

Because sustainable construction practice is comparatively new, several issues still need to be addressed in order to know how to operate within the parameters set by the tenets of sustainable construction (Tabassi et al., 2016). For example, the positive effects of setting goals pertaining to one principle can offset the negative effects of others. Therefore, for sustainable construction, there is no universal panacea, which means it is essential that relevant stakeholders strive to achieve overall compliance by devising a feasible plan.

2.3 Perception of Sustainability within a Construction Project

Within the construction sector there is a range of disparate stakeholders whose emphasis on factors such as cost, time, and quality may vary from one to another. Emphasising one factor can mean doing so at the expense of others. In the majority of cases, stakeholders' views of the role of sustainable construction in a project will vary with their view of how the components of sustainable construction accord with the aims of the project. Projects can therefore be undertaken using a variety of methods and approaches without certainty. Yılmaz and Bakış (2015) argue that such diversity of emphasis can make it problematic for project stakeholders to identify, with any clarity, the sustainable development requirements, or aspects they want to attain. Yet gaining agreement on substantive issues such as climate change, resource depletion, material utilisation, energy, and biodiversity that form the basis of sustainable development goals is vitally important to both current and future generations (Li, 2011).

2.3.1 Implementation of Sustainability in Construction Projects.

In the contemporary construction industry, it is believed that acknowledging the elements that determine whether a project is successful are intertwined with the

activities undertaken during a particular assignment. Project participants responsible for enacting sustainability principles need to consider the entire process from the conceptual design stage to completion (Correia, 2019). Thus, sustainable construction should be implemented by emphasising both the advantages and negative effects that occur throughout the course of a project.

Based on the life cycle of buildings and similar construction works, Ukaga et al., (2010) have identified and set in place the core tenets for ensuring sustainable construction which can be achieved by promoted and fulfilling six objectives. These are: (a) adopting a proactive stance; (b) enhancement of the construction industry; (c) decoupling economic growth from expanding negative effects; (d) innovation; (e) reconciling diverse interests that involve making short-term and long-term decisions; and (f) reducing negative effects, even when striving to improve values. By contrast, Bauer et al., (2010) and Kibert (2016) postulated nine goals that need to be attained in the (ISO 19650, 2018) to promote and implement sustainable construction.

- Holistic approach: with regard to the life cycle of the construction project, this encompasses all areas of sustainability.
- Equity: this consists of inter-regional and inter-generational considerations, ethics, and the triple bottom line.
- Responsibility: this refers to moral responsibility for all actions undertaken.
- Transparency: information about the materials and decision-making process should be truthful, all-encompassing, easily understood, and accessible.
- Long-term thinking: this includes the long-, medium-, and short-term effects of decisions made.
- Global thinking and local action: this consider global effects at a local level and how global policies and techniques affect local issues.
- Involvement of interested parties: stakeholders should consider the roles, importance, timing, and opinions of all those involved.
- Risk management: this should be applied in construction-related work to ensure all due precautions are taken.

- Continual improvement: there should be gradual improvements in the sustainability element of construction works.

2.3.2 Construction Sustainability Issues.

The most significant elements related to sustainability in construction projects are illustrated in the matrix presented in Table 2-1, with the relevant references given.

Embodied Carbon footprint: Climate change and global warming are serious issues for the construction industry which is estimated to be responsible for emission of 30 per cent of CO₂ and greenhouse gases. This is due to the extraction and manufacturing of construction materials, transportation, installation, maintenance and disposal of construction products and materials. The construction sector is making a great effort to adopt green practices – for instance, by selecting raw materials which have low embodied energy (Ajayi et al., 2019; Landolfo et al., 2022; Shurrab et al., 2019).

Energy efficiency: The construction industry is estimated to be responsible for 40 per cent of the world's energy consumption. The lifecycle environmental impact of a building is significantly affected by energy savings obtained by using appropriate technological methods – for instance, the utilisation of solar panels and energy efficient air-conditioning, lighting and heating systems. The UK government has established a goal of attaining a 60 per cent energy reduction by 2050. Buildings which consume a lower amount of energy, thereby leading to an enhanced living environment, are certified under the green rating system (Doan et al., 2017; Shurrab et al., 2019).

Table 2-1 Different sustainability issues related to an asset.

Element of Sustainable good practice	Embodied Carbon footprint	Minimize the use of resources	Sustainable construction site	Embodied impacts and material life costs	Supply chain reduced costs	Water efficiency	eco-refurbishment of existing buildings	Financial incentive and innovative fiscal arrangements	Improved energy efficiency (Heat transfer)	Off-site construction methods	Waste control
Reference											
Dinh & Dinh, 2021		X	X	X	X	X			X		
Shurrab et al, 2019	X	X					X	X	X	X	
Yılmaz & Bakış, 2015)	X	X				X	X		X		X

Danso, 2018	X	X	X	X		X			X		X
Pham & Kim, 2019	X	X	X	X	X				X		X
Sitota et al., 2021	X	X		X	X				X		X
Zuo, Jin, & Flynn, 2012	X	X	X			X			X		
Al-Osta et al., 2022)	X	X		X					X		X
Cruz, Gaspar, & de Brito, 2019	X	X	X		X		X		X		X
Olubunmi , 2016						X		X			
Ajayi et al., 2019	X	X	X	X		X	X			X	

Waste control: Waste management policies are now adopted by the majority of principal contractors (Li et al., 2022). Construction creates a massive amount of waste, ranging from manufacturing and application of materials to demolition and disposal of structures. A systematic method at an operational standard ought to be applied by sustainable construction and should include the use of recyclable and renewable construction materials (Al-Osta et al., 2022; Shi et al., 2013).

Cost control: Reduced transportation and energy costs, which are of long-term benefit to the environment, result in sustainable materials generating long-term savings in overall cost. Moreover, low-maintenance systems lead to a reduction in maintenance, repair, and replacement costs. The government offers monetary incentives to reduce the cost burden and motivate the private sector to become more sustainable. Such encouragement includes tax incentives, reduced development application fees, and direct grants. For instance, those who own green buildings are either granted tax deductions, or even offered complete exemption from paying taxes (Danso, 2018; Olubunmi et al., 2016; Sitota et al., 2021).

Water efficiency: Water conservation strategies and technologies are more frequently overlooked than any other element in a whole-building design strategy. However, the construction industry has the capacity to introduce water conservation methods into both new-build projects and refurbishments. This includes water efficient technology, such as reduced flow taps, low-water flush toilets, and domestic appliances, all of which can enhance energy and resource conservation (Akadiri et al., 2012; Dinh & Dinh, 2021).

Minimize Resources: Locally available and manufactured materials such as clay, grass, sand, stones, thatches, timber, clay blocks and clay bricks ought to be prioritized when building houses, helping satisfy housing demand while optimizing the environmental performance of materials by lifecycle assessment (LCA). Of course, adaptive re-use, should also be considered (Cavalliere et al., 2019; Park et al., 2017; Sizirici et al., 2021).

While the literature review highlighted the environmental, economic, and social sustainability practises in the building industry, BIM and construction managers were also interviewed, and the latter highlighted the challenges in selecting for sustainability, see Table 2-1. For example, selection of materials to minimise heat transfer, maximise energy efficiency and lower resource consumption which, in turn, can be incorporated into environmental concerns, such as CO₂ reduction. The necessary information on the material provider, material type and material properties is an essential component of any administrative data system supporting a construction project.

The embodied carbon footprint is a crucial sustainability issue because it accounts for a significant portion of a building's lifetime emissions. Reducing embodied carbon can contribute substantially to meeting climate goals, making it a key focus area for sustainable construction. Moreover, heat transfer in buildings directly impacts energy efficiency. Effective insulation and design measures can significantly reduce the need for heating and cooling.

In summary, focusing on both embodied carbon footprint and heat transfer in construction is essential for advancing sustainable construction practices, reducing environmental impacts, and enhancing occupant comfort. These issues are recognized as critical by scholars and researchers, underscoring their importance in addressing sustainability challenges in the built environment.

2.4 Overview of Building Information Modelling (BIM)

2.4.1 BIM Definition

BIM is an innovative modelling technology introduced in the architectural, engineering, and construction industries which includes all digital data throughout the life cycle of a construction project (Wan Mohammad et al., 2018). It was introduced by Charles Eastman in the 1970s, since when it has expanded in scope (Aryani et al., 2014). The construction industry in the USA had significantly increased its use of BIM by the late 1990s, following which it was introduced in other countries such as Singapore and the UK (Lee & Borrmann, 2020). Governments across the globe have acknowledged the potential of Building

Information Modelling (BIM) to reduce construction costs, save time, and minimize waste. Consequently, many governments have implemented regulations to promote and enhance the use of BIM in the construction industry. The UK, for instance, has made it mandatory, since 2016, for all public projects to employ BIM. Table 2-2 presents a list of countries that have implemented regulations regarding BIM, along with the dates of their first implementation. USA, Singapore, Denmark, Norway and Finland are regarded as early adopters, while France has been comparatively slower to adopt BIM.

Table 2-2 Sample Governments Requiring Use of BIM (Author).

	2007	2010	2011	2012	2014	2015	2016	2019
UK							X	
Netherlands				X				
Norway		X						
Singapore		X						
Denmark	X							
USA	X							
Hong- Kong					X			
South Korea							X	
Finland	X							
France								X

As detailed in Table 2-3, BIM has been defined in different ways by a broad range of researchers and organisations.

Table 2-3 Various definitions of BIM (Author).

Reference	Definition
(Kumar, 2015)	BIM is a technology and corresponding group of processes employed to develop communication and analyse information for the construction value chain.

(Gurevich, Sacks, and Shrestha, 2017)	BIM is a set of processes aimed at enhancing understanding of the project, enabling participants in the supply chain to communicate with each other and their clients.
(Chong, Lee, and Wang, 2017)	BIM is a process that handles the functioning of the construction value chain that denotes the physical and functional features of a building.
(Musa, et al., 2018).	BIM is a set of processes aimed at enhancing comprehension of the project and facilitating communication between value chain, designers, contractors, and maintenance teams, also
(König, Koch, and Beetz, 2018)	BIM refers to a wealth of in-depth information produced by stakeholders at all stages of a project life cycle from initial conception to final demolition.
(König, Koch, and Beetz, 2018)	BIM refers to the exchange of knowledge information resources between stakeholders throughout the life cycle of a project. It can be updated as and when needed.
(Amuda-Yusuf, 2018).	BIM is a 3D model constructed to digitally encompass all data from the construction chain to enhance the extent to which asset solutions are optimised, as well as increasing the value
(Nanisa, et al., 2021)	BIM is an intelligent digital 3D model designed to improve the project plan by denoting the physical and functional attributes of an asset.
This researcher's definition	Presented in a single 'BIM federated model', BIM refers to the digital representation of an asset and manages the information relating to construction projects.

Construction projects involve multiple parties such as designers, contractors, and clients. However, they often work independently and utilize different software, resulting in a lack of common understanding potentially leading to delays, additional costs, and discrepancies between the client's vision and reality. To address these challenges, the construction community has introduced the concept of Building Information Modelling (BIM), which aims to create a single integrated digital representation of the asset. BIM promotes collaboration and communication among all parties involved in the project and enables them to share a common vision, resulting in a more efficient and effective construction process as shown in Figure 2-2.

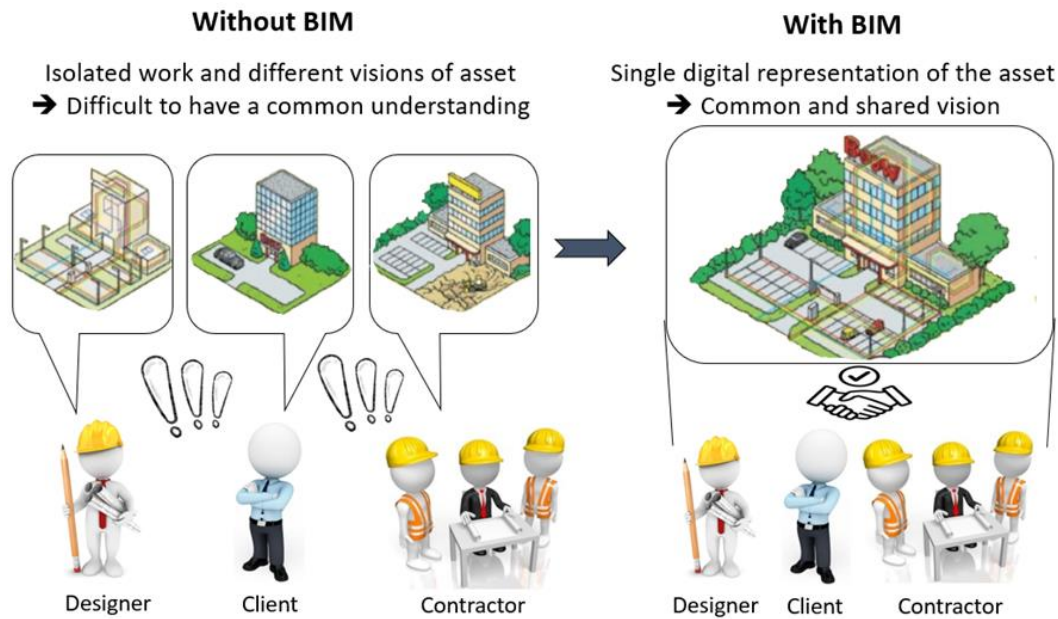


Figure 2-2 The Importance of BIM in construction industry (Author).

2.4.2 BIM Objects

A BIM object represents one single part of an asset, such as a door, wall, floor, or pipe. The geometric data, technical data and admin data can be added, updated or modified as illustrated in Figure 2-3. With clearer and more accurate information the BIM objects allow different members of the construction value chain to collaborate more efficient in carrying out an effective project plan (*BIM Object - Designing Buildings*, 2022).

- **Geometric Data:** is used for formal geometric modelling (1D wireframes, 2D surfaces, and 3D solids) to represent the different shapes of an object, whether a building space or a building. To build the BIM object libraries for a construction project a company must first locate the digital structure and physical characteristics of required objects (Al-Saeed et al., 2020). To link an objects' data to lifecycle analysis in individual software applications, a direct, unique, and unambiguous name should be created for each entity whether a product or a space, or a construction activity. It is essential that the information related to each named entity is fully defined, and that each entity contained within the database is correctly paired with a BIM object (Pavan et al., 2019).

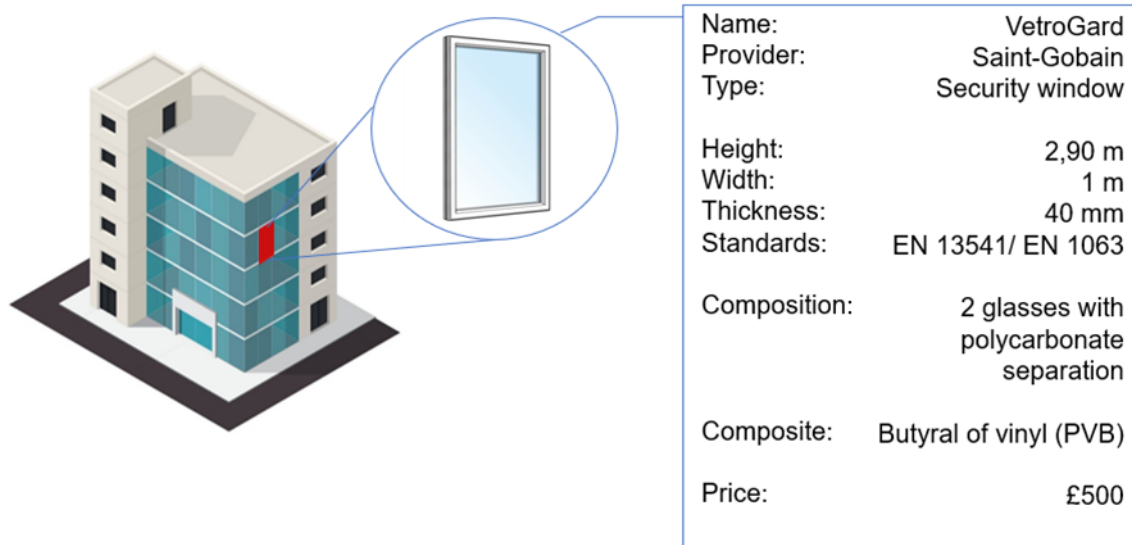


Figure 2-3 Illustration of the BIM object “window” (Author)

- **Technical information:** is associated with the geometric data to provide engineering data (i.e., properties of the materials; surface finish, thermal conductivity, structural strength, etc.). In the process of building a BIM model, technical information is an essential element in completing the classification of an object and to capture its relationships with other objects (Issa and Olbina, 2015). Providing accurate details of parametric objects can accelerate the process of architectural model creation (Baik et al., 2014).
- **Admin. information:** Refers to the non-geometric data associated with a BIM object such as the object's name, description, manufacturer, model number, and other relevant attributes that are not related to the object's physical geometry. Admin. information helps to classify and organize BIM objects and provides crucial information to stakeholders throughout the construction project's lifecycle. (RIBA Enterprises Limited, 2017; McPartland, 2017).

In the early stages of any project, designers must concern themselves with safety and its impact on, for example, constructability. The cross-linkages available in BIM models will greatly enhance this process. The information of the BIM object is clarified in BIM dimensions such as 2D, 3D, 4D, 5D, 6D and 7D and each BIM

object contains important information in each of these dimensions (Abbas et al., 2022).

2.4.3 BIM and Autodesk Revit

Revit is a CAD system developed by a small company in Massachusetts, and then bought by Autodesk and dedicated to architecture and construction applications. It has now become one of the core CAD systems in the BIM environment. Like all BIM tools, it offers integration through applications such as Revit Structure, Revit Architecture, and Revit MEP. Architect designers and construction engineers can use these to construct their own model as each software program is standalone, although a common RVT extension can be used to link all the files (Memon et al., 2014).

Regardless of the stage at which information is required, Revit provides data on both the design and quantities of the project. Also known as families, parametric elements denote the foundations for the design of all construction components under Revit (Shi & Xu, 2021).

Revit has only the capacity to handle primary aspects of design such as architecture, structure, and MEP (Bellido-Montesinos et al., 2019). For all other cases, connections are available with particular applications that make use of the same BIM model.

Revit is designed to work with other applications in the BIM process, allowing architectural designers and construction engineers to exchange data with different software programs and collaborate with other stakeholders involved in the construction project. Moreover, it has built-in tools that facilitate inter-operability, and it supports a variety of file formats, making it possible to integrate with other BIM applications such as Industry Foundation Classes. Revit supports IFC files, allowing users to exchange data with other BIM applications that support the IFC format (Ignatova et al., 2018).

Various exchange interfaces provided by Autodesk ensure inter-operability of all the aforementioned software. Revit is also compatible with other BIM software programs and can import and export data in a variety of formats, such as DGN,

DWG, DWF, DXF, SAT, and SKP. The software is used in a variety of industries, including architecture, engineering, construction, and facilities management, making it a versatile tool for building professionals. To enable every project stakeholder to participate, all the readers, videos, and images that Revit generates can be exported to common extension files such as JPG, TIF, BMP, PNG, TGA, or AVI (Vonhron et al., 2018).

2.4.4 BIM Dimensions

BIM dimensions are adopted at each stage to enhance the level of the collaboration and information exchange among the participants in the construction value chain (Abdel-Hamid & Abdelhaleem, 2021). These dimensions are defined to support the project data to be added to the BIM model using the CAD system. Figure 2-4 demonstrates the combinations of BIM dimensions that enables the project team to visualise, analyse and communicate problems to improve productivity (Charef, 2022; Montiel-Santiago et al., 2020). The BIM dimensions are defined as: -

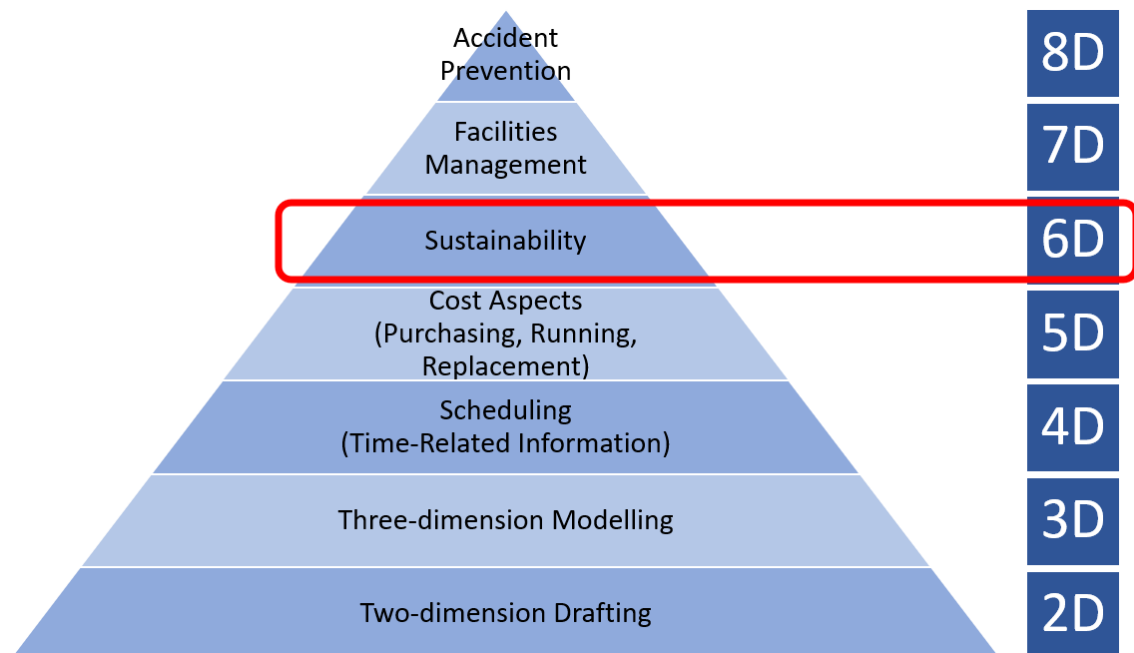


Figure 2-4 BIM Dimensions (Charef, 2022; Montiel-Santiago et al., 2020)

- 2D - is the earliest stage of construction building. In this stage the design model is made by hand or with a computer aided design, using two dimensions, such as width and height.
- 3D - is a shared information model (BIM) that creates the graphical and non-graphical data which will be shared through the common data environment.
- 4D – Scheduling represents time and space, which will be added to the 3D model. 4D provides a clear representation of how the project is operating, often in a graphical way by using a visualised data format to improve construction quality management and effective collaboration over the lifetime of the project. It also allows optimal utilisation of resources (Charef et al., 2018).
- 5D – Cost: Using competitive cost management within the BIM model enables better budget management, life cycle costing, and cost planning as well as evaluating the financial impacts of alternative scenarios that enhance the 4D BIM (Moses et al., 2020).
- 6D – Sustainability: Monitoring and management in the BIM environment can be combined to build a comprehensive life cycle (GhaffarianHoseini et al., 2017). The utilisation of models provides for more accurate assessments of energy consumption, including updates which accommodate changes in building occupation and should lead to reduced energy consumption (Montiel-Santiago et al., 2020).
- 7D – Facilities Management: Using the available project information combined with specific data from the operation and management of the project enables the BIM model to be extended to include facilities management. This enables the management of subcontractors and/or suppliers to be extended to the entire life cycle of the facility (Reizgevičius et al., 2018).

2.4.5 BIM Standards

The UK government has developed a strategy for implementing and introducing BIM Level 2 in 2011. Several Standards have established, such as BS 1192-4.

PAS 1192-2:2013, and PAS 1192-3:2014 (Pidgeon & Dawood, 2021). Table 2-4 Classifies the BSI and ISO standards. These standards are for companies working at Level 2 (Dadmehr and Coates, 2019). ISO 19650 is an international standard for managing the data across the construction value chain which has the same principles and requirements as the BSI standard. In addition, ISO19650 describes the concept and principles of model management as well as the delivery phase of the asset. ISO19650-1, 2018 outlines the concept and principles of the information delivery process for the construction value chain (Miceli Junior et al., 2020).

Table 2-4 Identifies relevant standards issued by the British Standards Institution (BSI) and International Organisation for Standardization (ISO) (Author).

Reference	Standards	Definition
(British Standards Institution, 2018)	BS1192	- Provides common methodology to manage the creation, distribution, and quality of construction information. - It applies to member in the supply chain - Through a common data environment (CDE) the data is exchanged as a single source
(BSI, 2016)	BS7000	Provides a framework for long-term innovation for companies to increase the prospect to react faster in the industry
(Publication, 2015)	BS8536-1:2015	It is about building infrastructure and it includes a code practice for facility management
(British Standards Institution (BSI), 2016)	BS8536-2:2016	- Specification for design and construction - It is part of BIM level 2 that help the industry to adopt BIM and it give a recommendation for the design and operational performance of infrastructure assets. It provides an evidence-based approach to design and construction, coordinating recommendations, not just from the asset management standards (ISO 55000 series), but also the BIM PAS's 1192-2, -3 and -5, and Government Soft Landings.
(British Standards Institution (BSI), 2015a)	BS8541	- This standard is related to the library object for the design and the construction phase - Includes codes of practices about identifications and classifications, shape, and measurement as well as attributes for specifications and assessment
(British Standards Institution (BSI), 2014)	PAS 1192-3:2014	- Provides specifications for the information management for the delivery and operational phase of assets - It includes a code of practices for facility management
(British Standards Institution (BSI), 2015b)	PAS 1192-5:2015.	Specifications for the security minded BIM and smart build management
(British Standards Institution (BSI), 2018)	PAS 1192-6:2018	Specification for an integrated information of health and safety using BIM
(BS EN ISO 19650-1:2018, 2018)	ISO19650-1:2018 ISO19650-2:2018 ISO19650-3:2020 ISO19650-5:2020	- Outlines the concept and principles - Supplies the requirements of delivery phase of the assets - Operational phase of the asset - Supplies the security minded management of data within BIM

2.4.6 BIM Level

The adoption of technological developments into company practices, has taken the industry from the traditional approach into the digital era (Abbasnejad et al., 2020). Nevertheless, the UK, Singapore and the US have realised that the full integration of the construction industry will be progressive and measured in terms of Levels 0 to 3 (Abdulkadir & Godfaurd, 2015), as shown in Figure 2-5.

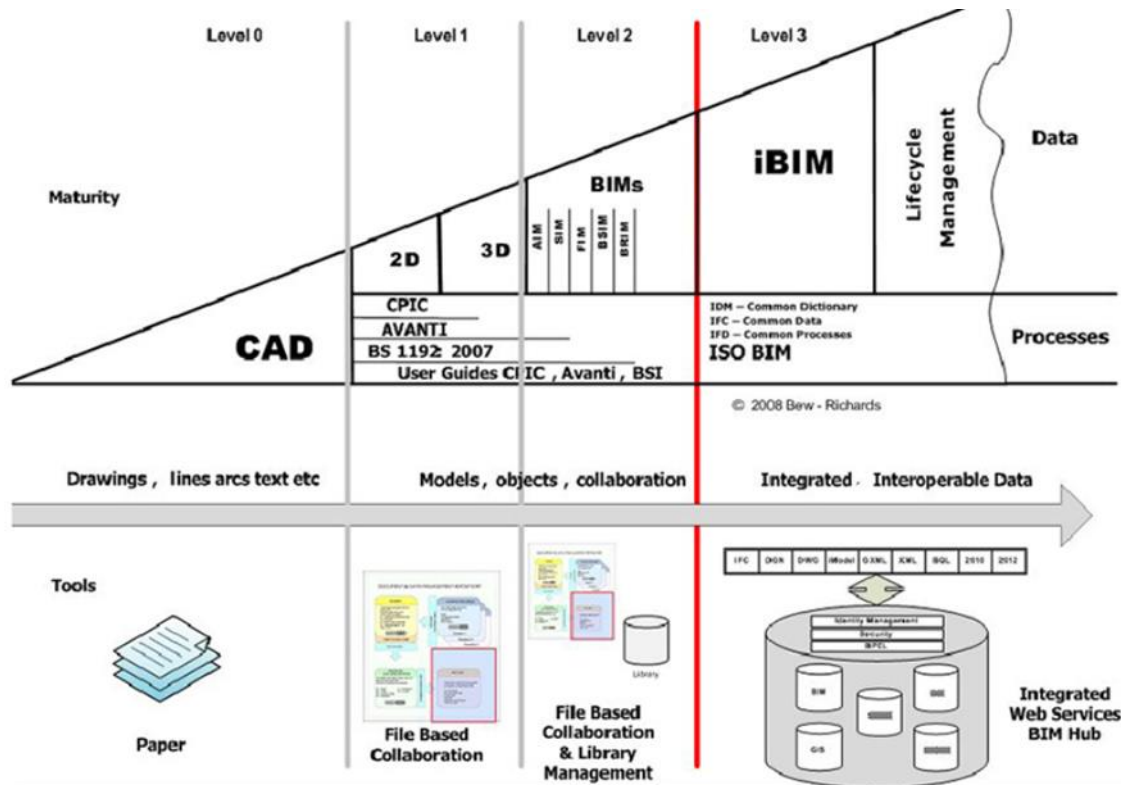


Figure 2-5 BIM Maturity Levels. PAS1192-2:2013

Different companies have organised themselves to accomplish different levels in these elements and also different levels of integration (Oyesode et al., 2022). In the BIM environment, Levels 0 to 3 are called BIM maturity levels classified according to related available standards.

- **Level 0:** The lowest level of integration which represent a lack of BIM, it is an incomplete level based on 2D and paper. The data in this level is exchanged through paperwork (Habib & Kadhim R., 2020).
- **Level 1:** Pre-formed level, has a mix of 2D and 3D formats. The former for drafting and the latter for concept work. CAD standards are managed to

BS 1192:2007 (BSI, 2007). Level 1 can be improved to Level 2 by including technical and admin data (Musa et al., 2018).

- **Level 2:** Is a 3D CAD model, in which all participants of the construction value chain collaborate to reach a common understanding throughout the project lifecycle, to achieve one single vision of a build (Fabozzi et al., 2021). BIM level 2 uses different BIM softwares such as, Revit, ArchiCAD, SketchUp, etc., to design a project (architectural, structural and system design), which provides a significant change in the construction industry. In addition, the UK government claims to have reduced by waste in construction projects by 20% (Shafiq, 2021). BIM level 2 enhances the management of the environmental impacts such site waste (Jallow et al., 2019) and improves the building project through cost, time and material savings (Blay et al., 2019). One way in which BIM level 2 enables construction companies to save cost and time is through a clash detection process carried out in the early stage of the construction value chain, another is to reduce the time spent on sharing the information across the construction value chain (Chahrour et al., 2021; Zieliński & Wójtowicz, 2019).

In the design stage, different models, such as an architectural design model, a structural design model, and a system design model are combined into a single model called the BIM Federated Model. A BIM federated model, even at the lowest Level of Development (LOD), requires the participants to have in place geometrical, technical and admin data which are combined in a common data environment which can then be accessed by all, which leads to improved design collaboration and a clearer strategy, since the participants are working on a single, shared model. An accurate clash detection service which is integral to BIM federated models reduces the likelihood of inconsistencies and identifies missing information. With more information available it becomes easier to estimate projects costs and timings.

The LOD is a theoretical concept to help and support BIM model development, it enables the participants to specify with a high degree of precision the content and

reliability of a BIM at a given stage of development. The level of the LOD defines the properties of the model based on the depth of information contained in the model in terms of the geometry, technical and admin data (Butkovic & Oloke, 2019; Cavalliere et al., 2019). LOD is divided into five categories, some of which have sub-categories:

- LOD100: represents general geometric information.
- LOD200: represents specific geometry of elements, such as shape and dimension.
- LOD300: represents the model as a specific system, it represents objects in terms of size, form, location, and orientation.
- LOD350: is LOD300 interfaced with column and foundation building elements.
- LOD400: represents information on fabrication, assembly, and fitting.
- LOD500: represents the real model as built.

The LOD (from LOD100 to LOD350) starts in the design phases (architectural, structural, system design) of the construction value chain, and optimises the data until it approaches the top of the implementation processes in the construction plan, 4D and 5D (time scheduling, cost estimation and material resources). LOD400 is used in the construction phase to support the contractors with detailed information on fabrication, assembly and fitting. LOD500 is BIM dimensions 6D and 7D, detailed information on sustainability and facilities management, including maintenance. The inclusion of 6D BIM information allows the owner to make decisions regarding the whole life-project at an early-stage in the construction value chain to drive the project to a better outcome (Dadashi Haji et al., 2021).

- **Level 3:** The UK construction industry was expected to expand by 70% by 2025. However, the challenges of Brexit and the Covid-19 pandemic have caused a deceleration in the process of the process of creating a continuous collaborative environment and there is still confusion over defining BIM level 3 requirements (HM Government, 2015). Current literature has assessed the following as challenges for BIM level 2

implementation that must be resolved: BIM obligation rights and risk allocation which are not yet clearly defined. BIM level 3 has not been reached yet as there are no existing standards for a construction company to work on BIM Level 3 which is considered as the fully integrated level. However, there are also technological barriers such as the BIM commercial software application which has yet to achieve accurate data exchange without relying on the Industry Foundation Class format (Shafiq, 2021).

2.4.7 BIM Libraries

BIM object libraries are an invaluable resource for professionals in the construction industry, including architects, engineers, and contractors. They offer a vast collection of 3D models, components, and other design elements that can be used in BIM software to create highly accurate and detailed building models. The objects are available in various formats, including Revit, ArchiCAD, and SketchUp. Table 2-5 shows some of the most popular open-access BIM object libraries available:

Table 2-5 List of open access BIM object libraries (Author).

Name	Logo	Official website	Country	Name	Logo	Official website	Country
1.BIMobject		http://bimobject.com/en-us	Sweden	6.BIMstore		https://www.bimstore.co.uk/	UK
2.NBS National BIM Library		https://www.nationalbimlibrary.com/en-gb/	UK	7.SpecifiedBy		https://www.specifiedby.com/search	UK
3.RevitCity		https://www.revitcity.com/downloads.php	International	5.BIM & CO		https://www.bimandco.com/en	France
4.CADdetails		https://www.caddetails.com/BIM-Models	US	9.BIMBOX		http://bimbox.co.uk/library/	UK
5.BIMsmith		https://market.bimsmith.com/	US	10.rubysketch		https://3dlibrary.rubysketch.com/specific_search/5	International

These open-access BIM object libraries provide an excellent resource for construction professionals to access a vast array of BIM objects and components to support their design work.

2.5 Review of Sustainability Research within the BIM Environment

Regulations have recently been implemented by a number of countries adopting resource and energy efficiency aims and promoting the reduction of emissions through new building developments and retrofitting programmes (Carvalho et al., 2019). To that end, various technologies and procedures have been developed, and a multitude of rating techniques have been implemented in numerous countries to assess the environmental performance of buildings. Such techniques include the Leadership in Energy and Environmental Design in the United States and the Building Research Establishment Environmental Assessment Methodology in the UK (Carvalho et al., 2021; Solla et al., 2016).

As awareness of global sustainability is growing, a rapidly expanding area of research is focusing on managing and reducing carbon emissions and energy consumption throughout the life cycles of buildings (Gustavsson et al., 2010; Smith, 2014). For instance, one strand of research focuses on how sustainable constructions that satisfy global challenges can be met by the use of construction information technologies, primarily BIM.

Sustainability within the construction industry alludes to the provision of a safe, healthy, and favourable environment for subcontractors, contractors, owners, end-users, and designers (Zuo & Zhao, 2014). However, it is essential to emphasise that the purpose of BIM guidelines and principles is to ensure smooth project delivery and not to replace the basic contract and delivery of the project (Haruna et al., 2021). Within the guidelines, environmental, economic, and social sustainability depends on the design.

Previous research indicates that a sustainable building design requires a BIM-based sustainability simulation at the early or pre-design stage (Lim, 2015). Using BIM encourages project participants to exchange information on design errors that visualisation is more likely to detect. This enhances financial control of the project and is better adapted to the needs of clients. (Niu et al., 2015) developed an energy data visualisation method to envisage the design of an urban energy landscape using a web-based BIM-GIS. To increase the sustainability of

infrastructure projects, (Kim et al., 2016) employed BIM and GIS to visually represent the walkability of the existing 'Safe Routes to School' programme.

Assisting in the shift towards sustainability, BIM has also been used in aiding the selection of materials for construction activities (Koutamanis, 2020) and it has been proposed that an information delivery manual should be used by BIM for off-site construction processes. The information acquired from BIM can also be used to manufacture modular units (Zhang et al., 2016) which enhances design flexibility and re-use, limits wastage of costly materials, and lessens air pollution and site disturbance.

With respect to maintenance and operation, (Eleftheriadis et al., 2017) revealed that to maintain long-term value, the facility management department must ensure cost-effective and robust maintenance environment for assets. In buildings that currently exist, there are immense benefits to be gained in extending the BIM function to real-time building operations and facilities management as this will serve to eliminate waste and ineffective facilities (McArthur, 2015).

Previous studies have revealed that the information required to visualise the energy performance of a building at an early stage, is lacking (Elbeltagi et al., 2017). Although several thermal simulation applications have been employed to assess building energy performance (Tian et al., 2019), these have necessitated the use of a building geometry information retrieval process developed using CAD with the capacity to access BIM and thermal modelling data (Jeong et al., 2016). Simulation of the detailed energy performance occurs in separate software with information obtained from an external database. Thus, one contribution this research makes to existing knowledge is to highlight sustainability issues in each single object within BIM.

A platform known as the Real-Time Replay System (RTRS) was created by (Chiang et al., 2015) to replay electricity usage events using the information produced by Revit, Unity 3D, and a Wi-Fi power socket sensor. To facilitate measures for conserving energy, the interactive smart system allows consumers to identify operations that are wasteful, which can also be suggested by the

RTRS. Furthermore, RTRS can define events and present energy-saving alternatives. This creative and novel technique may assist end users in managing electricity consumption, reducing both the effort and time needed to identify and make sense of raw information (Chong et al., 2017a).

One efficient way to reduce carbon emissions is to renovate existing buildings in order to reduce energy consumption. This will lead to healthier lifestyles as a result of an improved indoor climate and a reduction in air pollution. In addition, to estimate the amount of waste produced by construction, renovation, and demolition, an integrative BIM-based method has been developed (Kylili et al., 2016). This procedure extracts information from the BIM model and estimates the volume of waste produced at each stage of the project. Such research has been vital in improving project control and the extent to which renovation and demolition projects are sustainable (Al Hattab, 2021).

2.5.1 The Benefits and Advantages of Sustainability within BIM

BIM builds the asset in a virtual form before the physical construction, any proposed changes can be made to the virtual model prior to introducing them into the physical building process. This allows the effects of the changes to be assessed, possibly saving the cost of actually making the changes (Tang et al., 2017). The use of BIM enhances the possibility of making strategic changes in construction firm strategies (commercially, technically, and leadership) enabling better communication, which reduces the number of conflicts, while giving better time optimisation and building sustainability (Olawumi et al., 2018). BIM has the potential to improve the design, improve team communication and to create a more integrated proposal to provide a better material database, introduce a planning process and to discover errors in the design. BIM can accurately detect changes in building data in terms of discovering incompatibilities between components and the equipment specified for the project (Mellado & Lou, 2020) as indicated in Table 2-6.

Table 2-6 Integration of BIM and sustainability benefits (Author).

Reference	Sustainability integration with BIM
(Abbasnejad et al., 2020)	BIM application support a wide range of data
(Arantes et al., 2015)	Improved lifecycle management
(Blay et al., 2019)	Improved maintenance of project infrastructure.
(Borges Viana & Marques Carvalho, 2021)	Risk mitigation
(Chahrour et al., 2021)	Controlling cost performance and reduction of construction works.
(Dadashi Haji et al., 2021)	Optimisation of schedule compliance and planning.
(Antón & Díaz, 2014)	Exchange, collaboration and sharing of data between stakeholders.
(Habib & Kadhim R., 2020)	Automated collaborative solutions minimise the risk of project coordination errors.
(Ismail et al., 2021)	High level of flexibility to facilitate building layout.
(Khanzadi et al., 2020)	3D visualization and testing of the constructability of the design within the model before real construction.
(Raheem, 2021)	Conflict detection and reduction in errors.
(White & Marasini, 2014)	Sustainable design and analysis at an early stage.

According to Mohammed (2022), early decision making in the design process is important for improving the quality and reducing the cost of a building during its life cycle. BIM can help with this by providing a digital model of the building that can be used to predict building performance. This prediction can be used to identify potential problems and make changes to the design early on, which can save time and money. Chong et al., (2017b) agree that BIM-based sustainability

analysis software can be used to achieve the triple bottom line of sustainability, which includes economic, environmental, and social aspects.

Economic Aspects: BIM help to optimize the design of a building, minimizing whole life cycle costs and capital by improving material and energy efficiency. It can also improve teamwork and communication, leading to lower project costs and less construction waste. wastage (Goh et al., 2020b).

Environmental Aspect: BIM can be used to assess the environmental impact of a building, helping to reduce resource consumption (water, materials, and energy). It can also improve the efficiency of the project delivery process, further reducing environmental impact.

Social Aspect: BIM can be used to improve the quality of the design and construction of a building, enhancing the living environment for occupants. It can also be used to simulate the performance of a building, helping to ensure that it meets the needs of its users (Janjua et al., 2020).

2.5.2 Construction Value Chain in a BIM Environment

Construction companies began using BIM as a key element in their strategies because BIM brings an important change in the way that the different parties involved in the construction project work together, making the working environment more collaborative (Papadonikolaki et al., 2019). The construction value chain in the BIM environment is the whole project team working together across the value chain from early design stage to demolition (Kamel & Memari, 2019). The very idea of BIM brings all the participants in the construction value chain together in the project lifecycle, it becomes an integrated element for all its stakeholders.

Following a review of the published papers regarding the construction value chain, the primary phases have been identified, as have the essential stakeholders or actors for the project. Numerous components of the construction value chain which separately add value to the construction project, have to consider the sustainability issues presented in Figure 2-6. The authentic construction value chain comprises a network of relationships which are not linear

despite the perfect construction value being linear with low complexity. The following principal phases have been identified: design and engineering, construction, operation, maintenance and renovation, and demolition. Presently, BIM can design and analyse the following: the assets, the structure (analysing the finite elements) and the building systems; for example, plumbing, electrical and mechanical, IT, as well as the climatic and acoustic.

User experience needs to be a component of the design phase to produce the optimal solution. Both the main contractor and the subcontractors utilise the BIM paradigm which supplies the same information to everyone, and permits on-site construction, thereby reducing the duration and cost of the project with reduced risk. The owner of the building and its operator should be supplied with all asset information for the purpose of managing the building efficiently. BIM provides an accurate maintenance plan to more effectively avoid failures, and to eliminate them promptly when an incident occurs. Demolition contractors may use BIM in order to establish the optimal method of demolition (Begić & Galić, 2021; BSI PAS 1192-2, 2013; Malleson, 2016).

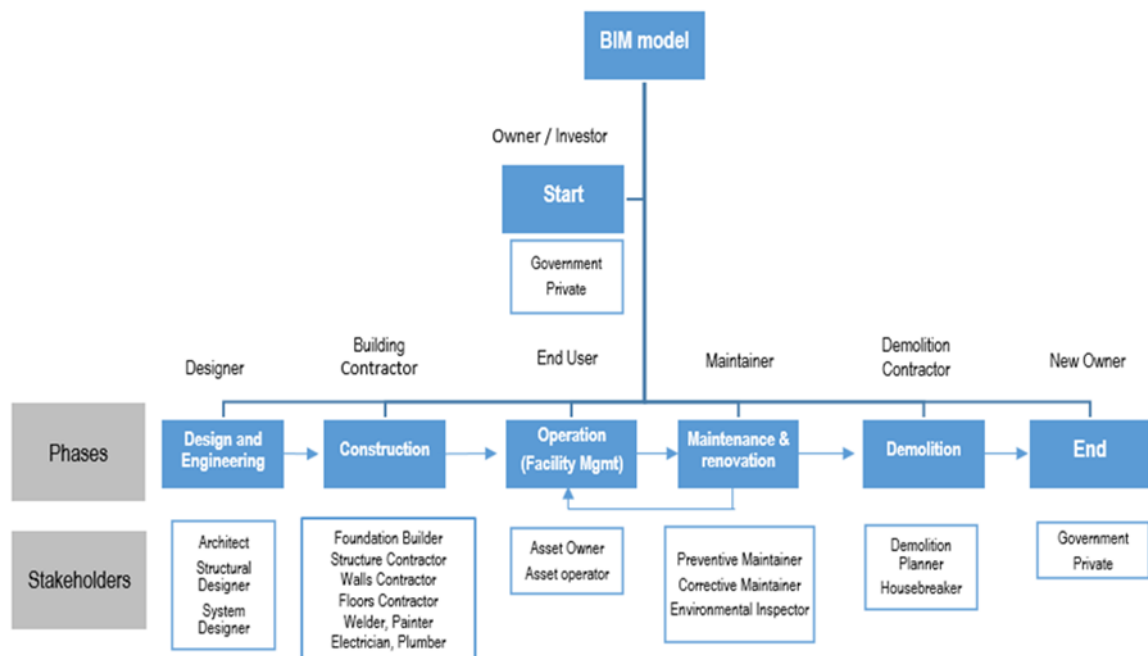


Figure 2-6 Construction Value Chain in a BIM Environment (Author).

2.6 Research Gap

The growth of BIM within construction industry around the world is a significant and noticeable. BIM has the potential to improve sustainability in the built environment. Subsequently, the literature review highlighted the following research gaps:

1. There is a lack of research of addressing the sustainability issues in the BIM environment.
2. There is a need to represent sustainability good practices in the BIM object.
3. There is a need for a practical framework that integrate the required project information, BIM database, stakeholders within the construction value chain and a platform to calculate different construction sustainability issues.

These identified research gaps not only underscore the challenges associated with integrating BIM into building sustainability assessment, as highlighted by Onososen & Musonda (2022), but also emphasize the imperative for a critical review of existing green BIM development to bridge gaps between industry requirements, available academic research, and conceptual understanding of deficiencies, as articulated by Ibrahim & Mohd (2022). Moreover, the insufficiency of information required for early-stage visualization of a building's energy performance, as elucidated by Elbeltagi et al. (2017), further accentuates the need for comprehensive research in this area. The mention of sustainability analysis as the sixth dimension in 6D BIM by Villena-Manzanares et al. (2020), without detailed elaboration, underscores the research gap in providing a robust emphasis on sustainable dimensions within the BIM framework. These gaps collectively form the foundation for the research problem at hand and necessitate focused investigations to advance the integration of BIM in building sustainability assessment and sustainable construction practices.

2.7 Closing Remarks

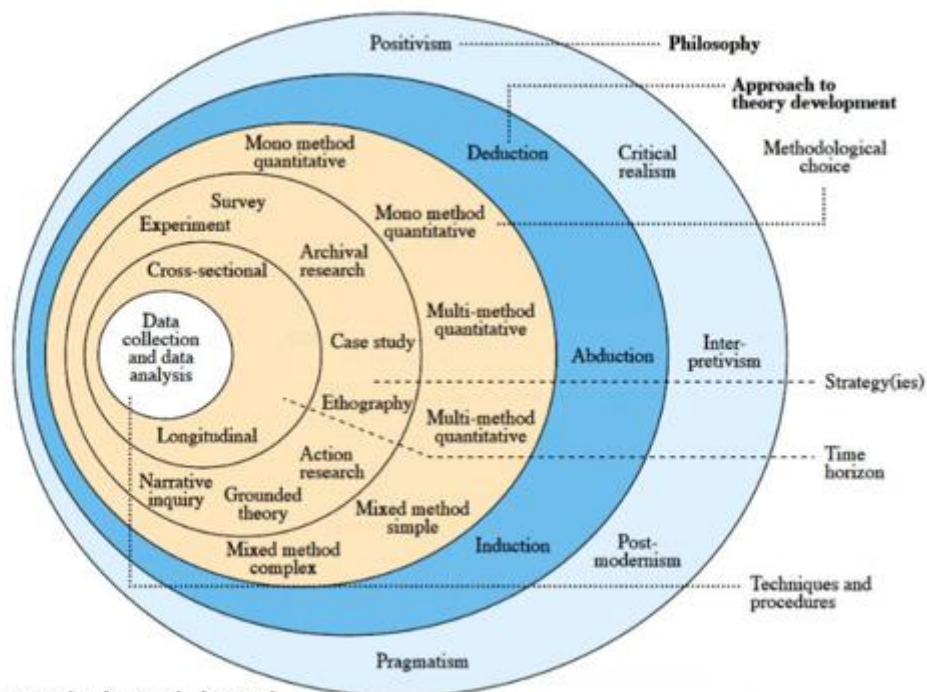
This chapter has presented the importance of addressing sustainable construction in a BIM environment. The literature review highlighted the embodied carbon footprint and heat transfer for better energy performance as the most sustainable practices in the construction sector. The literature review shows that the current BIM Level 2 object structure contains no detailed sustainability data. This thesis will present a framework that integrates project information management, construction value chain and construction sustainability issues within the BIM environment. Therefore, a stakeholder in construction value chain will have access to sustainability information in addition to geometrical, technical and admin information.

The next chapter presents the methodological approach to achieve the sustainability of a construction project in a BIM environment.

3 RESEARCH METHODOLOGY

3.1 Introduction

This chapter presents the overall research methodology of the thesis. It is crucial to understand that the research method and methodology are two important parts of the study. Saunders et al. (2009) created the 'research onion,' which was updated in Saunders et al. (2016) and is presented in Figure 3-1. The 'research onion' depicts multiple layers of research methodologies and checkpoints for researchers to follow. The discussion in this chapter begins by briefly examining the literature on research philosophies, approaches, methodical options, strategies, time frames, and selecting and justifying the most suitable for this study. The approach to the methodology to be used is divided into four phases, each of which has different key tasks and deliverables. The phases provide a structured approach for conducting the aim of this thesis, ensuring that the research process is transparent, replicable and reliable in relation to the construction industry.



Source: Sounder's et al. (2020)

Figure 3-1 Research onion model

The research onion consists of six main layers:

1. **Research philosophy** – provides the foundation of the research by defining ontology (the nature of reality), epistemology (the nature and sources of knowledge or facts), and axiology (values, beliefs, and ethics) (Saunders et al., 2019).

After a thorough review of literature on research philosophy, this study selects critical realism as its research philosophy. The critical aspect involves the practical implementation of sustainability practices in the BIM environment, which follows a design science approach. This approach aims to create and evaluate new solutions, methods, or models to address practical problems, here the problems are in construction and building design. The focus is on finding practical solutions and evaluating their effectiveness through case studies, experimentation, and implementation in real-world projects. The ultimate goal is to enhance sustainability performance in the built environment through the use of BIM technologies and methodologies. Hence, it is crucial to collect data related to sustainable construction projects in BIM. This thesis requires qualitative data to understand the reality of sustainable practices in BIM and quantitative data to further evaluate the reality of BIM.

2. **Approach to theory development** – There are three main approaches to theory development: deduction, induction, and abduction. Deduction starts with an existing theory, then raises a question or hypothesis, and collects data to confirm or reject the hypothesis. Induction starts with observations and data collection, leading to description and analysis to form a theory. Abduction starts with an empirical phenomenon and moves between induction and deduction to find the most likely explanation (Saunders et al., 2019; Tengli, 2020).
3. **Methodological choice** – The third layer of the "research onion" is the methodological choice, which decides whether to use quantitative or qualitative methods or a combination of both. For example, it involves building a BIM model based on sustainable practices for a construction

project and collecting both quantitative and qualitative data for validation (Melnikovas, 2018).

4. **Strategy** – The fourth layer is the strategy for collecting and analyzing data, which includes options such as experiment, survey, archival research, case study, ethnography, action research, grounded theory, and narrative inquiry. This thesis uses the case study strategy because it aims to develop and validate sustainable construction practices in the BIM environment. In this study, a hypothetical case, constructing one-bedroom house is chosen to validate the effectiveness of sustainable construction in BIM. The case study strategy is suitable for this study because it enables an in-depth analysis of project objectives within the construction industry and the adoption of sustainable practices using BIM.
5. **Time horizons.** Saunders et al., (2019) have as the fifth layer of the research onion the time horizon, which defines the duration of the study. It can be either cross-sectional or longitudinal, meaning collection of data sets at a specific point in time or repeatedly over a long period, respectively. For this study, a cross-sectional time horizon was chosen, as the goal is to validate the structure of sustainable practices in BIM through a hypothetical case study. Experts in the construction industry will provide their opinions on the proposed framework model, which will be a one-time occurrence.
6. **Techniques and procedures.** The final layer of the research onion involves the techniques and procedures for data collection and analysis, such as using primary or secondary data, selecting sample groups, creating questionnaire content, and conducting interviews (Melnikovas, 2018; Tengli, 2020).

The case study methodology was chosen for this research due to its suitability for gaining an in-depth understanding of a complex and context-dependent phenomenon. By focusing on a single or a limited number of cases, this approach allows for a thorough exploration of the intricate relationships, unique factors, and real-world intricacies associated with the research topic. Additionally, it aligns with

the study's qualitative data collection methods, such as interviews and content analysis, providing a structured framework for analysing and interpreting rich, qualitative data. This choice enables the research to delve deeply into the specific case, uncover patterns, generate insights, and contribute to the broader body of knowledge in the field.

3.2 Project Approach:

The methodological approach adopted in this research is divided into four phases to ensure the accomplishment of goals and objectives rationally, as shown in Table 3-1.

Table 3-1 Research Approach

phases	Key tasks	Deliverables
1. Construction sustainability practices	1.1 Extensive literature review 1.2 Capturing current good practices regarding industrial sustainability.	• Construction sustainability good practices.
2. Sustainability in a BIM environment	2.1 Sound understanding of BIM and its related standards. 2.2 Study Revit software as a primary CAD system for a BIM environment. 2.3 Understanding the structuring of BIM objects.	• The fundamentals of BIM • Revit BIM capabilities
3. Sustainability engineering calculations	3.1 The formulation of detail construction case study. 3.2 The engineering calculation of heat transfer as a sustainability issue. 3.3 The engineering calculation of embodied carbon as a sustainability issue.	• Sustainability engineering results.
4. Sustainable construction	4.1 The development of the BIM framework	• Integration into BIM

framework based on BIM.	4.2 Case study integration of embodied carbon results in BIM	
5. Validation & evaluation	5.1 Case study validations	• Validated framework

The following sub-sections are presenting each of the research methodology phases:

3.2.1 Construction Sustainability Practices

A comprehensive literature review is an essential component of the research methodology, as it helps identify and define research gaps in present knowledge. In this research, the researcher will identify different sustainability good practices in the construction industry. First, conducting a comprehensive search of relevant literature using academic databases such as Scopus, Web of Science and ScienceDirect. The researcher will use a combination of keywords, phrases, and subject headings to refine the search and identify relevant articles, books, and reports. Then, evaluate the quality of sources and this includes considering factors such as the relevance to the research question, the status of the journal in which the publication appears, the author's credentials, the publication date, and the research methodology used. Then the researcher will organize the information collected into a structured format, to identify the key sustainability practices in construction. The final step will be to synthesize the findings from the literature review and summarize the key themes and practices identified. Overall, capturing industrial sustainability good practices is crucial for promoting sustainability in the construction industry and creating a more sustainable future for all. The findings from the literature have been identified and documented in Section 2.3.2, Table 2-1.

The identified sustainability issues in Table 2-1 were highlighted and endorsed by the construction industry through the interview with:

- 1- (Director, Building Engineering. "IDOM" advance design & Analysis Dpt.)
- 2- (Quality and BIM Compliance Director. Voestalpine Metsec plc)

The outcomes of the interview represented as follows:

Q1: Do you believe that addressing the research questions would contribute effectively to the support and advancement of the BIM community?

- 1- I believe Identification of specific questions or areas of inquiry that have strong support within the BIM community, potentially guiding your research focus.
- 2- Insights into potential collaborators or stakeholders within the BIM community who share a common interest in addressing sustainability.

Q2: From your perspective, what level of progress has been achieved in addressing the 6D aspects of sustainability within BIM?

- 1- There are still a lot of works to be done in addressing sustainability. However, a benchmark of the current state of sustainability integration in BIM, allowing you to assess whether further efforts are needed and where improvements can be made.
- 2- Knowledge of any similar case studies or best practices in the field of BIM and sustainability, which can serve as valuable references for your work.

Q3: Could you elaborate on the current market demand for sustainability-related initiatives in the context of BIM?

- 1- Understanding of whether there is a growing market for sustainable BIM solutions, helping you to evaluate business opportunities or potential areas of investment.
- 2- Insight into specific sustainability-related challenges or opportunities that are currently prominent in the market.

Q4: In your expert view, what are the fundamental best practices in sustainability that should be a focal point for my research?

- 1- I believe embodied carbon footprint, energy efficiency and waste control are the most pressing issues.
- 2- I could say the focus should be more on embodied carbon footprint, water efficiency and energy efficiency.

Q5: How much you as a construction industry interested in addressing the sustainability issue?

- 1- We have a strong interest in sustainability within the construction industry, driven by ethical and economic considerations.
- 2- Interest in sustainability varies, but awareness is growing as we see its benefits for our industry.

Q6- Do you think that more challenges have to be solved before the construction industry can move towards level 3?

- 1- Yes, there are still several critical challenges that need to be addressed before the construction industry can effectively transition to Level 3 BIM. These challenges may include data interoperability, standardized processes, and widespread digital adoption throughout the industry.
- 2- While there are challenges to overcome, the construction industry has made significant progress in moving toward Level 3 BIM. Many of the foundational issues have been addressed, and with continued collaboration and innovation, Level 3 BIM can become a reality in the near future.

Q7- Do you think the sustainability in BIM environment is a valuable subject for the industry and BIM community?

- 1- Absolutely, sustainability in the BIM environment is of paramount importance. It aligns with global efforts to reduce environmental impact and enhance efficiency in construction. Addressing sustainability within BIM can lead to cost savings, improved resource management, and a more environmentally responsible industry.
- 2- While sustainability is an important topic, some in the industry may prioritize other aspects of BIM. However, there's a growing recognition that sustainability is a valuable subject that can contribute to long-term viability and competitiveness, making it increasingly relevant for the industry and BIM community.

3.2.2 Sustainability in a BIM Environment.

In sustainable construction, BIM can be used to evaluate the environmental impact of design decisions, such as the energy efficiency of building materials and systems. It also allows simulation of the building's energy performance, water consumption and indoor air quality and identify areas that need to be improved to meet sustainability goals. Therefore, defining BIM levels, dimensions and the related standards is required by the researcher, including ISO 19650 which is a comprehensive BIM standard that provides a framework for the management of information throughout the lifecycle of a built asset. According to (Dadmehr, N and Coates, 2019), ISO 19650 was developed to provide a common language and set of processes for BIM projects, helping to improve collaboration and reduce errors and misunderstandings. However, if BIM Level 2 guidelines are followed full collaboration is achievable.

Another important factor in the study of sustainability in BIM is understanding Autodesk Revit software which is the primary CAD package built for BIM. Therefore, a case study of a one-bedroom house will be demonstrated in Revit. The house is rectangular with total area = 10 m (length) $\times$ 5 m (width) = 50 m^2 . The four walls forming the perimeter are 3 m high, giving a total wall area of 90 m^2 , with two walls each of area 30 m^2 . and the other two wall each having an area of 15 m^2 . The one-bedroom house has three windows with dimension of $1.05\text{ m} \times 1.2\text{ m}$ and a front door with dimension of $2.134\text{ m} \times 0.915\text{ m}$, the areas of which are deducted from total wall area to calculate the number of bricks and plasterboards and the amount of mortar needed.

Since the model is designed in Revit, it is necessary to understand how objects in Revit are related to each other through their placement in the model, a process which defines their spatial relationships. For example, walls are placed in relation to other walls, floors, and ceilings, while doors and windows are placed in walls. As explained above, BIM objects in Revit are defined by a set of parameters that specify their dimensions, materials, and other properties. These parameters can be linked to other BIM objects in the model, allowing for changes to be made

across multiple objects at once. For example, if a wall is resized, the windows and doors in that wall will automatically adjust to fit the new dimensions.

BIM objects are typically structured with three main components: geometry, administrative information, and technical information. Consequently, a wall object in a building model contains:

1. **Geometry:** The geometry of the wall object would include 3D modelling of its shape, size, and position in relation to other objects in the building model. The wall object's dimensions would be defined by parameters such as height, length, and thickness, which can be adjusted as needed to reflect changes in design or construction.
2. **Administrative Information:** The administrative information for the wall object would include its name, description, and location within the project. For example, the wall object may be named "Exterior Wall" and described as a load-bearing wall located on the east side of the building.
3. **Technical Information:** The technical information for the wall object would include data on its physical properties, such as its materials, performance characteristics, and construction details.

3.2.3 Sustainability Engineering Calculations

The first step is to determine the number of bricks needed to cover the surface area. This involves considering factors such as the size of the individual bricks, the thickness of the mortar joint, and the overall area of the wall to be covered. The standard size of brick used in the UK $215\text{ mm} \times 102.5\text{ mm} \times 65\text{ mm}$ with 10 mm thick mortar joints as illustrated in Figure 3-2. The volume of one brick is 0.001432 m^3 , the volume of one brick including mortar is 0.0017297 m^3 , and the face area of the brick – including mortar – is $0.225 \times 0.075 = 0.016875\text{ m}^2$. The number of bricks needed can be calculated from the areas of the four walls after subtraction of window and door areas: $(90 - 5.73)/0.016875 = 4996$.

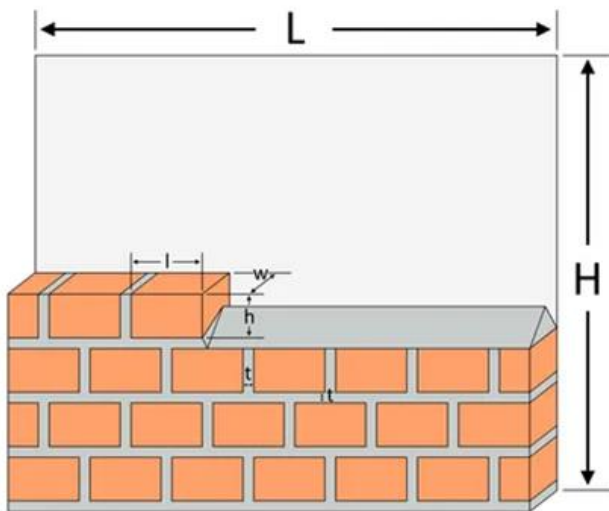


Figure 3-2 Bricks description

- **Quantity of Cement, Sand and Water for Brickwork.**

There are different mortar mix ratios (cement to sand ratios) for each element of the building construction. The mortar mix ratio for concrete bricks for building construction external and internal walls is in the ratio 1:4 (cement: sand), with the water/cement ratio, 0.5.

- **Quantity of Plasterboards.**

Thermally insulated plasterboard has been used, this type of plasterboard combines plasterboard with insulation material already attached to it. Insulated plasterboard helps prevent heat escaping the space and this results in a warmer and more comfortable home which is also more energy efficient. This type of plasterboard also contains a vapour layer to prevent moisture transfer through the board into the wall. The plasterboard selected is Celotex PL4000 from Celotex Saint-Gobain with wallboard size of 2400 x 1200 x 37.5 mm, and thermal conductivity of 0.022 W/mK, which meets national Building Regulations and guidance.

3.2.3.1 Calculation of Heat Transfer - Sustainability Issue

Fourier's law is a fundamental for the calculation of the rate of heat transfer through a solid material. It states that the rate of heat transfer through the material is proportional to the thermal conductivity of the material, the temperature

gradient across the material, and the surface area through which the heat is flowing, and is inversely proportional to the thickness of the material. The law is described mathematically as:

$$Q = kA \frac{T_1 - T_2}{L} \quad (3-1)$$

$$= U A \Delta T$$

where, (Q) is the heat transfer rate (in watts), (k) is the thermal conductivity (in watts/meter-Kelvin), (A) is the cross-sectional area perpendicular to the direction of heat flow (in square meters), (ΔT) is the temperature difference across the material (in Kelvin or Centigrade) and (L) is the thickness of the material (in metres).

The thermal conductivity of the material needs to be determined, usually from reference tables, and also the temperature difference across the material (usually a design specification). The temperature gradient can be determined by determining the temperatures of the two relevant faces, subtracting to find the temperature difference, and dividing by the distance between the faces. Once the thermal conductivity and temperature gradient have been determined, Fourier's law can be used. This information can be used to optimize the design of various systems to improve their energy efficiency and sustainability.

3.2.3.2 Calculation of Embodied Carbon - Sustainability Issue

Determining the embodied carbon in the given work at each stage of design enables engineers to target carbon reductions via material selection, specification, efficiency, and reuse. The Institution of Structural Engineers has released a guidance for calculating embodied carbon that focuses on life cycle modules A1-A5 (cradle to practical completion). The researcher found that the most important time to calculate embodied carbon is early in the design process. Typically, according to (Gibbons & Orr, 2020a) the fundamental element of an embodied carbon calculation can be done by multiplying the quantity of each material by a carbon factor, which is a measure of the amount of carbon dioxide emitted per unit of material.

$$\text{Embodied carbon} = \text{Quantity of material} \times \text{Carbon conversion factor} \quad (3-2)$$

The quantity of each material is an estimate that becomes more precise as the design process progresses. The carbon factors are separated by lifecycle module and are estimates whose precision increases as more is learned about the project's procurement procedure.

3.2.4 Sustainable Construction Framework Based on BIM.

The researcher has presented a framework for integrating sustainability data in construction using BIM. The framework involves key information that includes customer information requirements, identifying sustainability goals, project details, planning, creating a sustainability issues library that contains lists of such issues as heat transfer for energy efficiency and embodied carbon footprint. Then conducting detailed carbon embodied engineering calculations for the case study. This involves calculating the carbon emissions associated with the production, transportation and disposal of the materials. The results, which include the quantity and embodied carbon value of each material and the total embodied carbon of the project will be exported in an Excel format. The Excel data is then imported into Revit through a Revit plugin application, DiRoots (TableGen), which is used to integrate the model design and the engineering calculations. Integrating the results of the embodied carbon calculations into the software involves importing data into Revit and syncing it with BIM Collaborate Pro offering an integrated BIM solution for managing the projects' design, construction, and operation.

3.2.5 Validation Via Case Study.

The validation process of the framework to be applied on embodied carbon footprint for the specified one-bedroom house requires the information management of the house which includes, customer requirements regarding the house and sustainability concerns as well as the house project plan, also the construction value chain. Furthermore, defining the embodied carbon calculation parameters, calculating the embodied carbon using Excel, importing data into Revit, cross-checking the results, sharing results via BIM Collaborate Pro, and

then refining the calculations based on stakeholder feedback. This process ensures the accuracy and reliability of the embodied carbon calculations, which can help inform more sustainable building design and construction decisions. application

3.3 Closing Remarks

This chapter evaluates the literature on research methodology and identifies the appropriate methodology for this study. The methodological approach consists of four phases. Firstly, the study conducts an extensive literature review of construction sustainability practices to identify research gaps. Secondly, it investigates BIM in detail and its relation to sustainability in the construction industry. Additionally, a hypothetical case study is presented in Revit, which serves as the main CAD system in the BIM environment. Thirdly, the sustainability issues are selected, and related engineering calculations are carried out. Fourthly, the study presents a construction sustainability framework in the BIM environment. Finally, the validation of the study is carried out by applying the construction sustainability framework to the embodied carbon footprint of a, single floor, one-bedroom dwelling in the BIM environment.

The next chapter demonstrates the details of the structure of the case study.

4 THE FORMULATION OF THE CASE STUDY BASED ON ONE-BEDROOM SINGLE STOREY HOUSE

4.1 Introduction

This case study will examine the materials and construction methods used to build a one-bedroom house, single storey house. The house, see Section 3.2.3 has a rectangular shape with total floor area of 50 m^2 and the four perimeter walls are of common red bricks held together by mortar comprised of cement, sand, and water. The windows and door are made of wood and glass. The house is insulated with plasterboard, which helps to keep the heat in during the winter and out during the summer. The case study of one-bedroom house is providing the parameters and calculations that will be used in chapters 5 and 6 regarding sustainability issues calculations and framework.

4.2 Case Study of One-Bedroom House

As described above the one-bedroom house has a total floor area = $10 \text{ (length)} \times 5 \text{ (width)} = 50 \text{ m}^2$, the four outer walls having a total area of 90 m^2 , the two longer walls each having an area of 30 m^2 and the two shorter walls each having an area of 15 m^2 . The house has three windows and a front door which are deducted from total wall area to calculate the number of bricks, plasterboards and the amount of mortar required. As shown in Figure 4-1, Wall 4 has the door, Wall 3 has two windows, and Wall 2 has 1 window.

The standard size of a single window is 1050 mm high and 1200 mm wide and the selected door has height 2134 mm and width 915 mm . Thus, total area of the chosen windows and door are 3.78 m^2 and 1.95 m^2 respectively.

The materials selected for building the wall are commonly used red bricks, $215 \text{ mm} \times 102.5 \text{ mm} \times 65 \text{ mm}$ (Red & Red, 2011), and the number of bricks required is calculated. Second, the amount of cement, sand and water needed for the mortar for the given number of bricks for each wall is determined. Finally, the quantity of insulated plasterboard needed for each wall is calculated.

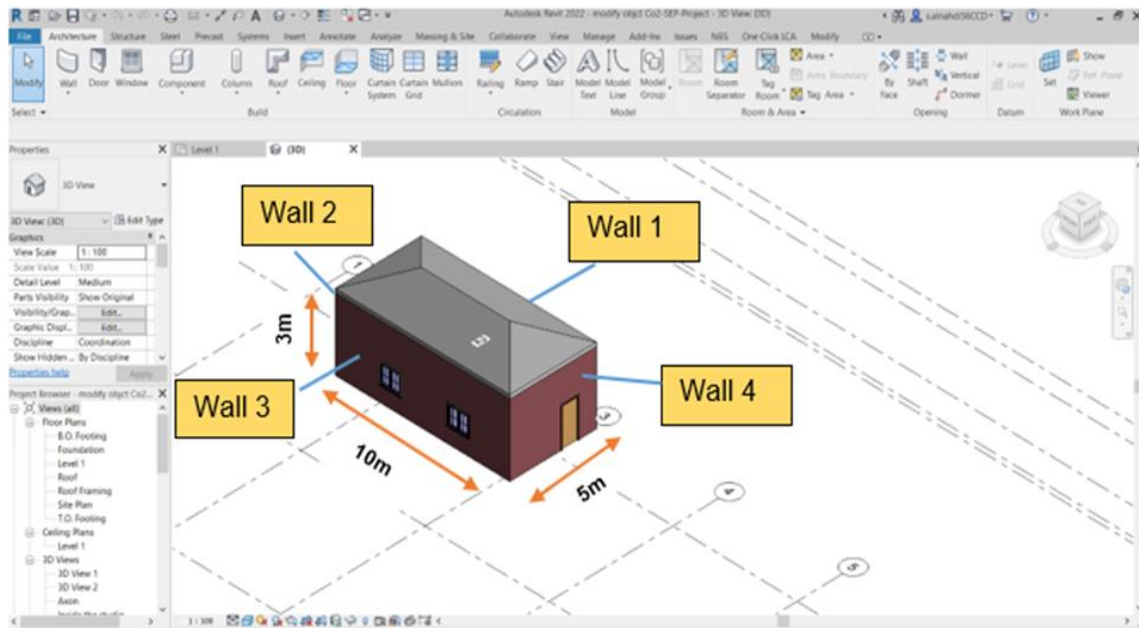


Figure 4-1 Case study design (Author)

4.3 Wall Structure and Quantities of Materials

4.3.1 Quantity of Bricks

➤ Number of bricks in Wall 1:

Area of Wall 1 = 30 m^2

Dimensions of standard brick = $215 \times 102.5 \times 65 \text{ mm}$

To compute the number of bricks needed to construct Wall 1.

- ❖ First, allow for standard brick work, 10 mm mortar joints should be added to the brick face area: $225 \times 75 = 0.016875 \text{ m}^2$.
- ❖ Area of Wall 1 = 30 m^2 , so number of bricks needed = $30/0.016875 = 1778$.
- ❖ Thus 1 m^2 of wall area requires $1/0.016875 = 60$ bricks per m^2 (to the nearest whole brick).

➤ Number of bricks in Wall 2:

Area of Wall 2 = 15 m^2 .

Window area $1.05 \text{ m} \times 1.2 \text{ m} = 1.26 \text{ m}^2$.

Wall area after deducting the area of window = 13.74 m^2 .

Number of bricks needed for Wall 2 = area of wall divided by face area of brick and associated mortar = $13.74/0.016875 = 815$ bricks.

➤ **Number of bricks in Wall 3:**

Area of Wall 3 = 30 m^2 .

Wall area after deducting the area of both windows = $30 - 2.52 = 27.48 \text{ m}^2$.

Number of bricks needed for Wall 3 = $27.48/0.016875 = 1629$ bricks.

➤ **Number of bricks in Wall 4:**

Area of Wall 4 = 15 m^2 .

Wall area after deducting the area of door = $15 - 1.95 = 13.05 \text{ m}^2$.

Number of bricks needed for Wall 4 = 774 bricks.

To sum up, the total number of bricks for the four walls = $1778 + 815 + 1629 + 774 = 4996$.

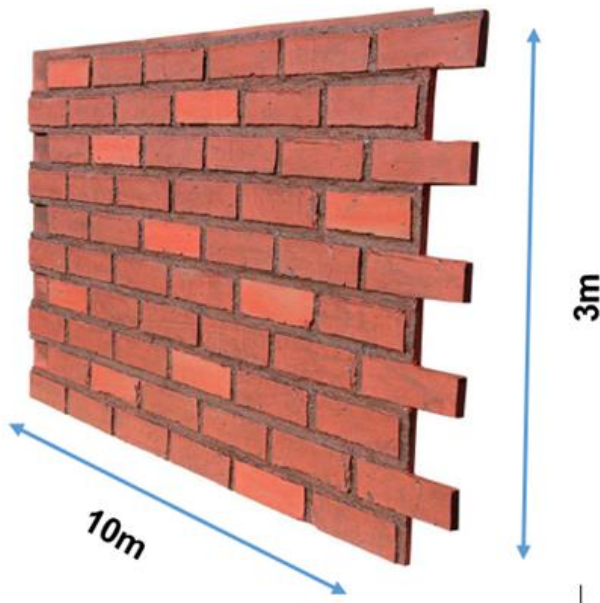


Figure 4-2 Wall dimensions 10m x 3m (Author)

4.3.2 Quantity of Cement, Sand and Water for Brickwork.

As described in Section 3.2.3 the mortar mix ratio for concrete bricks for building construction external and internal walls is in the ratio 1:4 (cement: sand) by

weight, with the water/cement ratio, 0.5. According to the Brick Development Association, (2018) this is the normal, most commonly used and best mix ratio for concrete bricks used for walling.

➤ **Calculation of quantities of cement, sand and water for brick work in Wall 1.**

- ❖ The ratio of 1:4 relates to the ratio of cement: sand.
- ❖ Because adjacent bricks share a layer of mortar, we need consider only 2 faces of the brick when determining the volume of mortar needed. So, for 1 brick the area of mortar required = $(215 \times 102.5 + 65 \times 102.5) = 0.0287 \text{ m}^2$.
- ❖ Volume of mortar for one brick = 0.0287×0.01 (thickness of mortar joint) = 0.000287 m^3 .
- ❖ Volume of mortar for Wall 1 = $0.000287 \times 1778 = 0.51 \text{ m}^3$.
- ❖ It follows that the volume of mortar per 1 m^2 of wall = $0.51/30 = 0.017 \text{ m}^2$.

When water is added to the dry mix the total volume decreases because the voids in the sand containing air are displaced. Thus, the volume of mortar cited above must be increased if, after adding the water, the total volume is to be sufficient to build the wall. It is usual to multiply the value of the volume calculated as above by a correction factor of 1.33 to determine the volume of wet mortar required (see Figure 4-3).

- ❖ The dry mortar volume (sand and cement only) for Wall 1 should be $0.51 \times 1.33 = 0.6783 \text{ m}^3$.

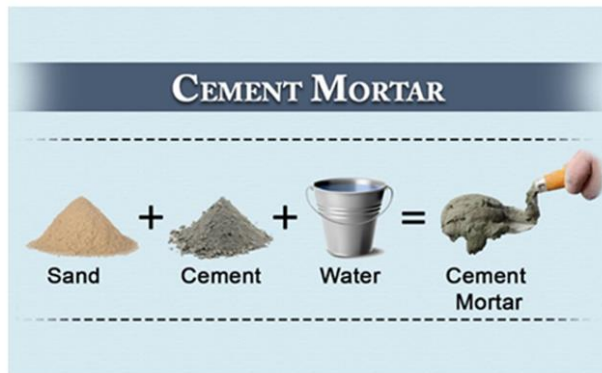


Figure 4-3 Brickwork process

Quantity of cement:

- ❖ Required cement volume = $(0.6873 \times 1) / 5 = 0.14 \text{ m}^3$, Required mass of cement = 0.14×1440 (cement density) = 201.6 kg .
- ❖ Number of cement bags = $201.6 / 50$ (weight of 1 bag) = 4.032 bag.
- ❖ It follows that 1 m^2 of wall will require 0.1344 bag of cement and 1 bag of cement is sufficient for $30/4.032 = 7.4 \text{ m}^2$ of wall.

Quantity of sand:

- ❖ Required volume of sand = $(0.6873 \times 4) / 5 = 0.55 \text{ m}^3$
- ❖ Total weight of sand required = $28.8 \times 30 = 864 \text{ kg}$
- ❖ Volume of sand per 1 m^2 of wall = $0.55 / 30 = 0.018 \text{ m}^3$,
- ❖ Weight of sand per 1 m^2 of wall = 0.018×1600 (sand density) = 28.8 kg

Quantity of water:

- ❖ Water-cement ratio = 0.5
- ❖ Required amount of water for Wall 1 = $201.6 \times 0.5 = 100.8 \text{ Litre}$,
- ❖ Required amount of water per 1 m^2 of wall = $100.8 / 30 = 3.36 \text{ L}$

➤ **Calculation of cement, sand and water for brick work in Wall 2.**

Following on from the calculations for Wall 1 above we have:

- ❖ Volume of mortar for Wall 2 = $0.000287 \times 815 = 0.234 \text{ m}^3$.
- ❖ The dry mortar volume (sand and cement only) for Wall 2 should be $0.234 \times 1.33 = 0.311 \text{ m}^3$.

Quantity of cement:

- ❖ Required cement volume = $(0.311 \times 1) / 5 = 0.06 \text{ m}^3$. Required mass of cement = 86.4 kg .
- ❖ Number of cement bags = 1.73 bags.

Quantity of sand:

- ❖ Required volume of sand = $(0.311 \times 4) / 5 = 0.25 \text{ m}^3$.
- ❖ Total weight of sand required = $28.8 \times 13.74 = 396 \text{ kg}$

Quantity of water:

- ❖ Water-cement ratio = 0.5.
- ❖ Required amount of water for Wall 2 = $86.4 \times 0.5 = 43.2 \text{ Litre}$.

➤ **Calculation of cement, sand and water for brick work in Wall 3.**

Following on from the calculations for Wall 1 above we have:

- ❖ Volume of mortar for Wall 3 = $0.000287 \times 1629 = 0.47 \text{ m}^3$.
- ❖ The dry mortar volume (sand and cement only) for Wall 2 should be $0.47 \times 1.33 = 0.6251 \text{ m}^3$.

Quantity of cement:

- ❖ Required cement volume = $(0.6251 \times 1) / 5 = 0.125 \text{ m}^3$, Required mass of cement = 180 kg .
- ❖ Number of cement bags = 3.6 bag.

Quantity of sand:

- ❖ Required sand volume = $(0.6251 \times 4) / 5 = 0.5 \text{ m}^3$.
- ❖ Total sand required - $28.8 \times 27.48 = 791.4 \text{ kg}$.

Quantity of water.

- ❖ Water-cement ratio = 0.5.
- ❖ Required amount of water for the wall = $180 \times 0.5 = 90 \text{ litre}$.

➤ **Calculation of cement, sand and water for brick work in Wall 4.**

Volume of mortar for Wall 4 = $0.000287 \times 774 = 0.22 \text{ m}^3$.

The dry mortar volume (sand and cement only) for Wall 2 should be $0.22 \times 1.33 = 0.293 \text{ m}^3$.

Quantity of cement.

- ❖ Required cement volume = $(0.293 \times 1) / 5 = 0.059 \text{ m}^3$, Required mass of cement = 85 kg .
- ❖ Number of cement bags = 1.7 bag.

Quantity of sand.

- ❖ Required sand volume = $(0.293 \times 4) / 5 = 0.23 \text{ m}^3$.
- ❖ Total sand required = 376 kg .

Quantity of water.

- ❖ Water-cement ratio = 0.5.
- ❖ Required amount of water for the wall = $85 \times 0.5 = 42.5 \text{ litre}$.

Therefore, the quantity of cement, sand and water for each wall is:

Wall 1: Quantities required to construct Wall 1, of 30 m^2 : 1778 bricks, 201.6 *kg* of cement, 864 *kg* of sand and 100.8 *litre* of water.

Wall 2: Quantity required to construct Wall 2, of 13.74 m^2 : 815 bricks, 86.4 *kg* of cement, 396 *kg* of sand, and 43.2 *litre* of water.

Wall 3: Quantity required to construct Wall 3, of 27.48 m^2 : 1629 bricks, 180 *kg* of cement, 791.4 *kg* of sand, and 90 *litre* of water.

Wall 4: Quantity required to construct Wall 4, of 13.05 m^2 : 774 bricks, 85 *kg* of cement, 376 *kg* of sand, and 42.5 *litre* of water.

Total for the four walls: 4996 bricks, 553 *kg* of cement, 2430.4 *kg* of sand and 276.5 *L* of water.

4.3.3 Quantity of Plasterboards.

Thermally insulated plasterboard has been used, this type of plasterboard combines the properties of plasterboard itself with those of the insulation material attached to it. Insulated plasterboard prevents heat escaping when the internal temperature exceeds the external and helps keep the interior cool when the exterior temperature exceeds the interior. This results in a warmer and more comfortable home which is more energy efficient. This type of plasterboard also contains a vapour layer to prevent moisture transmission into the wall. As stated above the plasterboard used was Celotex PL4000 which meets national Building Regulations and guidance (see Figure 4-4), (Celotex, 2011).

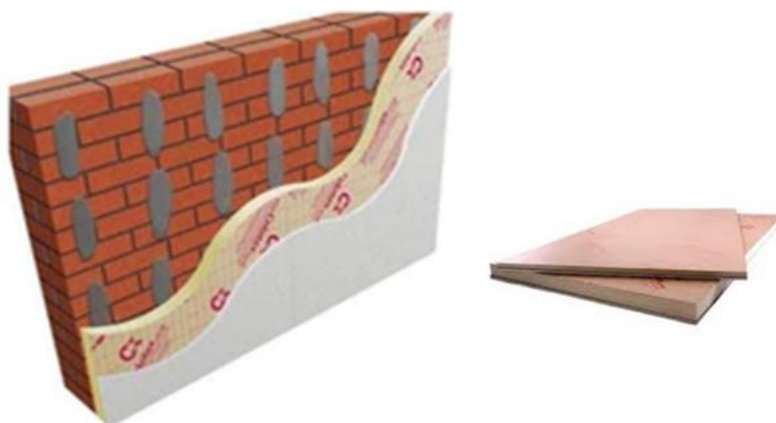


Figure 4-4 Type of Plasterboard (Sheet, 2021)

➤ **Plasterboard work for Wall 1.**

Wall area = 30 m^2 , and board dimensions $2.4 \text{ m} \times 1.2 \text{ m} = 2.88 \text{ m}^2$.

Thus, total number of plasterboard sheets needed $(30 / 2.88) = 11$ sheets.

➤ **Plasterboard work for Wall 2.**

Wall area = 13.74 m^2 , thus total number of plasterboard sheets needed = $(13.74 / 2.88) = 5$ sheets.

➤ **Plasterboard work for Wall 3.**

Wall area = 27.48 m^2 , thus total number of plasterboard sheets needed = $(27.48 / 2.88) = 10$ sheets.

➤ **Plasterboard work for Wall 4.**

Wall area = 13.05 m^2 , thus total number of plasterboard sheets needed $(13.05 / 2.88) = 5$ sheets.

4.4 The representation of One-bedroom house in BIM

It is important to explain all the calculations related to the design of the asset from the point of view: materials (brick, cement, sand and water, plasterboard) and dimensions that will be the data needed for the sustainability engineering calculations and used in the framework of case study validation. Figure 4-5 is representing the one-bedroom house in BIM environment.

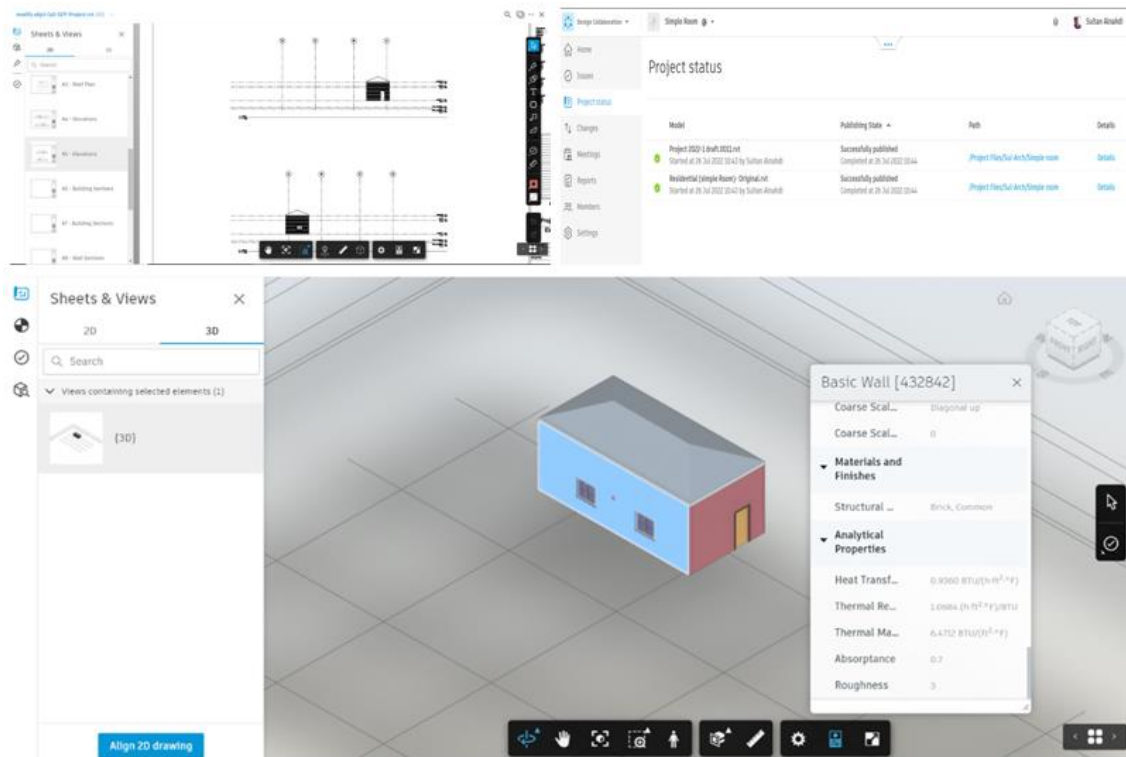


Figure 4-5: The representation of One-bedroom house in BIM (Author)

4.5 Closing Remarks

In conclusion, this case study has provided an overview of the materials used to build a simple one-bedroom, single storey house made from red bricks, mortar, wood, glass, and plasterboard. The walls were built in a traditional staggered pattern (the brick courses in the wall are staggered by half a brick relative to the courses immediately above and below) and the windows and door were installed after the walls were built. The house was insulated with plasterboard. This case study provides a good starting point for investigating sustainability issues related to the materials and construction methods used to build the house.

The next chapter will extend the case study by discussing the heat transfer through the walls of the house.

5 COMPARATIVE CONDUCTION HEAT TRANSFER IN SIMPLE CONSTRUCTION ELEMENTS

5.1 Introduction

This chapter is presenting one sustainability issue regarding heat transfer which is related to energy efficiency highlighted in Table 2-1. It shows a paper base engineering calculations of heat transfer. It is going to present what typical engineering calculations that need to be used and what are the data of these different parameters to be obtained from Revit. Heat transfer rate through a wall is influenced by several factors, including the material properties, wall thickness, surface area and the temperature difference across the wall. Based on these factors the heat transfer rate through a brick wall and a precast concrete wall are likely to differ, and the more sustainable choice may depend on the specific design and operational requirements of the building. A hypothetical case study of the one-bedroom house as shown in Figure 5-1 will demonstrate how the calculation of heat transfer can add value to sustainability.

The intension in this chapter is to evaluate how heat transfer through a simple wall structure can be investigated by examining the effect of constructing the wall with different materials. Here, for simplicity, the geometric, and admin information is the same for the different materials used, with the focus on determining how material selection can reduce heat transfer because the lower the thermal conductivity of an exterior wall, the less energy will be used for heating the enclosed space and that addresses one key sustainability issue.

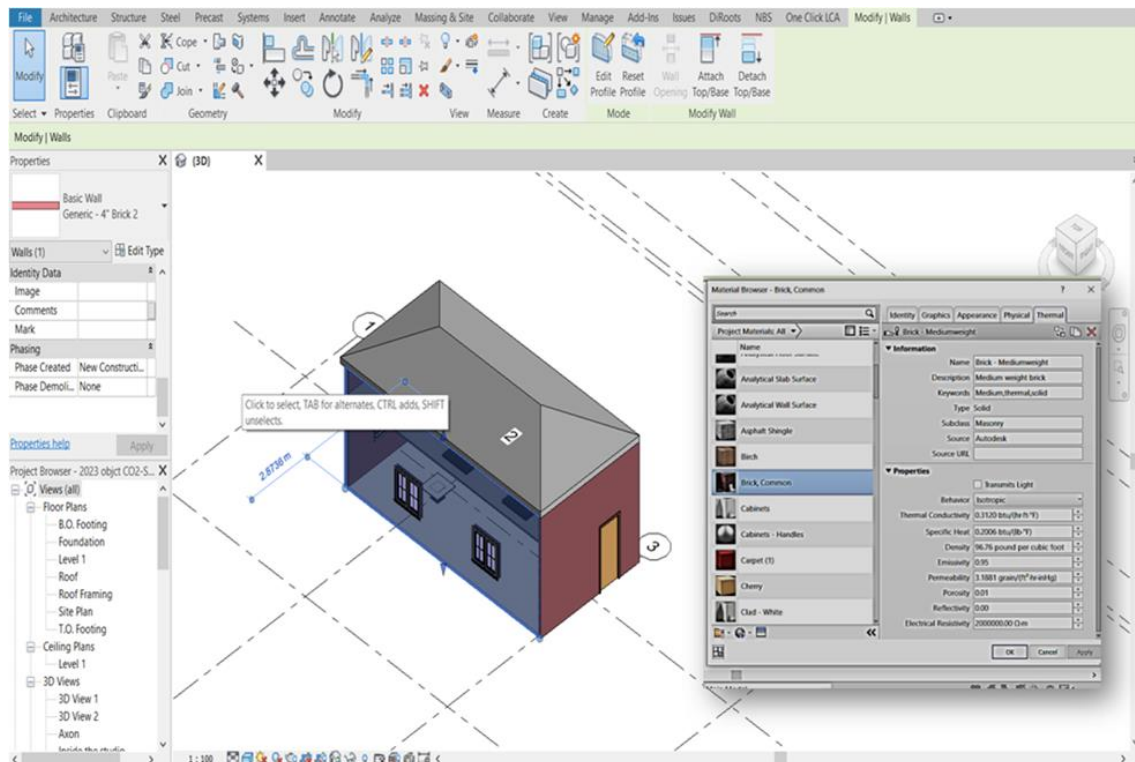


Figure 5-1 Detailed description of the structure (Author)

5.2 Conductive Heat Transfer Calculation for a Wall.

Here we are concerned with the difference in heat flow rates through the wall for two types of construction, brick plus plasterboard and precast concrete. Thus, there is no need to consider heat losses through the windows, door, floor or ceiling provided the internal and external temperatures do not change.

The thermal conductivity of a material is a property of the material and a measure of how well it conducts heat, so the rate of heat conduction is directly proportional to thermal conductivity of the material. Conduction is the transfer of heat through a solid material by molecular vibration. The following steps can be used to calculate the conductive heat transfer through a wall:

1. Determine the temperature difference across the wall. This can be done by measuring the temperatures of the inside and outside surfaces of the wall.
2. Determine the thermal conductivity of the walls, from their constituent parts, in this case, brick and plasterboard, and precast concrete. This

information is publicly available and can be found in the Revit, as shown in Figure 5-2.

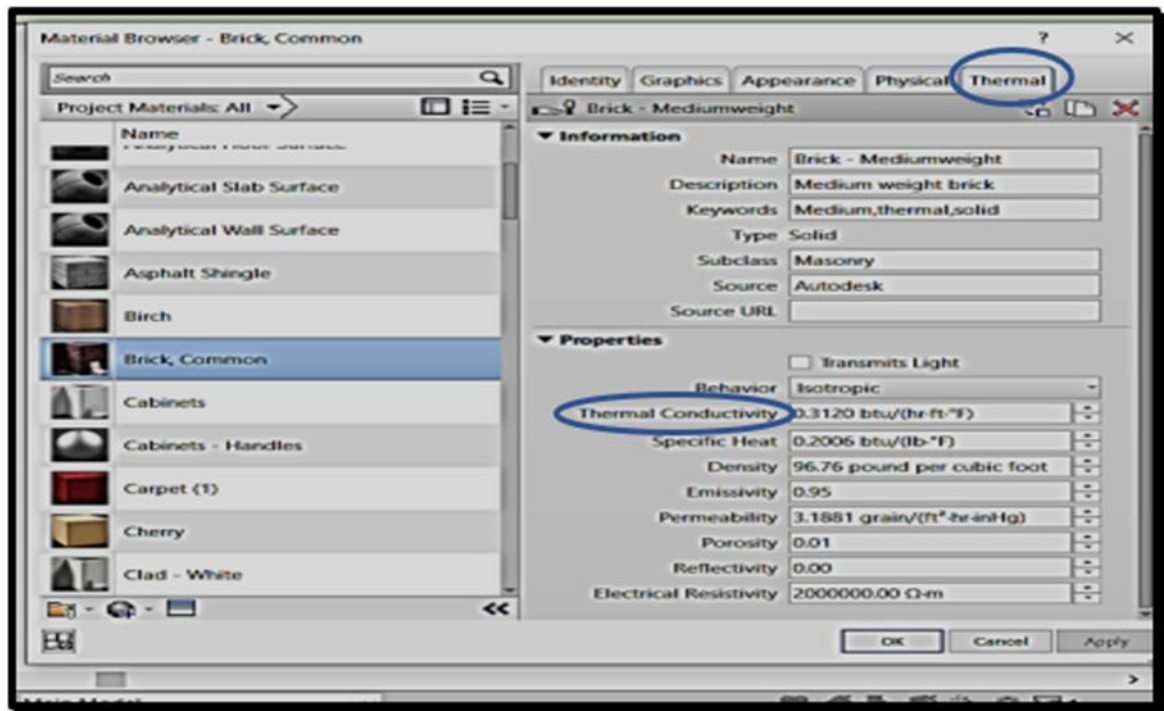


Figure 5-2 Different wall materials & parameters from Revit (Author)

3. Determine the thickness of the wall. This will be immediately available from the design.
4. Calculate the rate of heat conduction through a wall with multiple layers. This can also be done using Fourier's Law (Ali, 2020; Shahidian et al., 2020; Zohuri & Fathi, 2015).

$$Q = U A \Delta T \text{ Watts} \quad (5-1)$$

For the wall alone, the U value is the overall thermal transmittance of the two layers: $U = 1/(\frac{L_1}{k_1} + \frac{L_2}{k_2})$ where L_1 and L_2 are the thicknesses of the two layers in metres and k_1 and k_2 their respective thermal conductivities in $W/m^{\circ}C$.

However, in any design office the actual formula for the heat loss through a wall is not as simple. In real life the designer must take into account the surface thermal resistances of the layer of air adhering to

the inner face of the wall (typically $R_i = 0.13 \text{ m}^2\text{C}/W$) and the layer of air adhering to the outer face of the wall (typically $R_o = 0.04 \text{ m}^2\text{C}/W$) (CIBSE Environmental Design Guide A, Table 3.10, 7th edition).

In the formula $Q = U A \Delta T$, the value for U must include R_i and R_o .

$$\text{E.G., } U_{\text{brick wall}} = 1/(R_i + \frac{L_1}{k_1} + \frac{L_2}{k_2} + R_o).$$

$$U_{\text{brick wall}} = 1/(0.13 + 0.23/0.54 + 0.0375/0.022 + 0.04) = 1/2.30 = 0.435 \text{ m}^2\text{C}/W.$$

where,

Q = Rate of heat transfer (W).

K = Thermal conductivity of material ($W/m^\circ C$).

L = Material thickness (m).

A = Heat transfer area (m^2).

U = Overall thermal transmittance ($m^2\text{C}/W$).

ΔT = Temperature between the two faces of the wall ($^\circ C$).

5.2.1 Calculation Data for a Brick Wall with Plasterboard.

To calculate the heat transfer through a brick wall faced with a layer of plasterboard.

Thermal conductivity of brick from Revit is $0.540 \text{ m}^2\text{C}/W$.

Thermal conductivity of Celotex PL4000 plasterboard is $0.022 \text{ W}/m^\circ C$ (Sheet, 2021).

Thickness of the brick wall is 230 mm, and the thickness of the plasterboard is 37.5 mm.

Length and height of Wall 1 are 10 m by 3 m respectively.

The temperatures are taken to be $22^\circ C$ on the inside surface and $4^\circ C$ on the outside.

$$U_{\text{brick wall}} = 0.435 \text{ W/m}^2 \cdot ^\circ\text{C}.$$

For Wall 1 with brick and plasterboard, using Equation 5.1, $Q = 0.435 \times (30) \times (22-4) = 235 \text{ W}$.

If all walls are external walls the total wall area is 84.27 m^2 , so total rate of heat loss is 660 W .

5.2.2 Calculation Data for a Precast Concrete Wall.

For comparison we calculate the heat transfer through a precast concrete wall with no insulation.

Thermal conductivity of precast concrete from Revit is $1.040 \text{ W/m}^\circ\text{C}$.

The dimensions of the wall remain the same, thickness is 230 mm , length = 10 m , and height = 3 m . The internal and external surface temperatures remain 22°C on the inside surface and 4°C on the outside.

$$U_{\text{concrete}} = 1 / (0.13 + 0.23/1.04 + 0.04) = 1 / 0.391 = 2.56 \text{ W/m}^2 \cdot ^\circ\text{C}.$$

For Wall 1 with concrete, using Equation 5.1, $Q = 2.56 \times (30) \times (22-4) = 1382 \text{ W}$.

If all walls are external walls the total heat loss is 3.88 kW .

Thus, using brick plus plasterboard rather than concrete for Wall 1 reduces the heat loss by just over 1 kW , and for all four walls by over 3 kW .

5.3 Discussion

The above results demonstrate that selection of materials for a structural wall, taking into account thermal properties can significantly reduce the overall heat transfer rate for the building in the given site environment. Brick walls are typically made of clay or clay-based materials and have low thermal conductivity, meaning that they are good at insulating against heat transfer. Whereas, precast concrete walls are made of a mixture of concrete, water, and aggregate materials, and have higher thermal conductivity. This means that precast concrete walls are not as good at insulating against heat transfer as brick walls.

In terms of sustainability, both brick walls and precast concrete walls can be sustainable, depending on the specific design and operational requirements of the building. Ultimately, the most sustainable option will depend on the energy consumption goals, climate, and other operational requirements of the building. Here the reduction in rate of heat loss for Wall 1 by replacing precast concrete by brick is about 1.1 *kW* for the given wall area. Over the life of the building that might add up to a significant saving but how does it compare with change in cost of materials, maintenance, demolition and disposal. Applying the environmental heat transfer method to every wall in the asset can make the whole of the project more sustainable. Table 5-1 present the comparison of brick walls with plasterboard, and precast concrete walls regarding insulation and heat transfer:

Table 5-1 Comparison of wall materials (Author)

Feature	Brick wall with plasterboard	Precast Concrete Wall
Insulation	Good	Poor
Heat Transfer	Slow	Fast
R-Value	2.3	0.391

Plasterboard insulation is made of gypsum and paper. The selected type of plasterboard was discussed in Section 4.3.3. It is a good insulator because it traps air, which is a poor conductor of heat. When plasterboard is added to a brick wall, it significantly improves the wall's insulation and heat transfer properties. According to (Amro & Alibaba, 2020) The R-value is a measure of a material's ability to resist heat flow. The higher the R-value, the better the material insulates. Brick walls with plasterboard typically have an R-value in the range 2.3, while precast concrete walls without plasterboard have an R-value in the range 0.391.

5.4 Closing Remarks

In conclusion, the calculation of heat transfer as the key sustainability issue through the case study wall showed important factors regarding the sustainability of the case study. Brick walls with plasterboard are better insulators than precast concrete walls. This means that brick walls with plasterboard are more effective at preventing heat loss or gain, which can lead to lower heating and cooling costs. When selecting a material for a structural wall, it is important to consider the site environment and the energy consumption goals of the building. In this case, brick walls with plasterboard may be the better option for reducing energy costs and improving sustainability. To conclude, this chapter demonstrated that in order to show sustainability when it is calculated in paper based is significant starting point. However, it is crucial to acknowledge that the true benefits and advantages of assessing sustainability calculations in BIM environment.

The next chapter will demonstrate a framework of construction sustainability in a BIM environment.

6 THE DEVELOPMENT OF A SUSTAINABLE CONSTRUCTION FRAMEWORK BASED ON BIM

6.1 Introduction

The previous chapters achieved the following research objectives defined in Chapter One: reviewing relevant literature, identifying sustainability issues and demonstrating one case of a sustainability calculation. This chapter presents a framework that integrates key information, the construction value chain, the construction sustainability library, and required engineering calculation for each sustainable issue integrated into the CAD-Revit and BIM environment. This is to achieve the main aim of the research of enhancing the sustainability of construction projects.

6.2 Construction Sustainability Framework in a BIM Environment

A framework typically provides a conceptual structure or model for understanding and organizing complex phenomena or processes. It helps researchers conceptualize, categorize, and guide their thinking and analysis.

Based on that Figure 6-1 presents a two-stage structure. This aligns with the characteristics of a framework because it provides a conceptual model for understanding and organizing the process of addressing sustainability issues in a construction project within a BIM environment. The two stages represent broad categories of activities and components rather than a detailed sequence of actions.

The framework aims to address sustainability issues in a construction project in a BIM environment. The framework shown in Figure 6-1 is divided into two stages. Stage one involves managing the information related to the project and the construction value chain. In stage two, the focus is on addressing various sustainability issues and performing engineering calculations for each of them to establish a direct and integrated link with the CAD-Revit and BIM database.

Stage one: The BIM database is the core element of this stage, providing a single source of digital data about the construction project in real-time for all construction value chain phases and stakeholders as presented in Section 2.5.2 (Figure 2-6). Stage one is about information management, the three terms used at the top of the framework are defined as follows:

- A. **Customer requirements:** Are the requirements and wishes of the owner and may differ from those of the asset designers and construction contractors. These requirements could include location, area, overall conceptual design, number of rooms and floors, see Figure 6-1-A.
- B. **Sustainability issue requirements:** As this research project is about sustainability, so Figure 6-1-B has sustainability as a requirement. This include identifying key sustainability goals for the project also to track progress towards these goals and ensure that sustainability considerations are integrated throughout the project phases.
- C. **Detailed project planning:** All construction projects require detailed project planning of the asset as shown in Figure 6-1-C.
- D. **Project start:** All the contents of the construction value chain are given and presented to the key stakeholders. This process continues throughout the project as Illustrated in Figure 6-1-D. All stakeholders have real time access to the project information via BIM. Such information includes geometrical, technical and admin information. In this research, the author is proposing the addition of sustainability data in BIM which normally not available.

Construction Sustainability Framework in BIM Environment

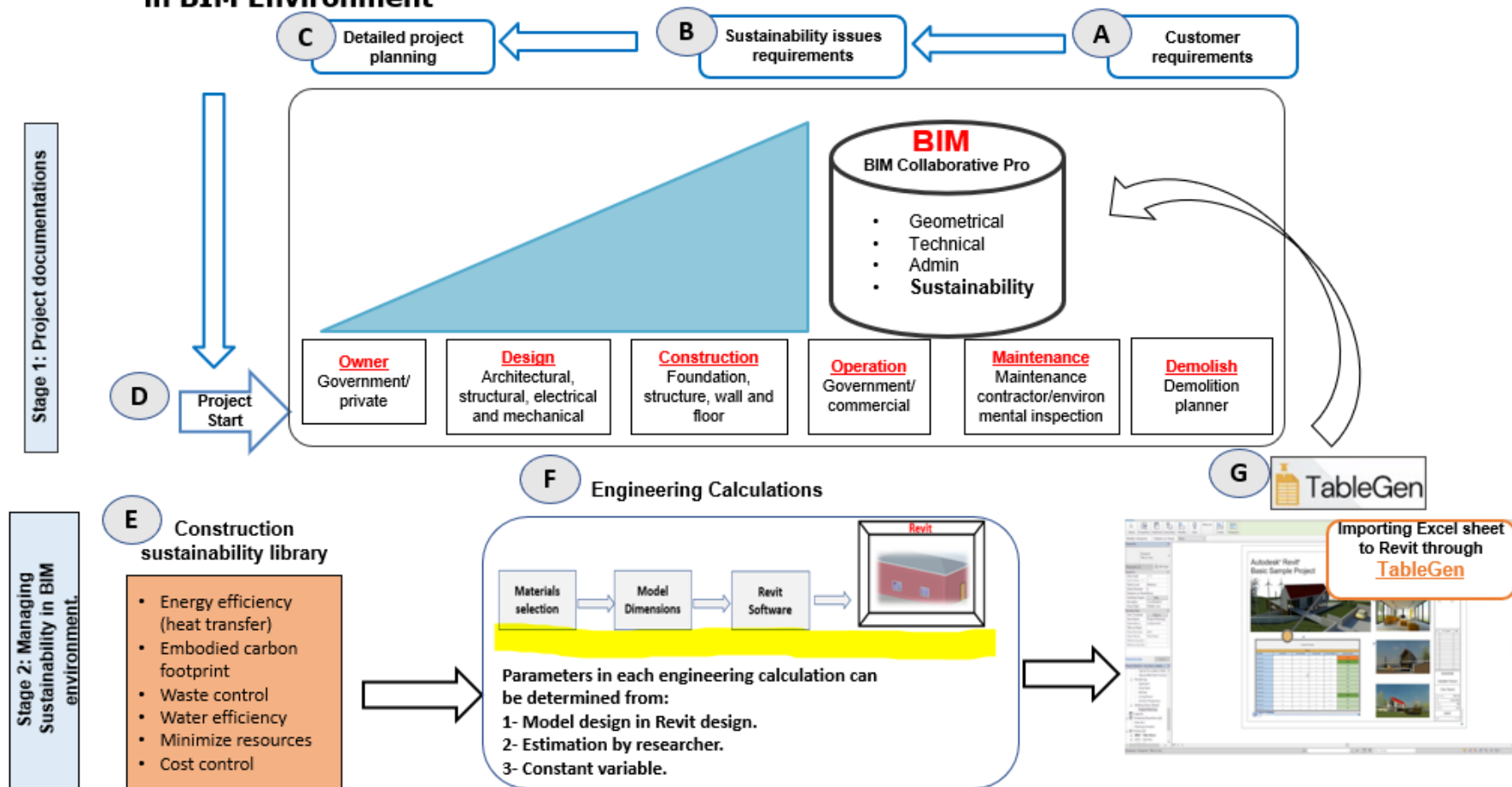


Figure 6-1 Illustration of a framework for managing sustainability issues in a BIM environment (Author).

Stage two: Is focused on highlighting sustainability issues in an integrated manner and providing integration with Revit and BIM in a seamless way, and to achieve that will require:

- E. **Construction sustainability library:** Which involves a list of sustainability issues identified previously in Table 2-1 as shown in Figure 6-1-E.
- F. **Sustainability issue engineering calculations:** Provide the correct engineering calculations as shown in Figure 6-1-F to show that different sustainability issues will require different engineering calculations. Each calculation will involve material selection for, and dimensions, of the asset. In addition, the framework will also provide different parameters required for each engineering calculation in an easy-to-use format, which could be an Excel file or within the Revit CAD system from BIM database.
- G. **TableGen:** This is a Revit plugin application that allows the importation of the results of sustainability engineering calculations into Revit. It allows the user to import Excel spreadsheets to Revit as shown in Figure 6-1-G. Furthermore, Excel tables can be imported to Revit as drafting schedule views. It also brings images from Excel tables into Revit automatically synchronised with the Excel file.

Finally, when the results from Excel are exported into the Revit model, the model will be uploaded, stored, visualized and read by BIM Collaborative Pro software. This allows stakeholders in the project value chain to easily understand, share and make informed decisions.

Overall, the proposed framework will effectively address sustainability in a user-friendly manner for companies to implement and do relevant calculations. The data will be transparently available to all construction value chain stakeholders. This generic construction sustainability framework in the BIM environment will be demonstrated in a hypothetical case study of calculating the embodied carbon emissions of the asset, see Section 6.3.

6.3 The Application of a Construction Sustainability Framework to the Embodied Carbon Footprint of a One-Bedroom House in a BIM Environment

The development of the framework is validated for a specific sustainability issue, the calculation of the embodied carbon of the hypothetical case study of a one-bedroom house as shown in Figure 6-2. The case is presented in the following sub-sections.

6.3.1 Information Management.

(A) Customer requirement of one bedroom house: The owner in this case is 'Mr Roy Smith' who has to fill the requirement report shown in Table 6-1. The key information required is contained in a document that defines the project outcomes and sets out what the client is seeking to achieve. It includes five main parts as follows:

1. **Project Overview:** Describes the aim of the owner: to build a one-bedroom house that can serve a single person or couple as occupants.
2. **Project Scope:** Includes key elements for constructing the house according to the owner's specification and sustainability concerns as shown in Table 6-1.
3. **Design requirements:** Mr. Roy Smith has provided design preferences and requirements such as floor plan, number of bedrooms, number of doors, number of windows and adequate natural lighting where feasible.
4. **Technical requirement:** Mr. Roy Smith expects the following technical specifications to be met: the overall square footage of the house, standard ceiling height, wall area to be constructed, Structural and insulation materials.
5. **Budget and timeline:** The owner in this case has allocated a budget of £90,000 for constructing the house. The timeline for completion should be February 2024.

(B) Sustainability issues requirement (Embodied carbon): The owner is environmentally conscious and emphasises the need to address the carbon

footprint of the house. Therefore, the sustainability issue of embodied carbon footprint must be calculated in detail in this project.

Table 6-1 The owner information requirements (Author).

[Project Name]: Construction of One-Bedroom House [Client Name]: Mr Roy Smith [Date]: 05/06/2023 [Client Contact Information]: Email: S1.Roy@gmail.com, Phone Number: 07898973151		
Project Overview	Serve as a comfortable living space for a single occupant or a couple.	
Project Scope:	- Construction with appropriate dimensions. - Compliance with local building codes. - Selection of sustainable construction materials. - Insulation for energy efficiency. - Controlling the embodied carbon footprint of the house	
Design Requirements:	Floor plan: Open floor plan No of bedrooms: 1 bedroom No of doors: 1 external door No of windows: 3 windows Lighting: Natural lighting Stairs: ----- Kitchen: ----- Bathroom: -----	
Technical Requirements:	Overall square footage: 50m ² Ceiling height: 3m Wall area: ----- Structural material: Brick Insulation material: Plasterboard Electrical outlets: ----- Lighting fixtures: -----	
Budget and Timeline:	Project budget: £90,000 Completion timeline: 8 months	

The Application of Construction Sustainability Framework on Embodied Carbon Footprint of One-bedroom House in A BIM Environment

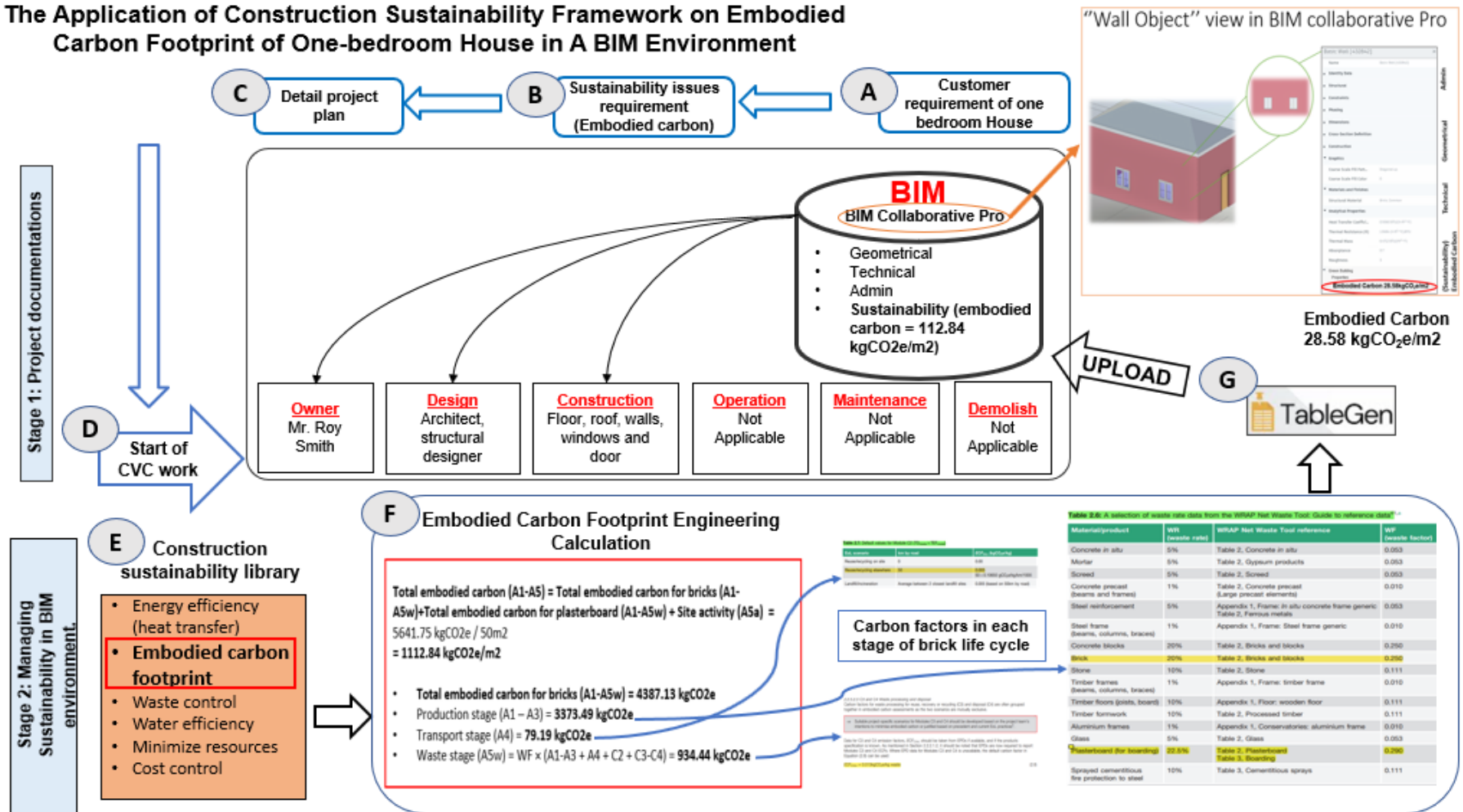


Figure 6-2 Illustration of the application of the BIM framework on embodied carbon of one-bedroom house (Author).

(C) Detail project plan: Includes the set of key phases and activities as shown in Figure 6-3 and detailed as follows:

1. **Project Initiation Phase:** Defines the objectives and requirements of the owner.
2. **Design and Planning Phase:** Creates detailed architectural drawings and plans as well as the structural design of the one-bedroom house. Finalizes the house layout and material selection. Finally, the calculation of embodied carbon footprint of the house is completed.
3. **Pre-Construction Phase:** preparing the construction site and ensuring the availability of utilities on site.
4. **Construction Phase:** The foundation work is begun, followed by constructing the walls. Simultaneously, windows and door will be installed, and the roofing work will take place. The installation of plumbing, electrical system will follow. Once work on these systems is finished the flooring installation will take place. Finally, the installation of bathroom and kitchen fixtures will be carried out.
5. **Finalization and Closure Phase:** A walkthrough with Mr Roy Smith will be conducted to review the finished house and address any concerns or final adjustments, ensuring documentation and paperwork are finalized. Finally, the keys and relevant documents will be handed over to Mr Roy Smith.

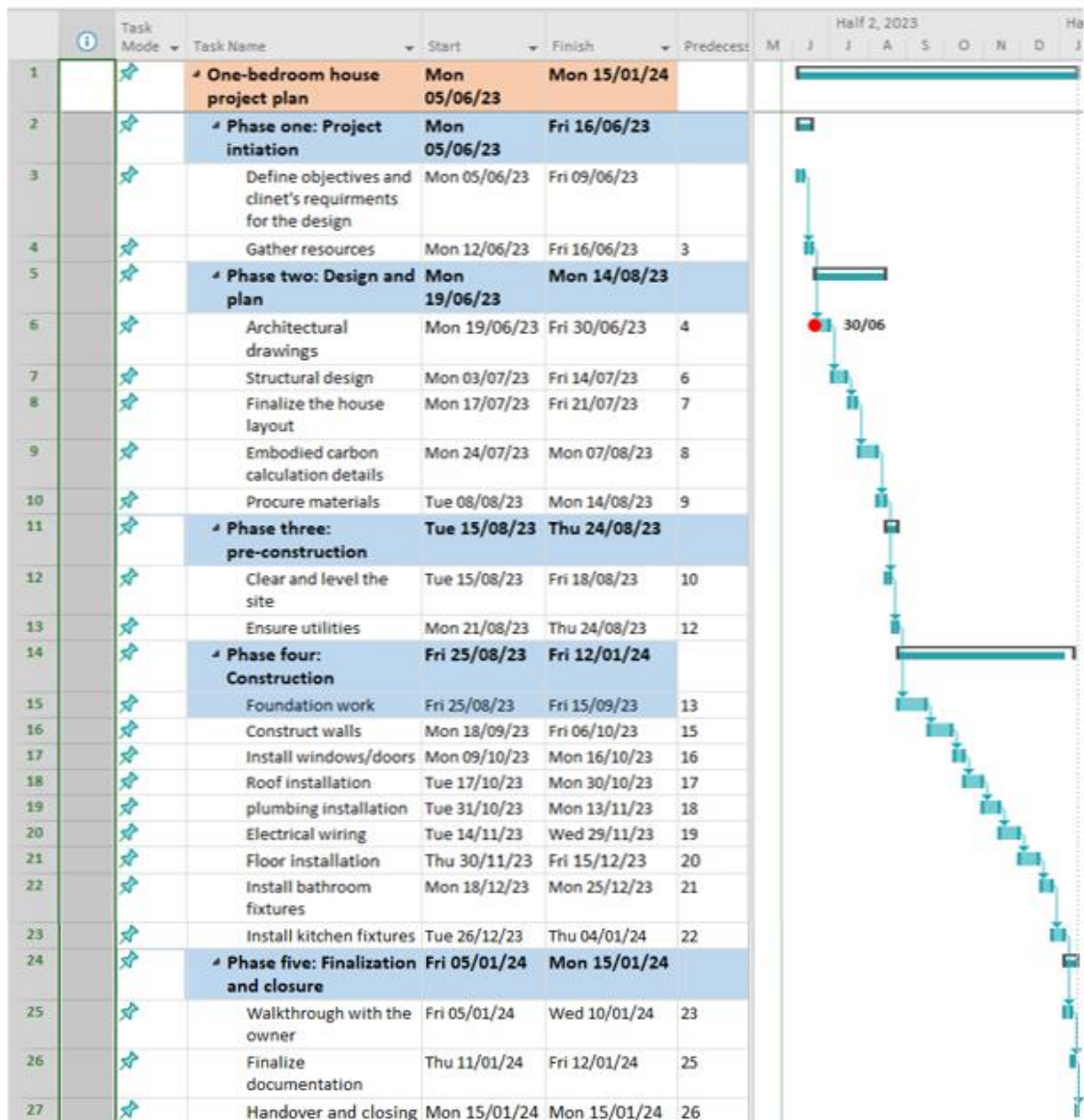


Figure 6-3 An example of detailed project plan of one-bedroom house (Author).

6.3.2 Start of Construction Value Chain Work.

1. Owner, as has been stated to be named, Mr Roy Smith.
2. The design phase: In this hypothetical case the architect and structural designer undertake the design of the house. They have access to all the necessary design information via BIM to start designing the house as shown in Figure 6-4.

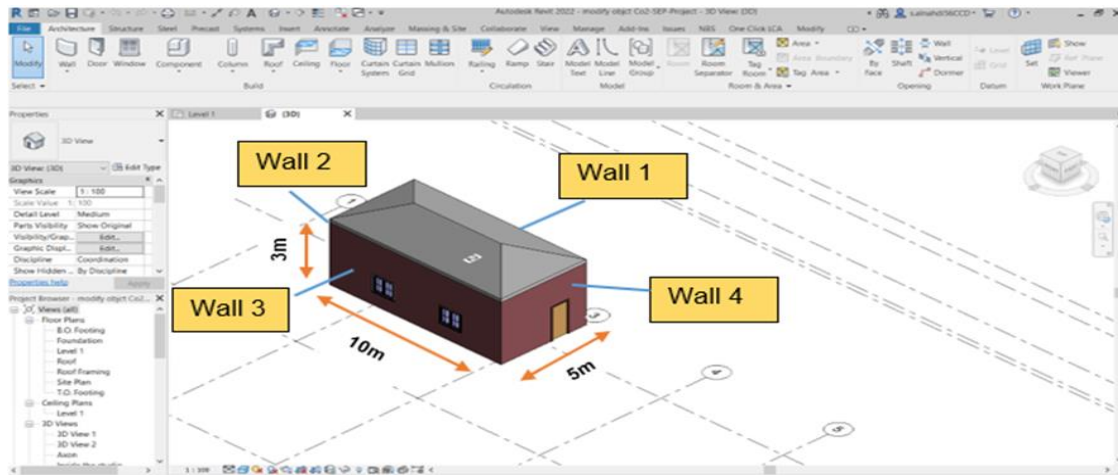


Figure 6-4 The overall design of the one-bedroom house (Author).

The design information for the house includes the following details as shown in Figure 6-5:

- Floor plans: The design shows the layout of the house's interior which is open floor plan, and includes the height and width of the windows and door as follows: 1050 mm by 1200 mm, and 2134 mm by 915 mm, respectively. The plan also shows the location of windows and door.
- Elevations: Show the exterior of the house from the front, back, and sides, including the dimensions of the house with total floor area of 50 m². It also shows the architectural style.

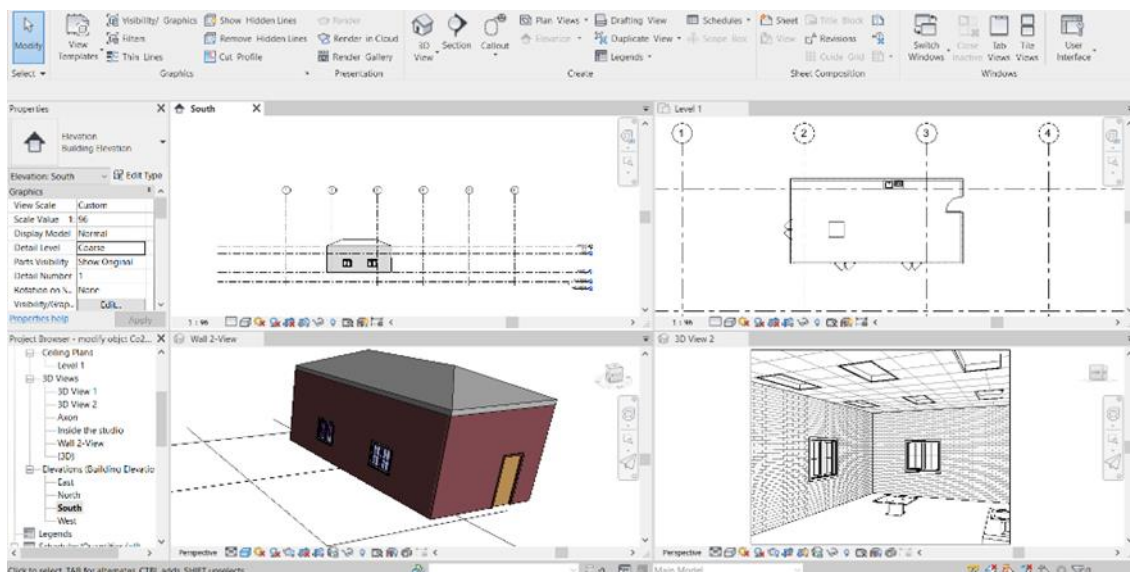


Figure 6-5 Elevation and floor plan of the one-bedroom house (Author).

- Sections: These drawings show the interior of the house. They include the dimensions of the walls, the floor, and the ceiling, as well as the location of the beams, joists, and other structural elements.
- Details: These drawings show specific details of the house, such as the construction of the roof, the installation of windows, and the finish of the walls.

The structural designer ensures that the house well-structured and meets the standard regulations. The work starting with the following activity:

- Selection of material:
 - a. Brick of standard size ($215\text{ mm} \times 102.5\text{ mm} \times 65\text{ mm}$), and the quantity needed for construction is 4996 bricks.
 - b. Plasterboard is Celotex PL4000 from Celotex Saint-Gobain with wallboard size of $2400\text{ mm} \times 1200\text{ mm} \times 37.5\text{ mm}$, with 31 sheets needed for the walls.
- The calculation of embodied carbon footprint for the one-bedroom house which will be explained in detail in Section 6.3.3.
- 3. The construction phase: The actual construction is outside the scope of this research project, however the planning for the construction is provided as part of the project planning, as shown in Figure 6-3.
- 4. The operation, maintenance and demolition phases are not included in this study.

6.3.3 Embodied Carbon Footprint: Engineering Calculation

Stage two: as shown in Figure 6-2-E the embodied carbon footprint is the major sustainability concern here. It has been selected from the construction sustainability library as the framework providing all the engineering calculations required plus details of all the parameters needed for the calculation. Figure 6-6 presents the life cycle stages of a design and construction project that has been adopted from the Institution of Structural Engineers (Gibbons & Orr, 2020a).

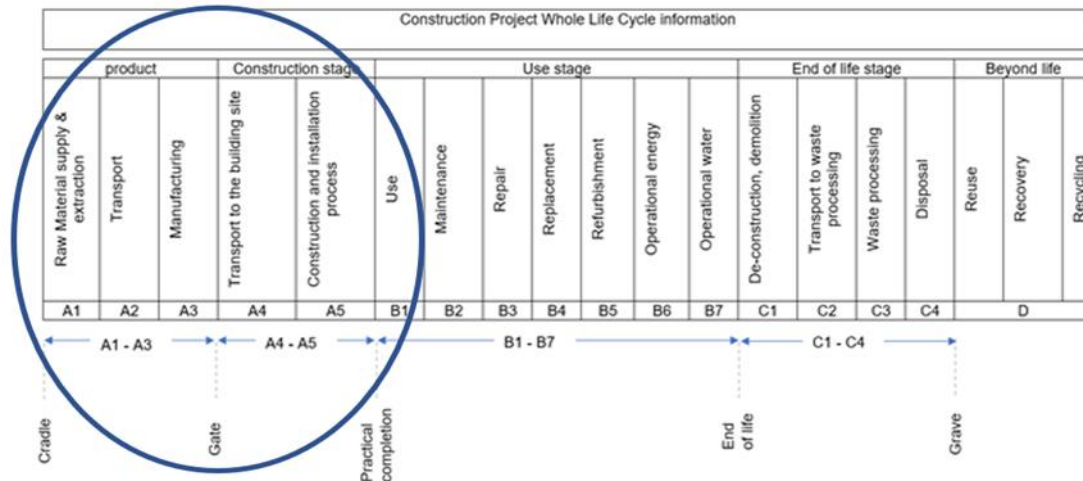


Figure 6-6 Construction project life cycle information (Gibbons & Orr, 2020b)

The concerns for this hypothetical case are the following:

A1–A3 Stage of production carbon factors: Embodied carbon related to A1-A3 modules. The carbon factor associated with these modules is dependent on the material specification, which varies based on constituent materials and manufacturing location.

A4 Transport carbon factors: Typically, 10% of a structure's total embodied carbon is attributable to A4 emissions, which pertain primarily to the transport of materials and products from factory to site. It depends on distance travelled and mode of transport.

A5 Carbon factors of construction and installation process: The emissions are divided into two categories. Emissions associated with materials discarded on site are identified as A5w emissions, whereas emissions associated with site activities such as construction equipment and site offices are identified as A5a emissions.

1. A5w Material wastage: Waste factor WF is used to determine how much material is wasted on site. The A5w factor is derived by multiplying the WF by the sum of the relevant embodied carbon factor. $A5w = WF \times (A1-A3 + A4 + C2 + C3-C4)$.
2. A5a Site activities: Emissions for A5a can be estimated using data from previous projects or industry studies.

According to (Gibbons & Orr, 2020a) the total embodied carbon in the materials used to construct one-bedroom house is presenting by the following equation:

$$\begin{aligned} \text{Total embodied carbon (A1 – A5)} & \quad (6-1) \\ &= \text{Total embodied carbon for bricks (A1 – A5w)} \\ &+ \text{Total embodied carbon for plasterboard (A1 – A5w)} \\ &+ \text{Site activity (A5a)} \end{aligned}$$

Moreover, Equation (6-2) presents the embodied carbon of each material during the lifecycle stage being considered (RICS, 2017).

$$\text{Embodied carbon} = \text{Quantity of Material} \times \text{Carbon conversion factor} \quad (6-2)$$

The quantity of material of brick and plasterboard was determined in Section 4.3 to be 4996 bricks and 31 sheets of plasterboard. The Carbon conversion factor for the stages A1-A5 is found in the project life cycle information of the material.

Following are the detailed calculation of the embodied carbon in the bricks and plasterboard materials for the given one-bedroom house.

6.3.3.1 Embodied Carbon Footprint for Brick.

Here we demonstrate the concept of embodied carbon by considering the walls.

Quantities: In Chapter 4 it was demonstrated that the total number of bricks required for each of the four walls was 1778, 815, 1629, and 774. A total of 4996. It was also shown that the volume of a single brick was 0.00143 m^3 . Thus, total volume of all bricks = $4996 \times 0.00143 = 6.994 \approx 7 \text{ m}^3$.

Mass of a brick = Volume of brick x density

Where the density of Staffordshire Red Brick (KETLEY BRICK, 2020) = 2200 kg/m^3 .

Thus, mass of single brick = $0.00143 \times 2200 = 3.15 \text{ kg}$.

Mass of brick in Wall 1 = number of bricks of Wall one x 3.15

$$= 1778 \times 3.15 = 5600 \text{ kg}.$$

Mass of bricks in the other walls are: 2656 kg, 5158 kg, 2424 kg respectively. A total mass of 15,838 kg.

a) Carbon Conversion Factors stages for Brick:

- Production stage (A1 – A3) = 0.213 kgCO₂e/kg (LETI, 2020)
- Transport stage (A4) = 0.005 kgCO₂e/kg, assume locally manufactured as shown in Table 6-2.

Table 6-2 Default distance values (Gibbons & Orr, 2020a)

A4 transport scenario	km by road	km by sea	ECF _{A4,i} (kgCO ₂ e/kg)
Locally manufactured	50	–	0.005 50km × 0.10650gCO ₂ e/kg/km / 1000
Nationally manufactured	300	–	0.032
European manufactured	1500	–	0.160
Globally manufactured	200	10000	0.183

- Waste stage (A5w) = WF × (A1-A3 + A4 + C2 + C3-C4).

Where, WF = 0.250 (see Table 6-3), for typical structural materials.

Table 6-3 Selection of waste rate data (Gibbons & Orr, 2020a)

Material/product	WR (waste rate)	WRAP Net Waste Tool reference	WF (waste factor)
Concrete <i>in situ</i>	5%	Table 2, Concrete <i>in situ</i>	0.053
Mortar	5%	Table 2, Gypsum products	0.053
Screed	5%	Table 2, Screed	0.053
Concrete precast (beams and frames)	1%	Table 2, Concrete precast (Large precast elements)	0.010
Steel reinforcement	5%	Appendix 1, Frame: <i>In situ</i> concrete frame generic Table 2, Ferrous metals	0.053
Steel frame (beams, columns, braces)	1%	Appendix 1, Frame: Steel frame generic	0.010
Concrete blocks	20%	Table 2, Bricks and blocks	0.250
Brick	20%	Table 2, Bricks and blocks	0.250
Stone	10%	Table 2, Stone	0.111
Timber frames (beams, columns, braces)	1%	Appendix 1, Frame: timber frame	0.010
Timber floors (joists, board)	10%	Appendix 1, Floor: wooden floor	0.111
Timber formwork	10%	Table 2, Processed timber	0.111
Aluminium frames	1%	Appendix 1, Conservatories: aluminium frame	0.010
Glass	5%	Table 2, Glass	0.053
Plasterboard (for boarding)	22.5%	Table 2, Plasterboard Table 3, Boarding	0.290
Sprayed cementitious fire protection to steel	10%	Table 3, Cementitious sprays	0.111

C2 = 0.005 kgCO₂e/kg (see Table 6-4), for the transport of waste material, assumed 50 km from site by road.

Table 6-4 Default values for module C2 (Gibbons & Orr, 2020a)

EoL scenario	km by road	$ECF_{C2,i}$ (kgCO ₂ e/kg)
Reuse/recycling on site	0	0.00
Reuse/recycling elsewhere	50	0.005
		$50 \times 0.10650 \text{ gCO}_2\text{e/kg/km}/1000$
Landfill/incineration	Average between 2 closest landfill sites	0.005 (based on 50km by road)

C3-C4 = 0.013 kgCO₂e/kg (see Figure 6-7), emission during processing of the waste material.

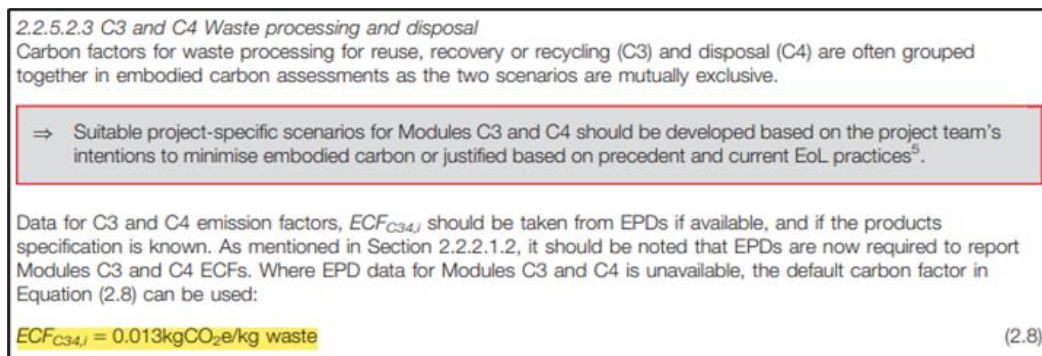


Figure 6-7 C3-C4 Waste processing values (RICS, 2017)

$$\begin{aligned} \text{Waste stage (A5w)} &= 0.250 \times (0.213 + 0.005 + 0.005 + 0.013) \\ &= 0.059 \text{ kgCO}_2\text{e/kg} \end{aligned}$$

Therefore, applying the parameters to Equation (6-2) for Wall 1

$$\text{Embodied carbon for production (A1–A3)} = 5600 \times 0.213 = 1192.8 \text{ kgCO}_2\text{e}$$

$$\text{Embodied carbon for transport (A4)} = 5600 \times 0.005 = 28 \text{ kgCO}_2\text{e}$$

$$\text{Embodied carbon for waste (A5w)} = 5600 \times 0.059 = 330.4 \text{ kgCO}_2\text{e}$$

$$\text{Total embodied carbon of bricks in Wall 1 (A1-A5w)} = 1551.2 \text{ kgCO}_2\text{e}$$

The same procedure is followed to calculate the embodied carbon of the bricks in Walls 2, 3 and 4; 735.7 kgCO₂e, 1428.8 kgCO₂e and 671.45 kgCO₂e respectively as shown in Figure 6-8. A total of ≈ 4387.13 kgCO₂e.

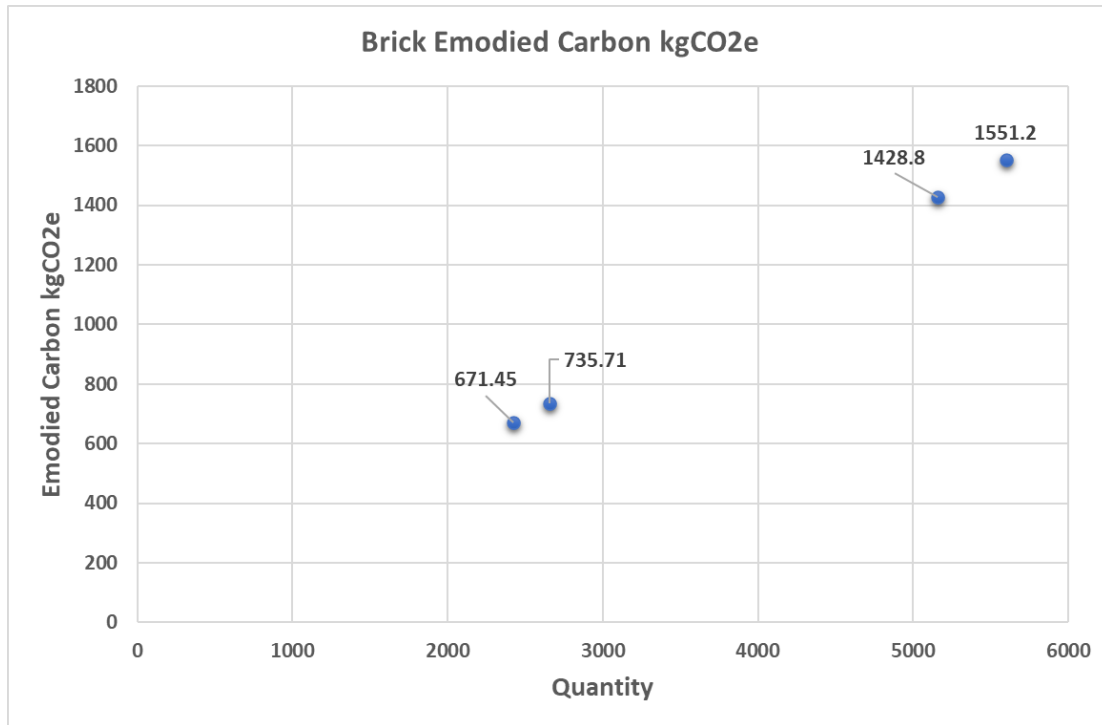


Figure 6-8 Total embodied carbon of brick walls (Author).

6.3.3.2 Embodied Carbon Footprint for Plasterboard.

- a. Mass of plasterboard: total number of sheets = 31, volume of single plasterboard sheet = $2400 \text{ mm} \times 1200 \text{ mm} \times 37.5 \text{ mm} = 0.108 \text{ m}^3$. According to Celotex PL4000 plasterboard specification, density of plasterboard is 30 kg/m^3 . So, mass of one sheet is $0.108 \times 30 = 3.24 \text{ kg}$.

In Section 4.3.3 it was shown that the number of plasterboards required for Wall 1 was 11, so mass required is $11 \times 3.24 \approx 35.6 \text{ kg}$.

Similarly, the mass of plasterboard for the other walls is: 16.2 kg , 32.4 kg and 16.2 kg respectively. Total mass of plasterboard $\approx 100 \text{ kg}$.

- b. Carbon Conversion Factors for Brick Material at Stages Listed.
 - Production stage (A1 – A3) = $0.39 \text{ kgCO}_2\text{e/kg}$ (see Table 6-5), Minimum 60% recycled content.
 - Transport stage (A4) = $0.032 \text{ kgCO}_2\text{e/kg}$ assumed nationally manufactured as shown in Table 6-2.

Table 6-5 Production embodied carbon factors (RICS, 2017).

Glass	General	Generic	1.44	Ref. 15
	Toughened	Generic	1.67	Ref. 15
Plasterboard	Partitioning/ceilings	Minimum 60% recycled content	0.39	Ref. 15
Intumescent paint	For steelwork	Amotherm Steel WB EPD	2.31	Ref. 24

- Waste stage ($A5w$) = $WF \times (A1-A3 + A4 + C2 + C34)$

Where, $WF = 0.290$ (see Table 6 3), waste factor for typical structural material.

$C2 = 0.005 \text{ kgCO}_2e/kg$ (see Table 6-4), Transporting waste material, assumed 50 km from site by road.

$C3-C4 = 0.013 \text{ kgCO}_2e/kg$ (see Figure 6-7), emission for processing the waste material.

$$\text{Wastage } (A5w) = 0.290 \times (0.39 + 0.032 + 0.005 + 0.013) = 0.128 \text{ kgCO}_2e/kg.$$

Therefore, applying the parameters to Equation (6-2) for Wall 1:

$$\text{Embodied carbon for production } (A1-A3) = 35.6 \times 0.39 = 13.88 \text{ kgCO}_2e$$

$$\text{Embodied carbon for transport } (A4) = 35.6 \times 0.032 = 1.14 \text{ kgCO}_2e$$

$$\text{Embodied carbon for waste } (A5w) = 35.6 \times 0.128 = 4.56 \text{ kgCO}_2e$$

$$\text{Embodied carbon for plasterboard in Wall 1 } (A1-A5w) = 19.58 \text{ kgCO}_2e$$

The same procedure is followed to calculate the embodied carbon of the plasterboard in Walls 2, 3 and 4; 8.91 kgCO_2e , 17.82 kgCO_2e and 8.91 kgCO_2e respectively as shown in Figure 6-9. A total of $\approx 55.22 \text{ kgCO}_2e$.

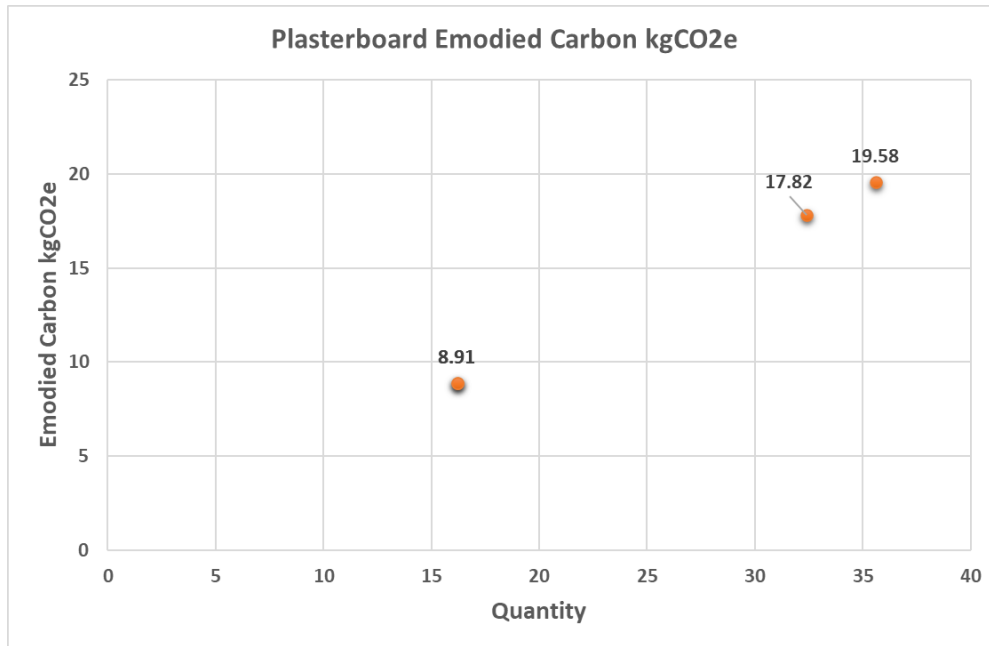


Figure 6-9 Total embodied carbon of plasterboard (Author).

6.3.3.3 A5a Site Activity:

Based on (RICS, 2017) Guide, site activity emission can be estimated. In the UK at the rate is A5a = 1400 $kgCO_2e$ per £100,000. However, the estimate is reduced by 50% for the construction of superstructure elements resulting in a rate of 700 $kgCO_2e$ per £100,000.

Here, the embodied carbon (A5a) for the total site activity = $700 \times (\text{£}90,000 / \text{£}100,000) = 630 \text{ kgCO}_2e = 0.63 \text{ tCO}_2e$

To summarize:

Overall, the embodied carbon footprint for the house, cradle–completion (A1–A5), based on one-bedroom and floor area 50 m^2 can be determined by summing the contributions of the individual embodied carbon for the materials used as follows:

- Brick (A1-A5w) = 4387.13 $kgCO_2e$
- Plasterboard (A1-A5w) = 55.22 $kgCO_2e$
- Wooden windows and door, the carbon footprints were calculated to be 327.6 $kgCO_2e$ and 241.8 $kgCO_2e$ respectively.
- Site activity (A5a) = 630 $kgCO_2e$

Therefore, applying Equation (6-1) to determine the total embodied carbon for a one-bedroom house that obtain in Table 6-6.

Table 6-6 Total embodied carbon footprint for one-bedroom house (Author).

Material	Quantity <i>kg</i>	ECF kgCO ₂ e/kg			Embodied Carbon <i>kgCO₂e</i>			Total <i>kgCO₂e</i>
		A1 - A3	A4	A5w	A1 - A3	A4	A5w	A1 - A5w
Brick wall 1	5600	0.213	0.005	0.059	1192.8	28	330.4	1551.2
wall 2	2656	0.213	0.005	0.059	565.73	13.28	156.70	735.71
wall 3	5158	0.213	0.005	0.059	1098.654	25.79	304.322	1428.8
wall 4	2424	0.213	0.005	0.059	516.31	12.12	143.02	671.45
Walls	15838	0.213	0.005	0.059	3373.49	79.19	934.44	4387.13
Plasterboard	35.6	0.39	0.032	0.128	13.884	1.14	4.56	19.58
wall 2	16.2	0.39	0.032	0.128	6.32	0.52	2.07	8.91
wall3	32.4	0.39	0.032	0.128	12.636	1.04	4.15	17.82
wall4	16.2	0.39	0.032	0.128	6.32	0.52	2.07	8.91
Walls	100.4	0.39	0.032	0.128	39.16	3.21	12.85	55.22
Windows and door								569.4
							A1-A5w Total	5011.75
Site activity							A5a	630
						Total embodied Carbon		5641.75

Total embodied carbon result for a one-bedroom house (A1–A5) = **5641.75 kgCO₂e**.

The embodied carbon per square meter of floor area is: 5641.75 kgCO₂e / 50 m²
= 112.84 kgCO₂e/m²

The embodied carbon emission of 112.84 *kgCO₂e/m²* for this one-bedroom house is relatively low compared to the embodied carbon benchmark of 500 *kgCO₂e/m²*. This means that the house was constructed using materials and methods that have a lower environmental impact. Figure 6-10 presents the embodied carbon benchmark which is a tool that can be used to assess the environmental impact of a building. It is based on the average embodied carbon emissions of buildings in a particular region.

Cradle to grave (A1-A4, B4-B5, C1-C4)	kg CO ₂ e/m ²
(< 200) A	112.84
(200-320) B	
(320-440) C	
(440-560) D	
(560-680) E	
(680-800) F	
(> 800) G	

Figure 6-10 Embodied carbon benchmark (Pasanen & Castro, 2019)

6.3.4 Embodied Carbon Footprint Results in a BIM Environment (BIM Collaborate Pro Software)

The embodied carbon calculation results will be imported from Excel to Revit model via the Revit plugin application TableGen in four steps, as follows:

1. In Excel, highlight the cells and information that need to be included in the Revit model. Then, Click Page Layout > Print Area as shown in Figure 6-11.

2. In Revit, under the DiRoots tab, double-click TableGen to collapse it as shown in Figure 6-12.
3. Select “add tables” tab, it will go to the Excel file, then click on docs. In this case the information automatically unfolds itself by worksheet, as “Sheet1” and worksheet region is the “Print_Area” as it has been saved in Excel, as indicated in Figure 6-13.
4. Click “Apply” to confirm the selected file, return to the schedule to see if a sheet, “Sheet 01”, has been added in Revit. Subsequently, the information when it comes through can be seen exactly as it appears in Excel, as shown in Figure 6-14.

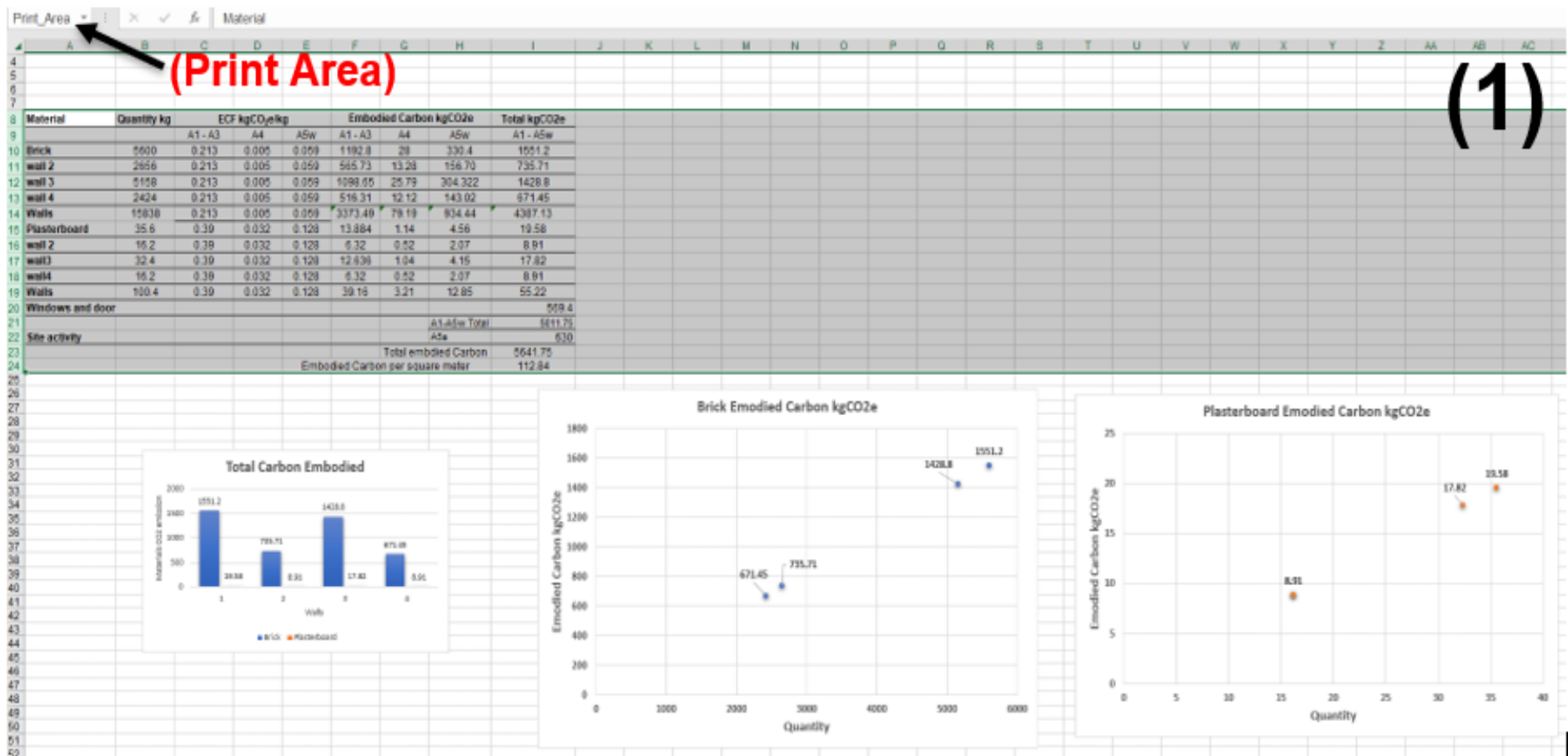


Figure 6-11 (1) TableGen application to Integrate calculation into Revit (Author).



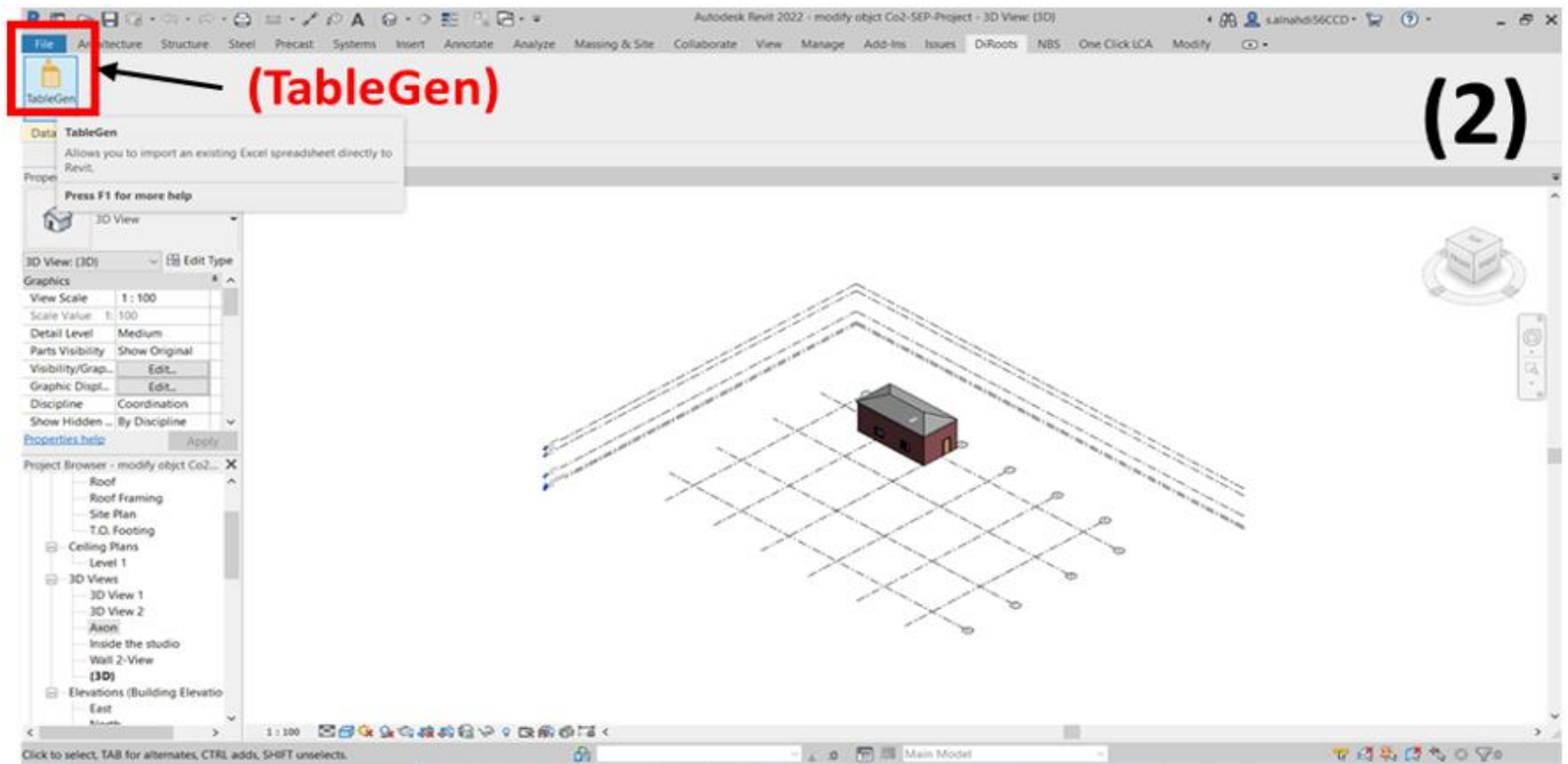


Figure 6-12 (2) TableGen application to Integrate calculation into Revit (Author).



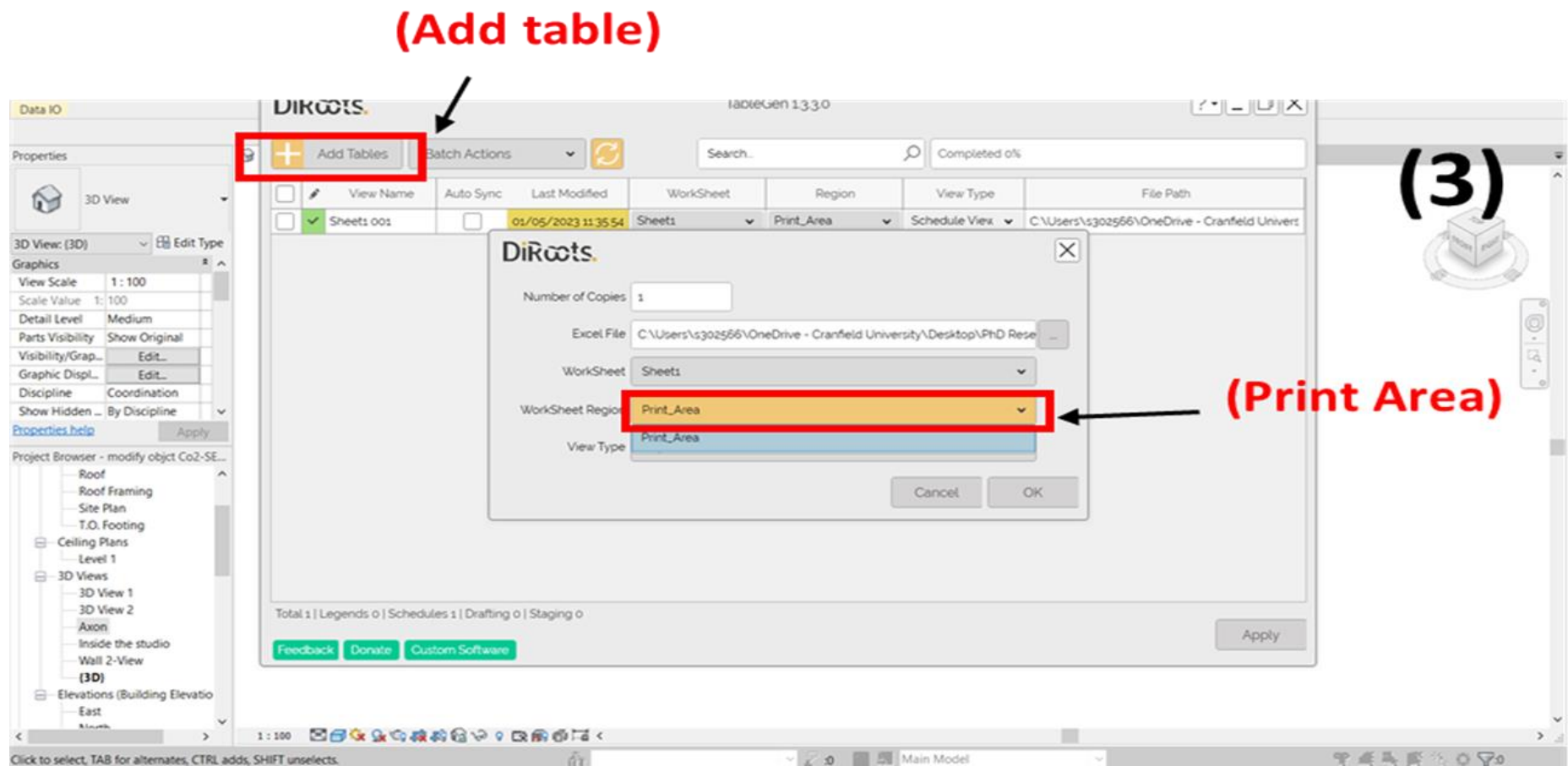


Figure 6-13 (3) TableGen application to Integrate calculation into Revit (Author).



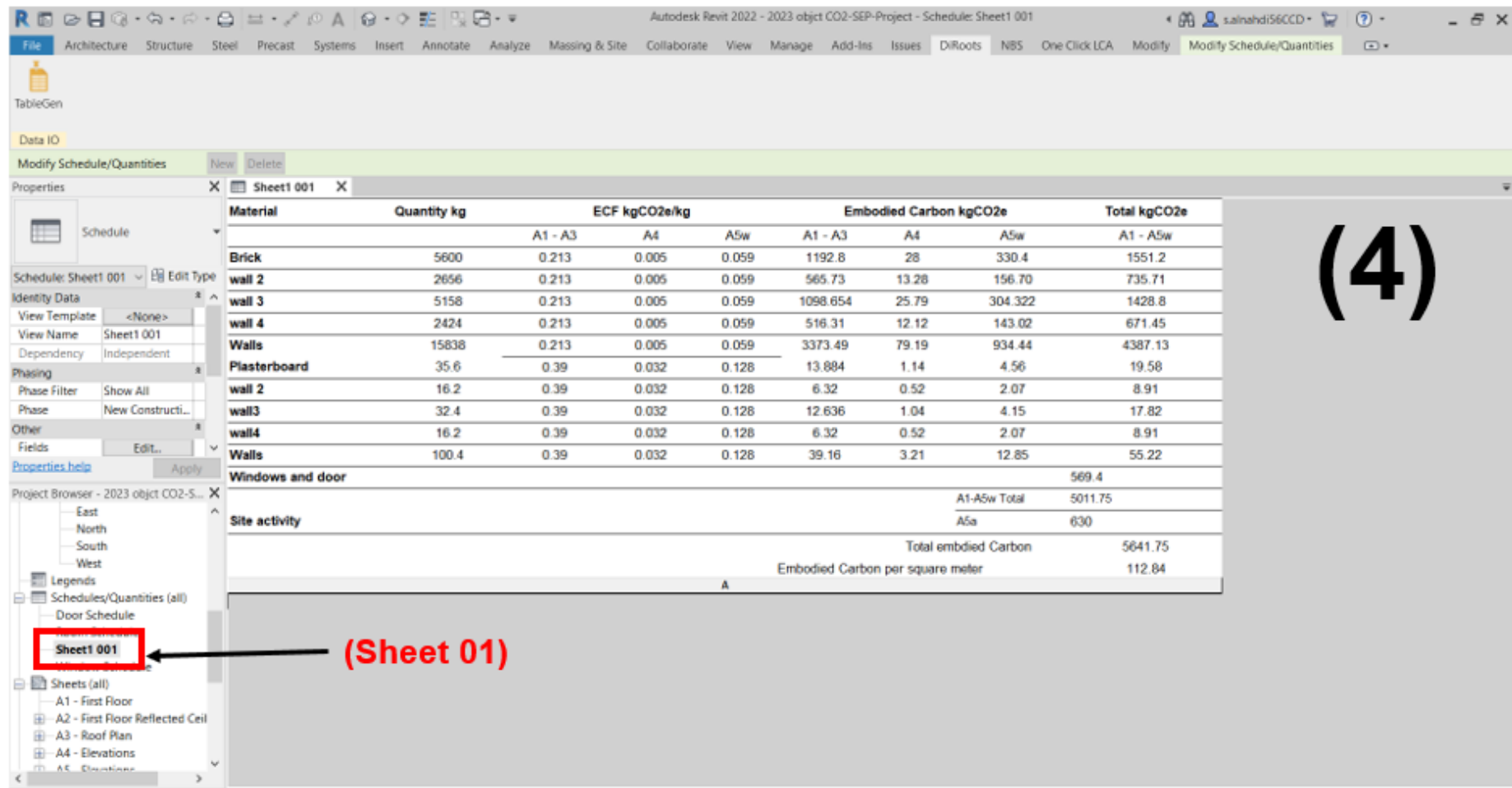


Figure 6-14 (4) TableGen application to Integrate calculation into Revit (Author).

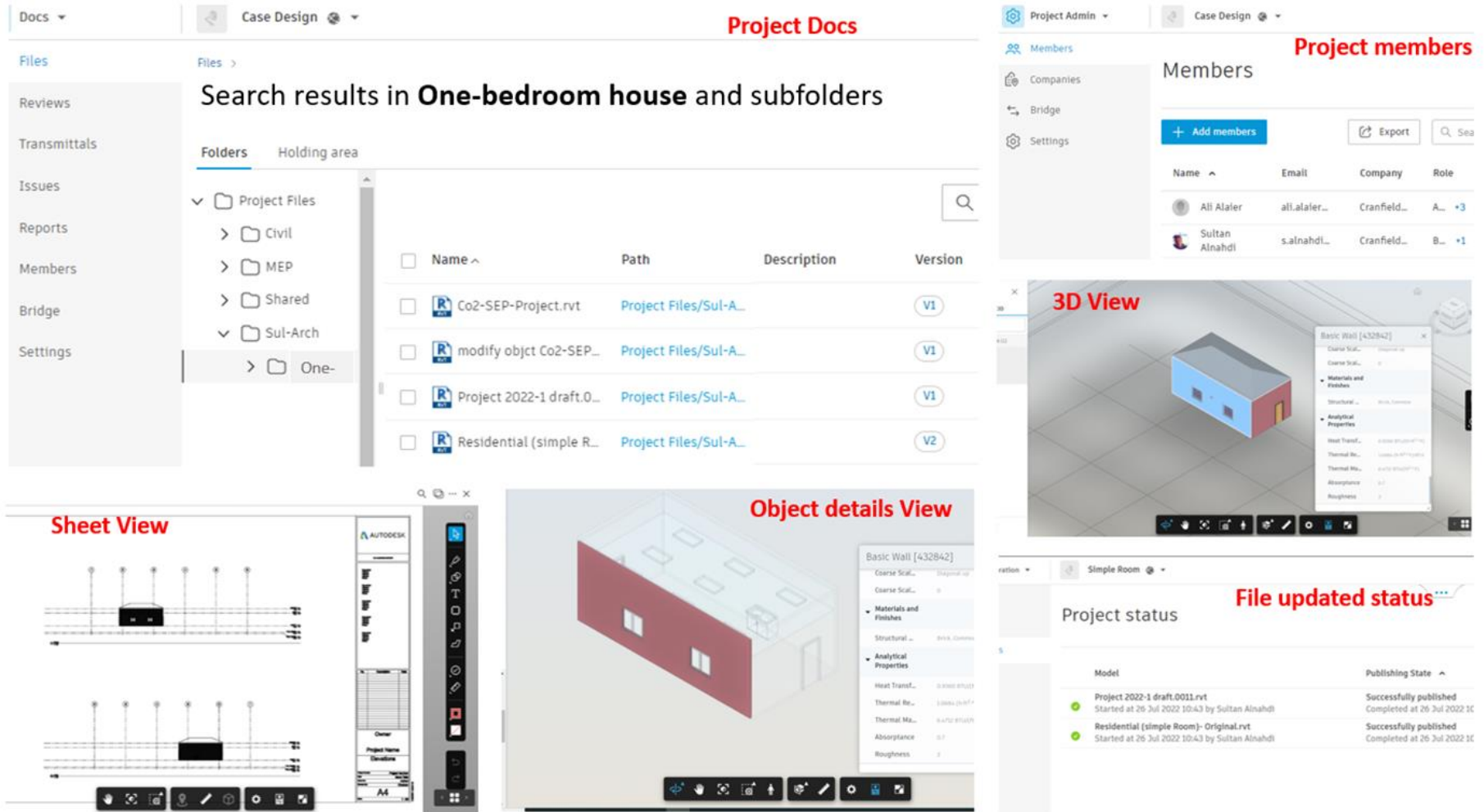


Figure 6-15 overview of one-bedroom house project in BIM (Author).

Figure 6-15 illustrate the case study of one-bedroom house project in BIM Collaborate Pro which utilize the collaborative features of BIM as explain as follows:

Project Docs: Different documents and files can be uploaded in Case Design, here we show the project of a one-bedroom house, see Figure 6-16. The platform is designed to cope with various types of files and documents related to the construction project.

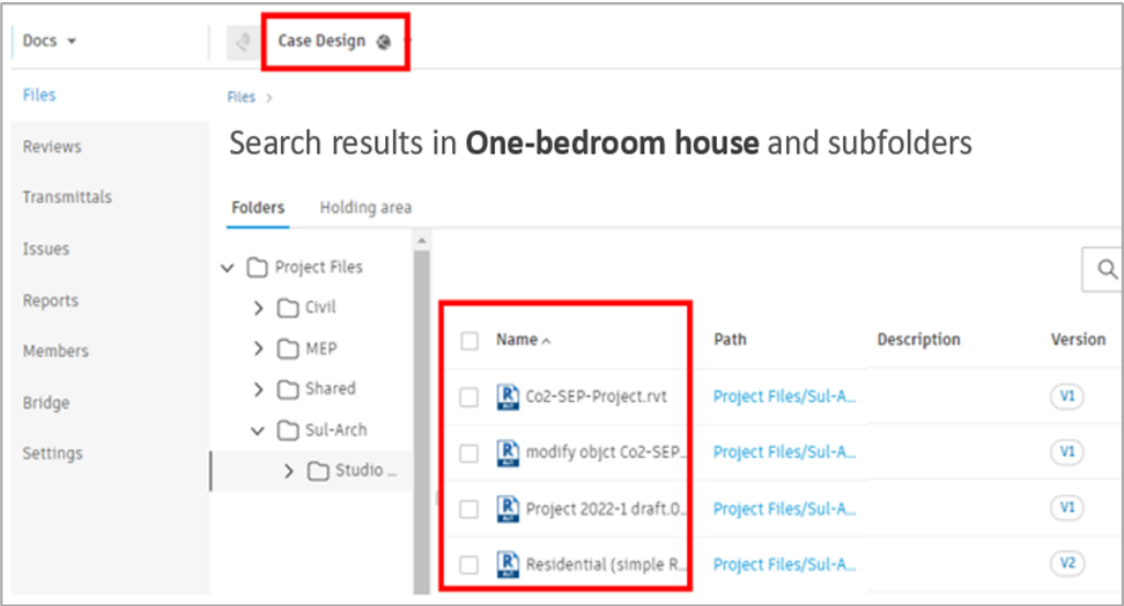


Figure 6-16 Project Docs view (Author).

Project members: The project members involved are listed in project admin information, such as, Project Manager, architects and engineers. It allows the project manager to invite and add more team members, assign specific roles and permissions, and define their access levels to project documents and models (see Figure 6-17).

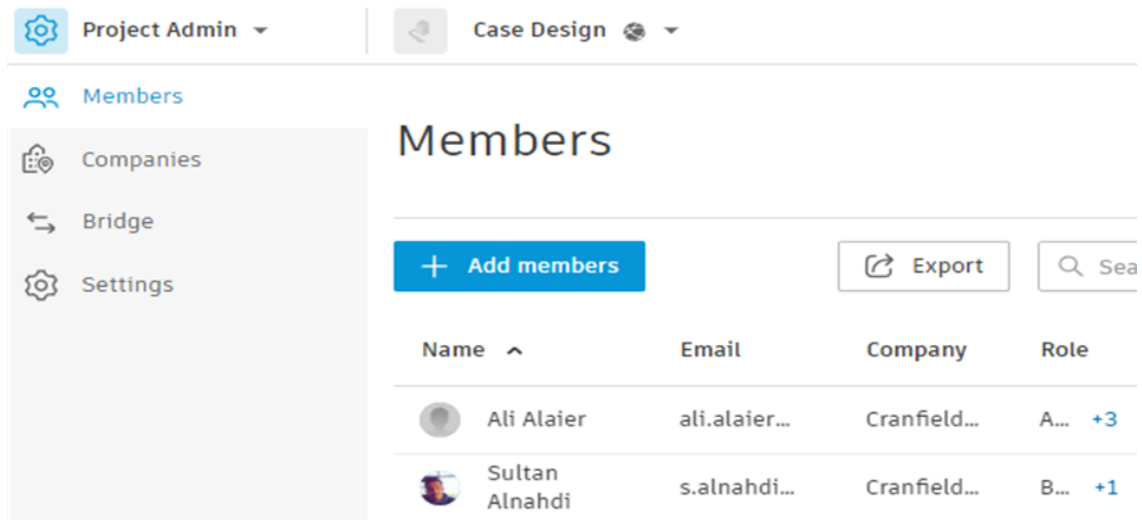


Figure 6-17 Project Members (Author).

3D view: 3D visualisation and specific details of the object in BIM Collaborate Pro are presented in Figure 6-18 and Figure 6-19. The 3D model provides a detailed and accurate representation of the building, including its layout, materials, and systems. BIM Collaborate Pro also allows users to view and edit the properties of individual objects in the 3D model, such as materials, dimensions, and system information.

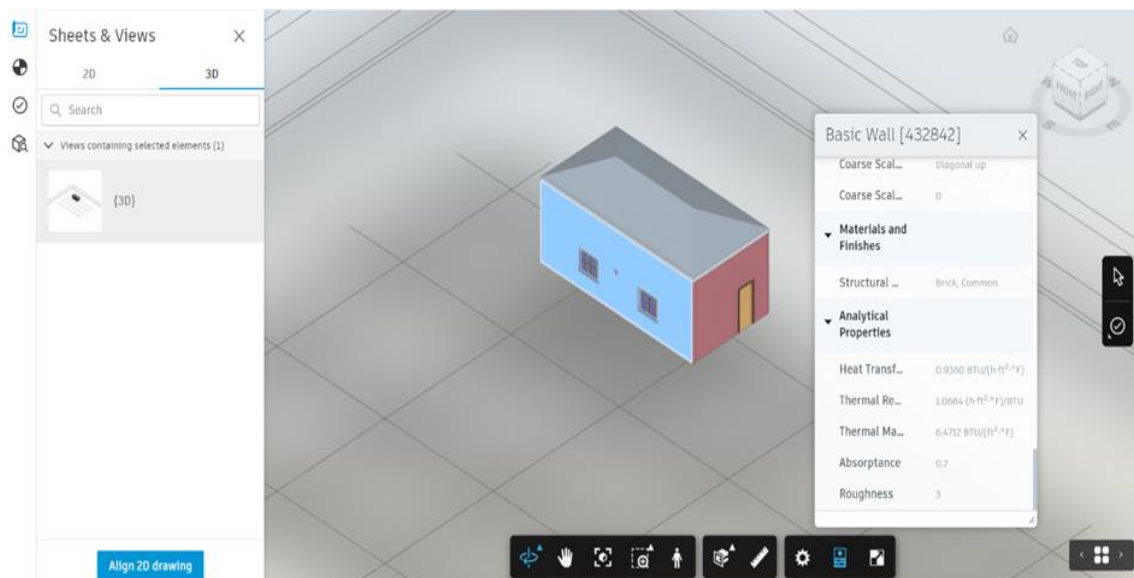


Figure 6-18 3D Model view (Author).

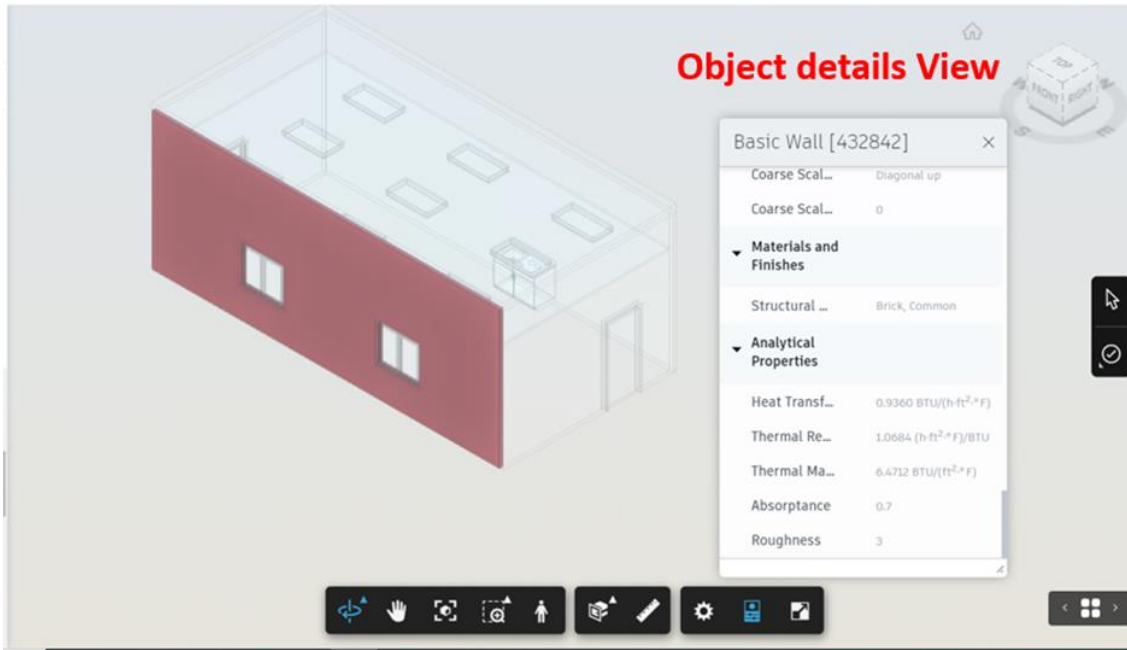


Figure 6-19 Object Properties (Author).

Sheet view: It allows the project members to navigate between different sheets in the project, such as floor plans, elevations, and sections, using a simple and intuitive interface. It can be easily switch between sheets and zoom in and out to view specific areas of interest (see Figure 6-20).

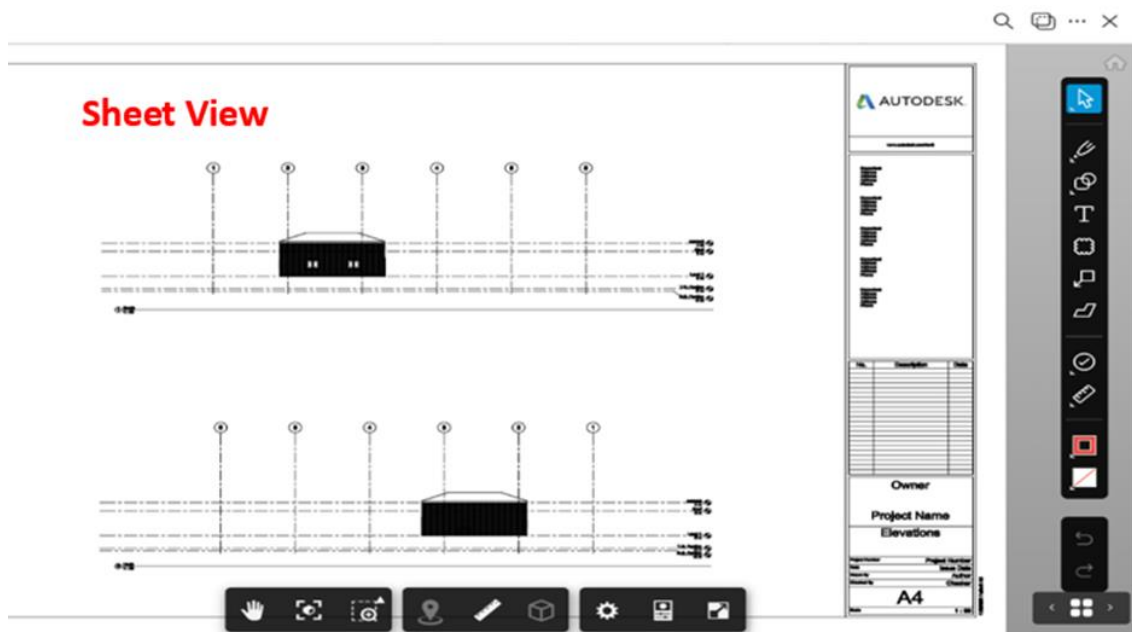


Figure 6-20: The Side Elevation view (Author).

The data can be edited and managed in TableGen, which can perform a wide range of operations, such as sorting, filtering, and calculating values. Also, it can edit the data directly, and any changes made will be marked in the original schedule view in BIM. The schedule view of the embodied carbon result can be uploaded and shared for collaborative actions by members on the project (see Figure 6-21). By using TableGen to manage and view schedule data in BIM, it is possible for the stakeholders to gain greater control over the project schedule and make better informed decisions based on up-to-date data.

Material	Quantity kg	ECF kgCO2e/kg			Embodied Carbon kgCO2e			Total kgCO2e
		A1 - A3	A4	A5w	A1 - A3	A4	A5w	
Brick	5600	0.213	0.005	0.059	1192.8	28	330.4	1551.2
wall 2	2656	0.213	0.005	0.059	565.73	13.28	156.70	735.71
wall 3	5158	0.213	0.005	0.059	1098.654	25.79	304.322	1428.8
wall 4	2424	0.213	0.005	0.059	516.31	12.12	143.02	671.45
Walls	15838	0.213	0.005	0.059	3373.49	79.19	934.44	4387.13
Plasterboard	35.6	0.39	0.032	0.128	13.884	1.14	4.56	19.58
wall 2	16.2	0.39	0.032	0.128	6.32	0.52	2.07	8.91
wall3	32.4	0.39	0.032	0.128	12.636	1.04	4.15	17.82
wall4	16.2	0.39	0.032	0.128	6.32	0.52	2.07	8.91
Walls	100.4	0.39	0.032	0.128	39.16	3.21	12.85	55.22
Windows and door								569.4
							A1-A5w Total	5011.75
							A5a	630
Site activity								
							Total embdied Carbon	5641.75
							Embodied Carbon per square meter	112.84

Figure 6-21 A screenshot presenting the embodied carbon result in BIM environment (Author).

Project status: It shows the state of the model when it is updated by any of the project members, making it visible to other members, as illustrated in Figure 6-22.

Project status		File updated status
Model		Publishing State ^
Project 2022-1 draft.0011.rvt	Started at 26 Jul 2022 10:43 by Sultan Alnahdi	Successfully published Completed at 26 Jul 2022 10:43
Residential (simple Room)- Original.rvt	Started at 26 Jul 2022 10:43 by Sultan Alnahdi	Successfully published Completed at 26 Jul 2022 10:43

Figure 6-22 Project Status (Author)

6.4 Closing Remarks

This chapter has presented a framework that integrates key asset information, the construction value chain, the construction sustainability library, required engineering calculations, and the BIM environment, with the objective of improving the sustainability of construction projects. The framework has been designed in a user-friendly manner to enable easy implementation and calculation by individuals and companies, while also ensuring transparency and accessibility of data to all stakeholders involved in the construction process. This study presented a generic framework which has the potential to bring significant positive changes to addressing sustainability issues in the construction industry. Finally, the framework developed was validated by the case study of designing a one-bedroom house and calculating the amount of embodied carbon, considered the key sustainability issue.

The validation process in this research aimed to confirm that the proposed framework effectively served its purpose in improving the sustainability of construction projects, with a focus on embodied carbon calculations. It involved practical application in a case study, comparison with sustainability standards, evaluation, and potential refinement. This validation helps establish the framework as a valuable tool for the construction industry.

The next chapter will present the conclusion of the research, aim and objectives, highlighting the contribution to knowledge. In addition, it will discuss possible future work.

7 DISCUSSIONS, CONTRIBUTION TO KNOWLEDGE, CONCLUSION AND FUTURE WORK

7.1 Introduction

The thesis concludes with Chapter 7. Section 7.2 presents a discussion of the research findings; this is followed by Section 7.3 which presents the contribution to knowledge made by the present research project and the research limitations. Sections 7.4 and 7.5 highlight the conclusions drawn and suggest relevant future research respectively.

7.2 Discussion

Currently, BIM plays a crucial role in driving digital transformation within the construction industry. Sustainability is an important issue for the construction sector, but has not yet been incorporated into BIM strategies due to a lack of knowledge and available applications. Hence, the subject matter discussed in this thesis is regarded as a significant advancement towards establishing a comprehensive understanding of sustainable construction projects based on a BIM environment.

The research methodology consisted of several key components that contributed to the overall investigation into construction sustainability practices and their integration with BIM. It included a literature review, BIM investigation, case study, sustainability issues, engineering calculations, framework development, and practical validation. By adopting this methodology, the study aimed to contribute to the understanding and implementation of sustainable practices within BIM in the construction industry.

The literature review was an important chapter of this thesis. It focused on conducting extensive research on sustainable practices in the construction sector, reviewing current literature, case studies, and reports from reputable sources. Importantly, a clear definition of what sustainability means in the context of the construction sector was established. This helped to guide the investigation and ensure that all findings are consistent with the established definition. In addition, the key stakeholders in the construction sector who have an interest in

sustainability were identified, such as government bodies, construction companies, architects, engineers, and building owners. Then interviews were conducted with different parties in the construction industry to gather their perspectives on sustainable practices and issues in the construction sector. Finally, it has promoted best practices based on the literature review and interviews.

BIM can be used in sustainable construction to evaluate the environmental impact of design decisions, simulate building performance, and identify areas for improvement to meet sustainability goals. The literature review also highlighted how the full implementation of BIM level 2 would improve collaboration and reduce errors and misunderstandings between stakeholders. The construction industry is showing interest in implementing full collaboration via level 3 in BIM, which involves the use of real-time data exchange between all stakeholders.

However, there are a number of challenges that the construction industry faces in moving towards BIM level 3. One is that not all the stakeholders in the construction value chain realise the importance of collaboration in a BIM environment. Many participants in the construction value chain have a lack of awareness, and insufficient understanding, of the capabilities and advantages of BIM, that complete adoption of BIM will achieve more effective collaboration and improved integration. Another important challenge is the lack of standards regarding sustainability in the construction industry.

After examining the literature an issue was identified regarding lack of standardized information within BIM objects, which can unnecessarily complicate collaboration in construction projects. The most viable solution for this problem is to utilize the BIM model as a central source accessible to all parties involved in the project. The literature review also encompassed various technical aspects of BIM, including administration, technology, geometry, and the standardization of ISO19650. Additionally, the review explores past concerns related to sustainability in the BIM environment and highlights numerous advantages and potential benefits of integrating sustainability into BIM.

The first key finding concerned the construction materials of a hypothetical case study of one-bedroom, single-storey house. This key finding focused on the examination of construction materials and methods employed. This served as a valuable starting point for further exploration regarding sustainability issues relating to heat transferred through the building fabric out of the house and to the external environment. This study aimed to gain a deeper understanding of the thermal performance and energy efficiency of the house, thereby contributing to the broader examination of sustainability issues in the construction industry. This case study showcased the practical application of sustainability principles, specifically in relation to energy management and thermal performance. By examining the concept of heat transfer and evaluating different material options, the case study demonstrated how sustainable decision-making can reduce energy consumption, enhance energy efficiency, and mitigate the environmental impact of a construction project. Overall, this key finding served as a crucial stepping stone towards the development of a comprehensive framework for presenting and addressing construction sustainability issues within the BIM environment.

Another key finding focused on the framework shown in Figure 6-1 for integrating sustainability issues within the BIM environment, describing two key stages that facilitate the incorporation of sustainability principles into the construction value chain. The first stage entails the management of project-related information and the construction value chain. Moving on to the second stage, the emphasis shifts towards tackling different sustainability concerns and conducting engineering calculations for each one. This is done to establish a seamless and interconnected connection with the CAD-Revit and BIM database.

The effectiveness of the framework for integrating sustainability was also evaluated by applying it to assess the embodied carbon footprint of the one-bedroom house in a BIM environment as shown in Figure 6-2. The evaluation offers the following implications and benefits:

1. Enhanced Decision-making: The evaluation of how to minimize embodied carbon emissions enables informed decision-making regarding material selection, construction techniques, and supply chain optimization.
2. Improved Carbon Performance: The framework allows for the identification and quantification of embodied carbon, facilitating the optimization of design choices to reduce carbon emissions associated with the construction process.
3. Stakeholder Collaboration: The integrated BIM environment fosters collaboration among and between stakeholders, ensuring a collective effort towards reducing embodied carbon and achieving sustainability goals.
4. Knowledge Transfer and Learning: The evaluation of the framework encourages knowledge transfer and learning within the construction industry. By implementing the framework and sharing the findings of the evaluation, stakeholders can disseminate best practices, lessons learned, and innovative approaches to reducing embodied carbon. This promotes continuous improvement and contributes to the overall advancement of sustainable construction practices.
5. Lifecycle Perspective: By evaluating the embodied carbon footprint within a BIM environment, a comprehensive lifecycle perspective is achieved. This includes considering carbon emissions during construction, as well as throughout the building's life cycle, informing decisions on renovation, operation, and end-of-life scenarios.

The framework introduced in Figure 6-1 represents a novel approach to integrating sustainability principles into the construction value chain within a BIM environment. This implies that it offers a fresh perspective and innovative methodology for addressing sustainability concerns in construction. The framework's significance lies in its potential to bring about significant positive changes in the construction industry by seamlessly incorporating sustainability principles. It acknowledges the growing importance of sustainability and the need

for robust solutions within the BIM environment. Furthermore, the description of the framework's two stages, one focusing on project information and the construction value chain and the other on sustainability concerns and engineering calculations, suggests a rigorous approach. This implies that the framework was developed with careful consideration of the various components and processes involved in integrating sustainability.

7.3 Contributions to Knowledge

The following are the key contributions to knowledge made by this research: -

1. The research uncovered a critical deficiency in the current BIM level 2 object structure has shown a lack of sustainability data. It underscored the imperative of incorporating vital sustainability aspects into BIM objects, such as heat transfer and embodied carbon footprint, illuminating crucial areas for improvement.
2. This study introduced a pioneering and versatile framework poised to catalyse substantial positive transformations in addressing sustainability challenges within the BIM environment. It established an integrated platform harmonizing project information, the BIM database, stakeholders across the value chain, a comprehensive library of construction sustainability issues, and their associated engineering calculations. Furthermore, it forged a seamless connection by integrating sustainability calculation results directly into the BIM database, promising a paradigm shift in sustainable construction practices.
3. The study made a compelling case for embedding construction sustainability considerations within the BIM environment. It advocated for the development of specialized software to enable seamless sustainability calculations, positioning BIM as a transformative tool for sustainability in construction.

7.4 Conclusions:

1. Construction sustainability issues have been studied for many years however, little has been done within the BIM environment. The research reported in this thesis has contributes to addressing this knowledge gap.
2. It is important to have a thorough understanding of construction sustainability issues and related engineering calculations in order to address and integrate them into the BIM environment.
3. The engineering calculations concerning construction sustainability issues have many different variables and parameters, and these should be taken directly from a BIM database if the different BIM objectives are to be fully met.
4. In order to achieve an integrated framework to address construction sustainability issues in a BIM environment, the following elements are needed; project information, BIM database, the construction value chain, sustainability library and related engineering calculation equations as well as the provision of the required data needed for the engineering calculations.
5. The validation case study of embodied carbon footprint of a one-bedroom house has demonstrated the effectiveness and the practicability of a construction sustainability framework within the BIM environment.
6. Revit was used to create a 3D model of the one-bedroom house, while BIM was used to create a database of information about the house. This demonstrated how a model would be shared between stakeholders to improve the quality of the house, identify potential problems, and track the progress of the project.
7. BIM Collaborate Pro is a cloud-based BIM platform, which provided a central location for the information regarding the one-bedroom house and could be extended to all types of construction project. Thus, the embodied

carbon results for different objects of the house can be visualized in 3D for all stakeholders involved in value chain within BIM Collaborate Pro.

The research has added fundamental aspects in the integration of sustainability considerations within BIM environment. Traditionally, BIM primarily focuses on the geometric and physical aspects of a construction project. However, in this study, the framework has been developed to incorporate sustainability as a core aspect of the BIM process. In addition, the framework involves the integration of stakeholders within the value chain. Moreover, The inclusion of a library of construction sustainability issues. Finally, the integration of sustainability calculation results into the BIM database represents a significant change. This ensures that the sustainability data is not isolated but becomes an integral part of the project's information.

7.5 Future Works

The framework for integrating sustainability issues in a BIM environment provides a solid foundation for future research work. Here are some potential areas for further exploration:

- This research presented a limited list of construction sustainability issues. However, a more comprehensive list needs to be compiled to cover all common aspects of construction sustainability issues.
- The automation of engineering calculations concerning sustainability issues within the BIM environment is a promising area for future research. By developing automated tools and algorithms, researchers can streamline the process of assessing sustainability factors, such as embodied carbon.
- The parameters of the construction engineering calculation equations could be taken directly from the BIM database if the right advanced micro coding could be established between the Excel spreadsheet and BIM database.

- Modifying the structure of BIM objects could help to better represent sustainability issues. However, that would require access to the source code of the BIM database which is currently under the control of BIM software houses.
- BIM technology requires specialized skills and knowledge, and the process of adding detailed technical data to the BIM model can be complex. Therefore, there is a need for a BIM developer who is responsible for creating, maintaining, and managing the BIM model.
- The framework has been tested and validated in one case study, but it is important to further test and validate it in a wider range of cases. This will help to ensure that the framework is effective and reliable in a variety of settings.
- There is a need to develop a standard for storing sustainability information in the BIM model. It is important to address this issue, as clear established standards will make it easier to share and use sustainability information across different projects and organizations.
- There is a need to emphasize the role of government in expanding the use of BIM to achieve sustainability in the construction industry and the design of sustainable buildings.

8 REFERENCES

- Abbas, M. A., Ajayi, S. O., Oyegoke, A. S., & Alaka, H. (2022). A cloud-based collaborative ecosystem for the automation of BIM execution plan (BEP). *Journal of Engineering, Design and Technology*. <https://doi.org/10.1108/JEDT-02-2022-0128>
- Abbasnejad, B., Nepal, M. P., Ahankoob, A., Nasirian, A., & Drogemuller, R. (2020). Building Information Modelling (BIM) adoption and implementation enablers in AEC firms: a systematic literature review. *Architectural Engineering and Design Management*, 1–23. <https://doi.org/10.1080/17452007.2020.1793721>
- Abdel-Hamid, M., & Abdelhaleem, H. M. (2021). Project cost control using five dimensions building information modelling. *International Journal of Construction Management*, 0(0), 1–10. <https://doi.org/10.1080/15623599.2021.1880313>
- Abdulkadir Ganah, & Godfaurd A. John. (2015). An Overview of the Feasibility of Achieving Level 2 Building Information Modeling by 2016 in the UK. *Journal of Civil Engineering and Architecture*, 9(8). <https://doi.org/10.17265/1934-7359/2015.08.001>
- Ahuja, R., Sawhney, A., Jain, M., Arif, M., & Rakshit, S. (2020). Factors influencing BIM adoption in emerging markets – the case of India. *International Journal of Construction Management*, 20(1), 65–76. <https://doi.org/10.1080/15623599.2018.1462445>
- Ajayi, S. O., Oyedele, L. O., & Ilori, O. M. (2019). Changing significance of embodied energy: A comparative study of material specifications and building energy sources. In *Journal of Building Engineering* (Vol. 23, pp. 324–333). <https://doi.org/10.1016/j.jobbe.2019.02.008>
- Akadiri, P. O., Chinyio, E. A., & Olomolaiye, P. O. (2012). Design of A Sustainable Building: A Conceptual Framework for Implementing Sustainability in the

- Building Sector. *Buildings*, 2(2), 126–152.
<https://doi.org/10.3390/buildings2020126>
- Al Hattab, M. (2021). The dynamic evolution of synergies between BIM and sustainability: A text mining and network theory approach. *Journal of Building Engineering*, 37(January). <https://doi.org/10.1016/j.jobe.2021.102159>
- Ali, M. (2020). *Solutions for Chapter 4 Steady Heat Conduction Solutions for Chapter 4 Steady Heat Conduction Dr . Mohammad Ali Department of Electrical & Electronic EngineeringTel , University of Nottingham Malaysia Campus Jalan Broga , 43500 Semenyih , Selangor Darul E. July.* <https://doi.org/10.13140/RG.2.2.31141.12003>
- Al-Osta, M. A., Al-Tamimi, A. S., Al-Tarbi, S. M., Baghabra Al-Amoudi, O. S., Al-Awsh, W. A., & Saleh, T. A. (2022). Development of sustainable concrete using recycled high-density polyethylene and crumb tires: Mechanical and thermal properties. *Journal of Building Engineering*, 45(October 2021). <https://doi.org/10.1016/j.jobe.2021.103399>
- Al-Saeed, Y., Edwards, D. J., & Scaysbrook, S. (2020). Automating construction manufacturing procedures using BIM digital objects (BDOs): Case study of knowledge transfer partnership project in UK. *Construction Innovation*, 20(3), 345–377. <https://doi.org/10.1108/CI-12-2019-0141>
- Amro, D. K., & Alibaba, H. Z. (2020). *The Effects of Flooring Material on Thermal Comfort in a Comparative Study Marble and Parquet Flooring.*
- Antón, L. Á., & Díaz, J. (2014). 9998219. 8(5), 1378–1382.
- Arantes, A., Ferreira, L. M. D. F., & Costa, A. A. (2015). Is the construction industry aware of supply chain management? The Portuguese contractors' perspective. *Supply Chain Management*, 20(4), 404–414. <https://doi.org/10.1108/SCM-06-2014-0207>
- Aryani, A. L., Brahim, J., & Fathi, M. S. (2014). The development of building information modeling (BIM) definition. *Applied Mechanics and Materials*, 567, 625–630. <https://doi.org/10.4028/www.scientific.net/AMM.567.625>

- Awadh, O. (2017a). Sustainability and green building rating systems: LEED, BREEAM, GSAS and Estidama critical analysis. *Journal of Building Engineering*, 11, 25–29. <https://doi.org/10.1016/j.jobe.2017.03.010>
- Awadh, O. (2017b). Sustainability and green building rating systems: LEED, BREEAM, GSAS and Estidama critical analysis. *Journal of Building Engineering*, 11, 25–29. <https://doi.org/10.1016/j.jobe.2017.03.010>
- Baik, A., Alitany, A., Boehm, J., & Robson, S. (2014). Jeddah historical building information modeling “JHBIM”-object library. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 2(5), 41–47. <https://doi.org/10.5194/isprsannals-II-5-41-2014>
- Bamgbade, J. A., Kamaruddeen, A. M., & Nawi, M. N. M. (2017). Malaysian construction firms’ social sustainability via organizational innovativeness and government support: The mediating role of market culture. *Journal of Cleaner Production*, 154, 114–124. <https://doi.org/10.1016/j.jclepro.2017.03.187>
- Bauer, M., Mösele, P., & Schwarz, M. (2010). Green building: Guidebook for sustainable architecture. In *Green Building: Guidebook for Sustainable Architecture*. Springer Berlin Heidelberg. <https://doi.org/10.1007/978-3-642-00635-7>
- Begić, H., & Galić, M. (2021). A systematic review of construction 4.0 in the context of the BIM 4.0 premise. *Buildings*, 11(8). <https://doi.org/10.3390/BUILDINGS11080337>
- Bellido-Montesinos, P., Lozano-Galant, F., Castilla, F. J., & Lozano-Galant, J. A. (2019). Experiences learned from an international BIM contest: Software use and information workflow analysis to be published in: *Journal of Building Engineering*. *Journal of Building Engineering*, 21(May 2018), 149–157. <https://doi.org/10.1016/j.jobe.2018.10.012>
- BIM object - Designing Buildings*. (2022). https://www.designingbuildings.co.uk/wiki/BIM_object

- Blay, K. B., Tuuli, M. M., & France-Mensah, J. (2019). Managing change in BIM-Level 2 projects: benefits, challenges, and opportunities. *Built Environment Project and Asset Management*, 9(5), 581–596. <https://doi.org/10.1108/BEPAM-09-2018-0114>
- Borges Viana, V. L., & Marques Carvalho, M. T. (2021). Prioritization of risks related to BIM implementation in brazilian public agencies using fuzzy logic. *Journal of Building Engineering*, 36(December 2020), 102104. <https://doi.org/10.1016/j.jobbe.2020.102104>
- Brick Development Association. (2018). *Mortar for Brickwork*. January, 15. <https://www.brick.org.uk/admin/resources/mortar-for-brickwork.pdf>
- Bridson, P. B., Stoner, J. M. S., Fransen, M. H., & Ireland, J. (2020). The aquaculture sustainability continuum – Defining an environmental performance framework. *Environmental and Sustainability Indicators*, 8(July), 100050. <https://doi.org/10.1016/j.indic.2020.100050>
- BSI PAS 1192-2. (2013). Specification for information management for the capital/delivery phase of construction projects using building information modelling. *BSI Standards Publication*, 1(March), 1–44. <http://www.hfms.org.hu/web/images/stories/PAS/PAS1192-2-BIM.pdf>
http://www.bimireland.ie/wp-content/uploads/2015/08/BSI_PAS_1192_2_2013.pdf
- Butkovic, B., & Oloke, D. (2019). Butkovic et al., pg. 256 construction projects. *Journal of Information Technology in Construction (ITcon)*, 24(March), 257. <http://www.itcon.org/2019/14>
- Carvalho, J. P., Almeida, M., Bragança, L., & Mateus, R. (2021). Bim-based energy analysis and sustainability assessment—application to portuguese buildings. *Buildings*, 11(6), 1–25. <https://doi.org/10.3390/buildings11060246>
- Carvalho, J. P., Bragança, L., & Mateus, R. (2019). Optimising building sustainability assessment using BIM. *Automation in Construction*,

- 102(September 2018), 170–182.
<https://doi.org/10.1016/j.autcon.2019.02.021>
- Cavalliere, C., Habert, G., Dell’Osso, G. R., & Hollberg, A. (2019). Continuous BIM-based assessment of embodied environmental impacts throughout the design process. *Journal of Cleaner Production*, 211, 941–952.
<https://doi.org/10.1016/j.jclepro.2018.11.247>
- Celotex. (2011). *Celotex PL4000*. 3, 5–6.
[http://www.grmltd.co.uk/Literature/PL4000 product datasheet.pdf](http://www.grmltd.co.uk/Literature/PL4000%20product%20datasheet.pdf)
- Chahrour, R., Hafeez, M. A., Ahmad, A. M., Sulieman, H. I., Dawood, H., Rodriguez-Trejo, S., Kassem, M., Naji, K. K., & Dawood, N. (2021). Cost-benefit analysis of BIM-enabled design clash detection and resolution. *Construction Management and Economics*, 39(1), 55–72.
<https://doi.org/10.1080/01446193.2020.1802768>
- Chan, E., & Lee, G. K. L. (2008). Critical factors for improving social sustainability of urban renewal projects. *Social Indicators Research*, 85(2), 243–256.
<https://doi.org/10.1007/s11205-007-9089-3>
- Charef, R. (2022). The use of Building Information Modelling in the circular economy context: Several models and a new dimension of BIM (8D). *Cleaner Engineering and Technology*, 7, 100414.
<https://doi.org/10.1016/j.clet.2022.100414>
- Charef, R., Alaka, H., & Emmitt, S. (2018). Beyond the third dimension of BIM: A systematic review of literature and assessment of professional views. *Journal of Building Engineering*, 19(April), 242–257.
<https://doi.org/10.1016/j.jobbe.2018.04.028>
- Charles J. Kibert. (2016). *Sustainable Construction*.
- Chiang, C. T., Chu, C. P., & Chou, C. C. (2015). BIM-enabled Power Consumption Data Management Platform for Rendering and Analysis of Energy Usage Patterns. *Procedia Engineering*, 118, 554–562.
<https://doi.org/10.1016/j.proeng.2015.08.480>

- Chong, H. Y., Lee, C. Y., & Wang, X. (2017a). A mixed review of the adoption of Building Information Modelling (BIM) for sustainability. *Journal of Cleaner Production*, 142, 4114–4126. <https://doi.org/10.1016/j.jclepro.2016.09.222>
- Chong, H. Y., Lee, C. Y., & Wang, X. (2017b). A mixed review of the adoption of Building Information Modelling (BIM) for sustainability. *Journal of Cleaner Production*, 142, 4114–4126. <https://doi.org/10.1016/j.jclepro.2016.09.222>
- Correia, M. S. (2019). Sustainability: An Overview of the Triple Bottom Line and Sustainability Implementation. *International Journal of Strategic Engineering*, 2(1), 29–38. <https://doi.org/10.4018/IJoSE.2019010103>
- Cruz, C. O., Gaspar, P., & de Brito, J. (2019). On the concept of sustainable sustainability: An application to the Portuguese construction sector. *Journal of Building Engineering*, 25(June), 100836. <https://doi.org/10.1016/j.jobbe.2019.100836>
- Dadashi Haji, M., Taghaddos, H., Sebt, M. H., Chokan, F., & Zavari, M. (2021). The effects of bim maturity level on the 4d simulation performance: An empirical study. *International Journal of Engineering Transactions C: Aspects*, 34(3), 606–614. <https://doi.org/10.5829/ije.2021.34.03c.03>
- Dadmehr, N and Coates, S. (2019). *An approach to " National Annex to ISO*.
- Danso, H. (2018). Identification of Key Indicators for Sustainable Construction Materials. *Advances in Materials Science and Engineering*, 2018. <https://doi.org/10.1155/2018/6916258>
- Darko, A., & Chan, A. P. C. (2017). Review of Barriers to Green Building Adoption. In *Sustainable Development* (Vol. 25, Issue 3, pp. 167–179). John Wiley and Sons Ltd. <https://doi.org/10.1002/sd.1651>
- Dinh, T. H., & Dinh, T. H. (2021). Building A Comprehensive Conceptual Framework for Material Selection in Terms of Sustainability in The Construction Preliminary Design Phase. *International Journal of Sustainable Construction Engineering and Technology*, 12(4), 73–84. <https://doi.org/10.30880/ijscet.2021.12.04.007>

- Djokoto, S. D., Dadzie, J., & Ohemeng-Ababio, E. (2014). Barriers to sustainable construction in the Ghanaian construction industry: Consultants perspectives. *Journal of Sustainable Development*, 7(1), 134–143. <https://doi.org/10.5539/jsd.v7n1p134>
- Doan, D. T., Ghaffarianhoseini, A., Naismith, N., Zhang, T., Ghaffarianhoseini, A., & Tookey, J. (2017). A critical comparison of green building rating systems. *Building and Environment*, 123(July 2018), 243–260. <https://doi.org/10.1016/j.buildenv.2017.07.007>
- Elbeltagi, E., Wefki, H., Abdrabou, S., Dawood, M., & Ramzy, A. (2017). Visualized strategy for predicting buildings energy consumption during early design stage using parametric analysis. *Journal of Building Engineering*, 13(August), 127–136. <https://doi.org/10.1016/j.jobbe.2017.07.012>
- Eleftheriadis, S., Mumovic, D., & Greening, P. (2017). Life cycle energy efficiency in building structures: A review of current developments and future outlooks based on BIM capabilities. *Renewable and Sustainable Energy Reviews*, 67, 811–825. <https://doi.org/10.1016/j.rser.2016.09.028>
- Elmqvist, T., Andersson, E., Frantzeskaki, N., McPhearson, T., Olsson, P., Gaffney, O., Takeuchi, K., & Folke, C. (2019). Sustainability and resilience for transformation in the urban century. *Nature Sustainability*, 2(4), 267–273. <https://doi.org/10.1038/s41893-019-0250-1>
- Fabozzi, S., Biancardo, S. A., Veropalumbo, R., & Bilotta, E. (2021). I-BIM based approach for geotechnical and numerical modelling of a conventional tunnel excavation. *Tunnelling and Underground Space Technology*, 108(December 2020), 103723. <https://doi.org/10.1016/j.tust.2020.103723>
- GhaffarianHoseini, A., Zhang, T., Nwadigo, O., GhaffarianHoseini, A., Naismith, N., Tookey, J., & Raahemifar, K. (2017). Application of nD BIM Integrated Knowledge-based Building Management System (BIM-IKBMS) for inspecting post-construction energy efficiency. *Renewable and Sustainable Energy Reviews*, 72(February), 935–949. <https://doi.org/10.1016/j.rser.2016.12.061>

- Gibbons, O. P., & Orr, J. J. (2020a). How to calculate Embodied Carbon. In *The Institution of Structural Engineers*.
<https://www.istructe.org/IStructE/media/Public/Resources/istructe-how-to-calculate-embodied-carbon.pdf>
- Gibbons, O. P., & Orr, J. J. (2020b). How to calculate Embodied Carbon. In *The Institution of Structural Engineers*.
<https://www.istructe.org/IStructE/media/Public/Resources/istructe-how-to-calculate-embodied-carbon.pdf>
- Glass, J. (2012). The state of sustainability reporting in the construction sector. *Smart and Sustainable Built Environment*, 1(1), 87–104.
<https://doi.org/10.1108/20466091211227070>
- Goh, C. S., Chong, H. Y., Jack, L., & Mohd Faris, A. F. (2020a). Revisiting triple bottom line within the context of sustainable construction: A systematic review. *Journal of Cleaner Production*, 252, 119884.
<https://doi.org/10.1016/j.jclepro.2019.119884>
- Goh, C. S., Chong, H. Y., Jack, L., & Mohd Faris, A. F. (2020b). Revisiting triple bottom line within the context of sustainable construction: A systematic review. *Journal of Cleaner Production*, 252, 119884.
<https://doi.org/10.1016/j.jclepro.2019.119884>
- Gustavsson, L., Joelsson, A., & Sathre, R. (2010). Life cycle primary energy use and carbon emission of an eight-storey wood-framed apartment building. *Energy and Buildings*, 42(2), 230–242.
<https://doi.org/10.1016/j.enbuild.2009.08.018>
- Habib, H. M., & Kadhim R., E. (2020). Employ 6D-BIM Model Features for Buildings Sustainability Assessment. *IOP Conference Series: Materials Science and Engineering*, 901(1). <https://doi.org/10.1088/1757-899X/901/1/012021>

- Harish Raju.P, Krithika, P. (2016). *Identification of Major Barriers for Sustainable Development in Indian Construction Industry*. c, 4345–4358. <https://doi.org/10.15680/IJIRSET.2016.0503234>
- Haruna, A., Shafiq, N., & Montasir, O. A. (2021). Building information modelling application for developing sustainable building (Multi criteria decision making approach). *Ain Shams Engineering Journal*, 12(1), 293–302. <https://doi.org/10.1016/j.asej.2020.06.006>
- HM Government. (2015). 3-Digital Built Britain Level 3 Building Information Modelling - Strategic Plan. *UK Government, February*, 1–47.
- Ignatova, E., Zotkin, S., & Zotkina, I. (2018). The extraction and processing of BIM data. *IOP Conference Series: Materials Science and Engineering*, 365(6). <https://doi.org/10.1088/1757-899X/365/6/062033>
- Ismail, N. A. A., Rooshdi, R. R. R. M., Sahamir, S. R., & Ramli, H. (2021). Assessing bim adoption towards reliability in qs cost estimates. *Engineering Journal*, 25(1), 155–164. <https://doi.org/10.4186/ej.2021.25.1.155>
- ISO 19650. (2018). *ISO 19650-1:2021 BSI Standards Publication Organization and digitization of information about buildings and civil engineering works , including building information modelling (BIM) — Information management using building information modelling. Part 1 Co. 44(0)*.
- Issa, R.R.A. and Olbina, S. (2015). *Building information modeling: Applications and practices*. American Society Civil Engineers.
- Iyer-Raniga, U. (2019). Zero energy in the built environment: A holistic understanding. *Applied Sciences (Switzerland)*, 9(16). <https://doi.org/10.3390/app9163375>
- Jallow, H., Renukappa, S., Suresh, S., & Alneyadi, A. (2019). Implementing a BIM collaborative workflow in the UK infrastructure sector. *ACM International Conference Proceeding Series*, 103–108. <https://doi.org/10.1145/3325917.3325957>

- Janjua, S. Y., Sarker, P. K., & Biswas, W. K. (2020). Development of triple bottom line indicators for life cycle sustainability assessment of residential bulidings. *Journal of Environmental Management*, 264(March), 110476. <https://doi.org/10.1016/j.jenvman.2020.110476>
- Jeong, W. S., Kim, J. B., Clayton, M. J., Haberl, J. S., & Yan, W. (2016). A framework to integrate object-oriented physical modelling with building information modelling for building thermal simulation. *Journal of Building Performance Simulation*, 9(1), 50–69. <https://doi.org/10.1080/19401493.2014.993709>
- Jum'a, L., Zimon, D., Ikram, M., & Madzík, P. (2022). Towards a sustainability paradigm; the nexus between lean green practices, sustainability-oriented innovation and Triple Bottom Line. *International Journal of Production Economics*, 245. <https://doi.org/10.1016/j.ijpe.2021.108393>
- Kamel, E., & Memari, A. M. (2019). Review of BIM's application in energy simulation: Tools, issues, and solutions. *Automation in Construction*, 97(October 2018), 164–180. <https://doi.org/10.1016/j.autcon.2018.11.008>
- KETLEY BRICK. (2020). *Staffordshire Clay Building Products*.
- Khanzadi, M., Sheikhhoshkar, M., & Banihashemi, S. (2020). BIM applications toward key performance indicators of construction projects in Iran. *International Journal of Construction Management*, 20(4), 305–320. <https://doi.org/10.1080/15623599.2018.1484852>
- Kim, J. I., Koo, B., Suh, S., & Suh, W. (2016). Integration of BIM and GIS for formal representation of walkability for safe routes to school programs. *KSCE Journal of Civil Engineering*, 20(5), 1669–1675. <https://doi.org/10.1007/s12205-015-0791-4>
- Kivilä, J., Martinsuo, M., & Vuorinen, L. (2017). Sustainable project management through project control in infrastructure projects. In *International Journal of Project Management* (Vol. 35, Issue 6, pp. 1167–1183). <https://doi.org/10.1016/j.ijproman.2017.02.009>

- Koutamanis, A. (2020). Dimensionality in BIM: Why BIM cannot have more than four dimensions? *Automation in Construction*, 114(November 2019), 103153. <https://doi.org/10.1016/j.autcon.2020.103153>
- Kreider, R. G., & Messner, J. I. (2013). The Uses of BIM: Classifying and Selecting BIM Uses. *The Pennsylvania State University*, September, 0–22. http://bim.psu.edu/Uses/the_uses_of_BIM.pdf
- Kylili, A., Fokaides, P. A., Vaiciunas, J., & Seduikyte, L. (2016). Integration of Building Information Modelling (BIM) and Life Cycle Assessment (LCA) for sustainable constructions. *Journal of Sustainable Architecture and Civil Engineering*, 13(4), 28–38. <https://doi.org/10.5755/j01.sace.13.4.12862>
- Landolfo, R., Formisano, A., Di Lorenzo, G., & Di Filippo, A. (2022). Classification of european building stock in technological and typological classes. *Journal of Building Engineering*, 45(August 2021). <https://doi.org/10.1016/j.jobe.2021.103482>
- Lee, G., & Borrmann, A. (2020). BIM policy and management. *Construction Management and Economics*, 38(5), 413–419. <https://doi.org/10.1080/01446193.2020.1726979>
- LETI. (2020). *Carbon Primer*.
- Li, W. (2011). Sustainable design for low carbon architecture. *Procedia Environmental Sciences*, 5, 173–177. <https://doi.org/10.1016/j.proenv.2011.03.064>
- Li, X., Qin, D., Hu, Y., Ahmad, W., Ahmad, A., Aslam, F., & Joyklad, P. (2022). A systematic review of waste materials in cement-based composites for construction applications. *Journal of Building Engineering*, 45(July 2021). <https://doi.org/10.1016/j.jobe.2021.103447>
- Lim, Y. W. (2015). Building information modeling for indoor environmental performance analysis. *American Journal of Environmental Sciences*, 11(2), 55–61. <https://doi.org/10.3844/ajessp.2015.55.61>

- Malleson, A. (2016). International BIM Report 2016 - The International picture. *Nbs*, 24.
- Marcelino-Sádaba, S., González-Jaen, L. F., & Pérez-Ezcurdia, A. (2015). Using project management as a way to sustainability. from a comprehensive review to a framework definition. *Journal of Cleaner Production*, 99, 1–16. <https://doi.org/10.1016/j.jclepro.2015.03.020>
- Mavi, R. K., Gengatharen, D., Mavi, N. K., Hughes, R., Campbell, A., & Yates, R. (2021). Sustainability in construction projects: A systematic literature review. In *Sustainability (Switzerland)* (Vol. 13, Issue 4, pp. 1–24). <https://doi.org/10.3390/su13041932>
- McArthur, J. J. (2015). A Building Information Management (BIM) Framework and Supporting Case Study for Existing Building Operations, Maintenance and Sustainability. *Procedia Engineering*, 118, 1104–1111. <https://doi.org/10.1016/j.proeng.2015.08.450>
- Mellado, F., & Lou, E. C. W. (2020). Building information modelling, lean and sustainability: An integration framework to promote performance improvements in the construction industry. *Sustainable Cities and Society*, 61(October 2019), 102355. <https://doi.org/10.1016/j.scs.2020.102355>
- Melnikovas, A. (2018). Towards an explicit research methodology: Adapting research onion model for futures studies. *Journal of Futures Studies*, 23(2), 29–44. [https://doi.org/10.6531/JFS.201812_23\(2\).0003](https://doi.org/10.6531/JFS.201812_23(2).0003)
- Memon, A. H., Rahman, I. A., & Harman, N. M. E. (2014). *Implementation of building information modeling in Malaysian construction industry*. 1621(Icfas), 343–349. <https://doi.org/10.1063/1.4898490>
- Miceli Junior, G., Pellanda, P. C., & Reis, M. C. (2020). *Management Procedure for Sensitive Projects in the Context of a BIM Adoption in a Public Organization*. August, 232–247. <https://doi.org/10.46421/2706-6568.37.2020.paper017>

- Mohammed, A. B. (2022). Applying BIM to achieve sustainability throughout a building life cycle towards a sustainable BIM model. *International Journal of Construction Management*, 22(2), 148–165. <https://doi.org/10.1080/15623599.2019.1615755>
- Montiel-Santiago, F. J., Hermoso-Orzáez, M. J., & Terrados-Cepeda, J. (2020). Sustainability and energy efficiency: Bim 6d. study of the bim methodology applied to hospital buildings. value of interior lighting and daylight in energy simulation. *Sustainability (Switzerland)*, 12(14), 1–29. <https://doi.org/10.3390/su12145731>
- Moore, J. E., Mascarenhas, A., Bain, J., & Straus, S. E. (2017). Developing a comprehensive definition of sustainability. *Implementation Science*, 12(1). <https://doi.org/10.1186/s13012-017-0637-1>
- Moses, T., Heesom, D., & Oloke, D. (2020). Implementing 5D BIM on construction projects: contractor perspectives from the UK construction sector. *Journal of Engineering, Design and Technology*, 18(6), 1867–1888. <https://doi.org/10.1108/JEDT-01-2020-0007>
- Musa, S., Marshall-Ponting, A., Nifa, F. A. A., & Shahron, S. A. (2018). Building information modeling (BIM) in Malaysian construction industry: Benefits and future challenges. *AIP Conference Proceedings*, 2016(September). <https://doi.org/10.1063/1.5055507>
- Niu, S., Pan, W., & Zhao, Y. (2015). A BIM-GIS Integrated Web-based Visualization System for Low Energy Building Design. *Procedia Engineering*, 121, 2184–2192. <https://doi.org/10.1016/j.proeng.2015.09.091>
- Olawumi, T. O., Chan, D. W. M., Wong, J. K. W., & Chan, A. P. C. (2018). Barriers to the integration of BIM and sustainability practices in construction projects: A Delphi survey of international experts. *Journal of Building Engineering*, 20(June), 60–71. <https://doi.org/10.1016/j.jobbe.2018.06.017>

- Olubunmi, O. A., Xia, P. B., & Skitmore, M. (2016). Green building incentives: A review. *Renewable and Sustainable Energy Reviews*, 59, 1611–1621. <https://doi.org/10.1016/j.rser.2016.01.028>
- Oyesode, S. A., Dare-abel, O., & Daramola, S. A. (2022). *BIM Maturity Level of Architectural firm BIM Operators in Lagos State Nigeria*. December. <https://doi.org/10.13140/RG.2.2.32219.44326>
- Papadonikolaki, E., van Oel, C., & Kagioglou, M. (2019). Organising and Managing boundaries: A structurational view of collaboration with Building Information Modelling (BIM). *International Journal of Project Management*, 37(3), 378–394. <https://doi.org/10.1016/j.ijproman.2019.01.010>
- Park, J., Yoon, J., & Kim, K. H. (2017). Critical review of the material criteria of building sustainability assessment tools. *Sustainability (Switzerland)*, 9(2). <https://doi.org/10.3390/su9020186>
- Pasanen, P., & Castro, R. (2019). Carbon Heroes Benchmark Program - Whole building embodied carbon profiling. *IOP Conference Series: Earth and Environmental Science*, 323(1). <https://doi.org/10.1088/1755-1315/323/1/012028>
- Pavan, A., Mirarchi, C., Amosso, G., Nesa, L. M., Pasini, D., Daniotti, B., & Spagnolo, S. L. (2019). BIMReL: A new BIM object library using Construction Product Regulation attributes (CPR 350/11; ZA annex). *IOP Conference Series: Earth and Environmental Science*, 296(1). <https://doi.org/10.1088/1755-1315/296/1/012052>
- Pidgeon, A., & Dawood, N. (2021). BIM adoption issues in infrastructure construction projects: Analysis and solutions. *Journal of Information Technology in Construction*, 26(May), 263–285. <https://doi.org/10.36680/j.itcon.2021.015>
- Raheem, M. I. (2021). The Effect of Using Building Information Modelling (BIM) (Stages: Design, Execution and Post-Execution). *IOP Conference Series:*

- Materials Science and Engineering*, 1076(1), 012013.
<https://doi.org/10.1088/1757-899x/1076/1/012013>
- Reading, U. of, Bre, Rtpi, Council, U. G. B., East, S., & University, O. B. (2012). Sustainable Design and Construction Cross Sector Group on Sustainable building. *BRE Global*, March, 1–16.
http://www.breeam.org/filelibrary/BREEAM_Planning/Good_Practice_Guidance_-_Sustainable_Design_and_Construction.pdf
- Red, S., & Red, S. (2011). *Staffordshire Red*.
- Reizgevičius, M., Ustinovičius, L., Cibulskienė, D., Kutut, V., & Nazarko, L. (2018). Promoting sustainability through investment in Building Information Modeling (BIM) technologies: A design company perspective. *Sustainability (Switzerland)*, 10(3). <https://doi.org/10.3390/su10030600>
- RIBA Enterprises Limited. (2017). BIM Object Standard. *Nbs*, January, 44.
- Richard McPartland. (2017). *What are BIM objects?* | NBS.
<https://www.thenbs.com/knowledge/what-are-bim-objects>
- RICS. (2017). *Whole life carbon assessment for the built environment: RICS professional statement*, UK. 41.
http://www.rics.org/Global/Whole_life_carbon_assessment_for_the_BE_PG_guidance_2017.pdf
- Safinia, S., Al-Hinai, Z., Yahia, H. A. M., & Abushammala, M. F. M. (2017). Sustainable Construction in Sultanate of Oman: Factors Effecting Materials Utilization. *Procedia Engineering*, 196(June), 980–987.
<https://doi.org/10.1016/j.proeng.2017.08.039>
- Saunders, M. N. K., Lewis, P., & Thornhill, A. (2019). “Research Methods for Business Students” Chapter 4: Understanding research philosophy and approaches to theory development. In *Researchgate.Net* (Issue January). www.pearson.com/uk%0Awww.pearson.com/uk%0Ahttps://www.researchgate.net/publication/330760964_Research_Methods_for_Business_Student

s_Chapter_4_Understanding_research_philosophy_and_approaches_to_theory_development

- Shafiq, M. T. (2021). Client-Driven Level 2 BIM Implementation: A Case Study from the UAE. *The Open Construction and Building Technology Journal*, 15(1), 129–140. <https://doi.org/10.2174/1874836802115010129>
- Shahidian, A., Ghassemi, M., Mohammadi, J., & Hashemi, M. (2020). Bio-Engineering Approaches to Cancer Diagnosis and Treatment. In *Bio-Engineering Approaches to Cancer Diagnosis and Treatment*. <https://doi.org/10.1016/c2018-0-02702-4>
- Sheet, P. D. (2021). *Celotex*. May.
- Shen, L. yin, Tam, V. W. Y., Tam, L., & Ji, Y. bo. (2010). Project feasibility study: the key to successful implementation of sustainable and socially responsible construction management practice. *Journal of Cleaner Production*, 18(3), 254–259. <https://doi.org/10.1016/j.jclepro.2009.10.014>
- Shi, Q., Zuo, J., Huang, R., Huang, J., & Pullen, S. (2013). Identifying the critical factors for green construction - An empirical study in China. In *Habitat International* (Vol. 40, pp. 1–8). <https://doi.org/10.1016/j.habitatint.2013.01.003>
- Shi, Y., & Xu, J. (2021). BIM-based information system for econo-enviro-friendly end-of-life disposal of construction and demolition waste. *Automation in Construction*, 125(January), 103611. <https://doi.org/10.1016/j.autcon.2021.103611>
- Shurrab, J., Hussain, M., & Khan, M. (2019). Green and sustainable practices in the construction industry: A confirmatory factor analysis approach. *Engineering, Construction and Architectural Management*, 26(6), 1063–1086. <https://doi.org/10.1108/ECAM-02-2018-0056>
- Sitota, B., Quezon, E. T., & Ararsa, W. (2021). Assessment on Materials Quality Control Implementation of Building Construction Projects and Workmanship:

- A Case Study of Ambo University. *SSRN Electronic Journal*, 15(1001), 138–155. <https://doi.org/10.2139/ssrn.3901438>
- Sizirici, B., Fseha, Y., Cho, C. S., Yildiz, I., & Byon, Y. J. (2021). A review of carbon footprint reduction in construction industry, from design to operation. *Materials*, 14(20), 1–18. <https://doi.org/10.3390/ma14206094>
- Smith, P. (2014). BIM & the 5D Project Cost Manager. In *Procedia - Social and Behavioral Sciences* (Vol. 119, pp. 475–484). <https://doi.org/10.1016/j.sbspro.2014.03.053>
- Solla, M., Ismail, L. H., & Yunus, R. (2016). Investigation on the potential of integrating BIM into green building assessment tools. *ARPN Journal of Engineering and Applied Sciences*, 11(4), 2412–2418.
- Tabassi, A. A., Roufechaei, K. M., Ramli, M., Bakar, A. H. A., Ismail, R., & Pakir, A. H. K. (2016). Leadership competences of sustainable construction project managers. In *Journal of Cleaner Production* (Vol. 124, pp. 339–349). <https://doi.org/10.1016/j.jclepro.2016.02.076>
- Tang, L., Chen, C., Tang, S., Wu, Z., & Trofimova, P. (2017). Building Information Modeling and Building Performance Optimization. *Encyclopedia of Sustainable Technologies*, December 2019, 311–320. <https://doi.org/10.1016/B978-0-12-409548-9.10200-3>
- Tengli, M. (2020). Research Onion: A Systematic Approach to Designing Research Methodology. *Agricultural Extension in South Asia*, August, 1–20. <https://doi.org/10.13140/RG.2.2.24466.12489>
- Tian, M., Zhang, L., Su, Y., Xuan, Q., Li, G., & Lv, H. (2019). An evaluation study of miniature dielectric crossed compound parabolic concentrator (dCCPC) panel as skylights in building energy simulation. *Solar Energy*, 179(December 2018), 264–278. <https://doi.org/10.1016/j.solener.2018.12.058>
- Tokbolat, S., Karaca, F., Durdyev, S., & Calay, R. K. (2020). Construction professionals' perspectives on drivers and barriers of sustainable

- construction. *Environment, Development and Sustainability*, 22(5), 4361–4378. <https://doi.org/10.1007/s10668-019-00388-3>
- Ukaga, O., Maser, Chris., & Reichenbach, Mike. (2010). *Sustainable development : principles, frameworks, and case studies*. CRC Press.
- Virtanen, P. K., Siragusa, L., & Guttorm, H. (2020). Introduction: toward more inclusive definitions of sustainability. In *Current Opinion in Environmental Sustainability* (Vol. 43, pp. 77–82). Elsevier B.V. <https://doi.org/10.1016/j.cosust.2020.04.003>
- Vonthron, A., Koch, C., & König, M. (2018). Removing duplicated geometries in IFC models using rigid body transformation estimation and flyweight design pattern. *Visualization in Engineering*, 6(1). <https://doi.org/10.1186/s40327-018-0061-x>
- Wan Mohammad, W. N. S., Abdullah, M. R., Ismail, S., & Takim, R. (2018). Overview of Building Information Modelling (BIM) adoption factors for construction organisations. *IOP Conference Series: Earth and Environmental Science*, 140(1). <https://doi.org/10.1088/1755-1315/140/1/012107>
- White, H., & Marasini, R. (2014). Management of Interface between Main Contractor and Subcontractors for Successful Project Outcomes. *Journal of Engineering, Project, and Production Management*, 4(1), 36–50. <https://doi.org/10.32738/jepm.201401.0005>
- Yates, J. K. (2013). Sustainable methods for waste minimisation in construction. *Construction Innovation*, 13(3), 281–301. <https://doi.org/10.1108/CI-Nov-2011-0054>
- Yılmaz, M., & Bakış, A. (2015). Sustainability in Construction Sector. *Procedia - Social and Behavioral Sciences*, 195, 2253–2262. <https://doi.org/10.1016/j.sbspro.2015.06.312>

- Zhang, J., Long, Y., Lv, S., & Xiang, Y. (2016). BIM-enabled Modular and Industrialized Construction in China. *Procedia Engineering*, 145, 1456–1461. <https://doi.org/10.1016/j.proeng.2016.04.183>
- Zieliński, R., & Wójtowicz, M. (2019). Different BIM levels during the design and construction stages on the example of public utility facilities. *AIP Conference Proceedings*, 2078(March). <https://doi.org/10.1063/1.5092078>
- Zohuri, B., & Fathi, N. (2015). Thermal-hydraulic analysis of nuclear reactors. *Thermal-Hydraulic Analysis of Nuclear Reactors*, January 2015, 1–651. <https://doi.org/10.1007/978-3-319-17434-1>
- Zuo, J., & Zhao, Z. Y. (2014). Green building research-current status and future agenda: A review. *Renewable and Sustainable Energy Reviews*, 30, 271–281. <https://doi.org/10.1016/j.rser.2013.10.021>