Northumbria University
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Enhancing the integration of sustainability assessment within dynamic BIM enabled design projects

Rana Ayman Anwar

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Enhancing the integration of sustainability assessment within dynamic BIM enabled design projects

A thesis submitted in partial satisfaction of the requirements of the University of Northumbria in Newcastle for the degree of Doctor of Philosophy in Architecture.

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Declaration

I declare that the work contained in this thesis has not been submitted for any other award and that it is all my own work. I also confirm that this work fully acknowledges opinions, ideas and contributions from the work of others.

Any ethical clearance for the research presented in this thesis has been approved. The ethics approval application was prepared on the 11/02/2020 under the submission number: **21492** and was approved on the **13/02/2020** with an update on **11/02/2021**.

I declare that the Word Count of this Thesis is **55,755** words

Name: Rana Ayman Anwar

Signature:

Date: 24/05/2022

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Abstract

In the last decade, building information modelling has created a revolution transforming the architecture, engineering, and construction (AEC) industry. New ways to utilise new technologies and processes in visualising, managing, exchanging, predicting and monitoring project information are in continuous development and investigation. At the same time, global and governmental pressures have been acting as motivators towards delivering sustainable and low carbon buildings, and industry stakeholders are therefore committed to delivering buildings with reduced carbon. One of the main sources responsible for carbon in buildings is embodied carbon, which relies on the choice of building materials. Life cycle assessment is a methodology developed to assess the sustainability of the materials, dealing with the embodied factors throughout the whole life cycle of the material. Although there are promising possibilities for incorporating building system life cycle assessment (LCA) of materials into building information modelling platforms, dynamic and early design assessment is still lacking.

The aim of this thesis is to investigate the problems faced in incorporating sustainability evaluation aspects with a focus on life cycle assessment, and to propose and test a framework and tool to facilitate the design of low carbon buildings. It begins with an exploratory phase where synthesis and analysis of the literature took place, aligned with an exploratory case study. By examining previous studies through a systematic literature review, this study highlighted current limitations and benefits between BIM and sustainability practices. A theoretical contribution was made through clustering six areas for future investigation of successful integration, which are: representation; performance simulation; transaction and exchange; documentation; automation; and standardisation and guidance. The scope of the study was then narrowed down to develop and test a model and framework for life cycle analysis as one of the main sustainability aspects that needs to be dynamically integrated in BIM workflow.

The study design incorporated abductive mixed methods research involving the following three stage process: investigation phase of problematic areas in incorporation and existing platforms; designing and implementing a framework and dynamic LCA approach; and then evaluating its usability to validate it. The selected approach illustrates the LCA workflow possibility within a BIM environment using Revit platform, a UK current EC material database, and visual

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programming language (Dynamo) to link BIM objects to a database and optimise Embodied carbon (EC) within the design process.

Eliminating ad-hoc work, manual mapping, the need for expertise, and complexity of required input information were the main objectives of the proposed approach. It was also important to test the usability of the simplified LCA methodology in order to validate the efficiency of using the system iteratively from the early design stage and through design development. Therefore, validation of the framework and tool was carried out through conducting qualitative and quantitative usability testing. The usability testing included a showcase presentation, online workshop testing and evaluation via a questionnaire and semi-structured interviews.

The main outcome was the development of a model and framework to enhance informed decision making, reduce error, support the design of low carbon buildings, and reduce time end effort. It also provided an expandable framework that can be used with other different paraments in future, providing flexible opportunities for expansion and customisation. A key theocratical contribution in the developed model is the proposed use of a correction factor to overcome the problem associated with low detail. The workshop feedback provided insights into utilisation of visual programming language (VPL) and suggested areas for potential improvement including: more visualisation and optimisation options, development of an advanced user interface, and finally the inclusion of more environmental indicators and expansion of the model system boundary.

In conclusion, the findings of the research contribute to fill the gap identified by providing a dynamic and automated approach to calculate embodied carbon. The novel way proposed by adding correction factor; to increase accuracy of calculation of low detailed BIM model, is an area of development for material database developers. In addition, the results from the usability testing are considered a basis for future development to be addressed by researchers and practitioners to increase adoption of the new VPL integrated approach. They provide evidence of the need to enhance the calculation model, visualisation and optimisation options, and develop a more advanced user interface for the tool.

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List of abbreviations

AEC	Architecture, Engineering and Construction
BEP	BIM Execution Plan
BIM	Building Information Modelling
BOQ	Bill of Quantities
BPA	Building Performance Analysis
BRE	Building Research Establishment
BREEAM	Building Research Establishment Environmental Assessment Method
BI	British Standard
CAD	Computer-Aided Drafting
COBie	Construction Operations Building Information Exchange
EPD	Environmental Product Declarations
EC	Embodied Carbon
EE	Embodied Energy
GWP	Global warming potential
HCI	Human computer interaction
ICE	Inventory of Carbon and Energy
IFC	Industry Foundation Classes
ISO	International Organization for Standardization
KBOB	Koordinationskonferenz der Bau- und Liegenschaftsorgane der öffentlichen Bauherren
LCA	Life-Cycle Assessment
LCI	Life-Cycle Inventory
LEED	Leadership in Energy and Environmental Design
LOD	Level of Detail
LOI	Level of Information
NBS	National Building Specification
PAS	Publicly Available Specification

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RIBA	Royal Institute of British Architects
RICS	Royal Institution of Chartered Surveyors
SD	Sustainable Development
VPL	Visual Programming Language

Chapter 1 : Introduction

This chapter presents an introduction to the research significance justified by motivational factors towards adoption of BIM-based sustainability. An outline of the thesis structure and guide is clarified. The contribution to knowledge is stated with a description of the research design process.

1.1 Research background

The first established use of the term "sustainable" in the literature appeared in the 1970s, coinciding with a wave of UN-led efforts aimed at bringing attention to humanity's alarming ecological footprint and the fact that it had outgrown the planet's carrying capacity, making humanity's way of life unsustainable. Then later the Brundtland Commission (MRCGP, 1987) (World Commission on Environment and Development 1987) accepted the concept of sustainability, leading to a debate on how sustainability might be defined, used, and evaluated since then (Muchlis, 2021). This debate has intensified as people have learned about the consequences of their activities on the environment and climate, which will have an influence on human and other animal life on Earth, as well as endangering future generations' ability to meet their needs. This has raised awareness and led to global pressure to take action in the architecture, engineering and construction industry (AEC), as one of the greatest contributors to climate change and pollution.

Consequently, over the last decade delivering sustainable projects has become a high priority in AEC practice due to different motivation factors, which has created global and governmental pressure on industry stakeholders (Olubunmi *et al.*, 2016; Shazmin *et al.*, 2017). The main motivator towards sustainability is the construction industry's high consumption of resources and negative impacts on the environment, accounting for an estimated 30-35% of global energy consumption and waste generation, and 25% of global water consumption (International Energy Agency, 2017). Therefore, national building legislations and international green building rating systems - such as BREEAM, LEED, and Green Star – have been developed to influence the commitment of building stakeholders to sustainability. The goal of these rating systems is to reduce the environmental impacts of buildings, and at the same time maintain the health and comfort of their occupants. Currently, these rating systems, also known as environmental assessment methods (EAM), are used by building professionals and require

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quantitative and qualitative performance evidence on the design of environmental aspects. Previous research has identified challenges in the delivery of green-rated buildings, as it has been argued that delivering the design of such high performance buildings requires complex, iterative, and non-linear processes (Hwang & Tan, 2012; Ahmad *et al*., 2016).

Industry stakeholders are committed to working towards the targets of these sustainable rating systems; at the same time existing research recognises the critical role played by BIM in improving work efficiency (Azhar *et al.*, 2011; Wong & Zhou, 2015). Therefore, the synergy between BIM and sustainability is considered to be an area of major interest with extensive attention in the AEC industry (Raouf & Al-Ghamdi, 2018). It has been discussed in the literature how BIM technologies and processes could enhance the delivery of environmentally sustainable projects (Wong & Zhou, 2015). These studies highlight the integration and BIM synergy in terms of facilitating data exchange, providing visualised analysis, and simulation of green building attributes, such as energy, emissions, material environmental impacts (Lu *et al*., 2017). Awareness of the importance of synergy has been raised because of global demand for delivering sustainable projects with increased process efficiency and client satisfaction. However, BIM-enabled sustainability practices are still relatively immature and inconsistent. Therefore, this study aims to contribute to this growing area of research by exploring potential and deficiencies in the current synergies.

1.2 Scope of the research

Several scholars have developed BIM frameworks which categorise the areas of research within the BIM field into people, tools, processes, technology, and legal and financial. The most recognised and comprehensive framework was developed by Succar (2009), and is divided into three fields: (i) the policy field, (ii) the technology field, and (iii) the process field. On the other hand, the main pillars that are used to define sustainability in the built environment are ecological, social and economic factors, known as the 'triple bottom line'(Rodriguez et al., 2002). It is argued by several scholars that environmental aspects are mostly dependent on building performance, which BIM helps to quantify (Azhar & Brown, 2009; Baeza Salgueiro & Ferries, 2015; Kamel & Memari, 2019). This research scope will focus on environmental/ecological sustainability with more specific emphasis on energy and materials categories with relation to the process and technology BIM fields (see figure 1.1). The scope of this research is to investigate the highlighted synergies in academia and explore the uptake

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of those frameworks within architect design workflow using methods developed in theories related to human computer interaction (Blandford *et al*., 2016).

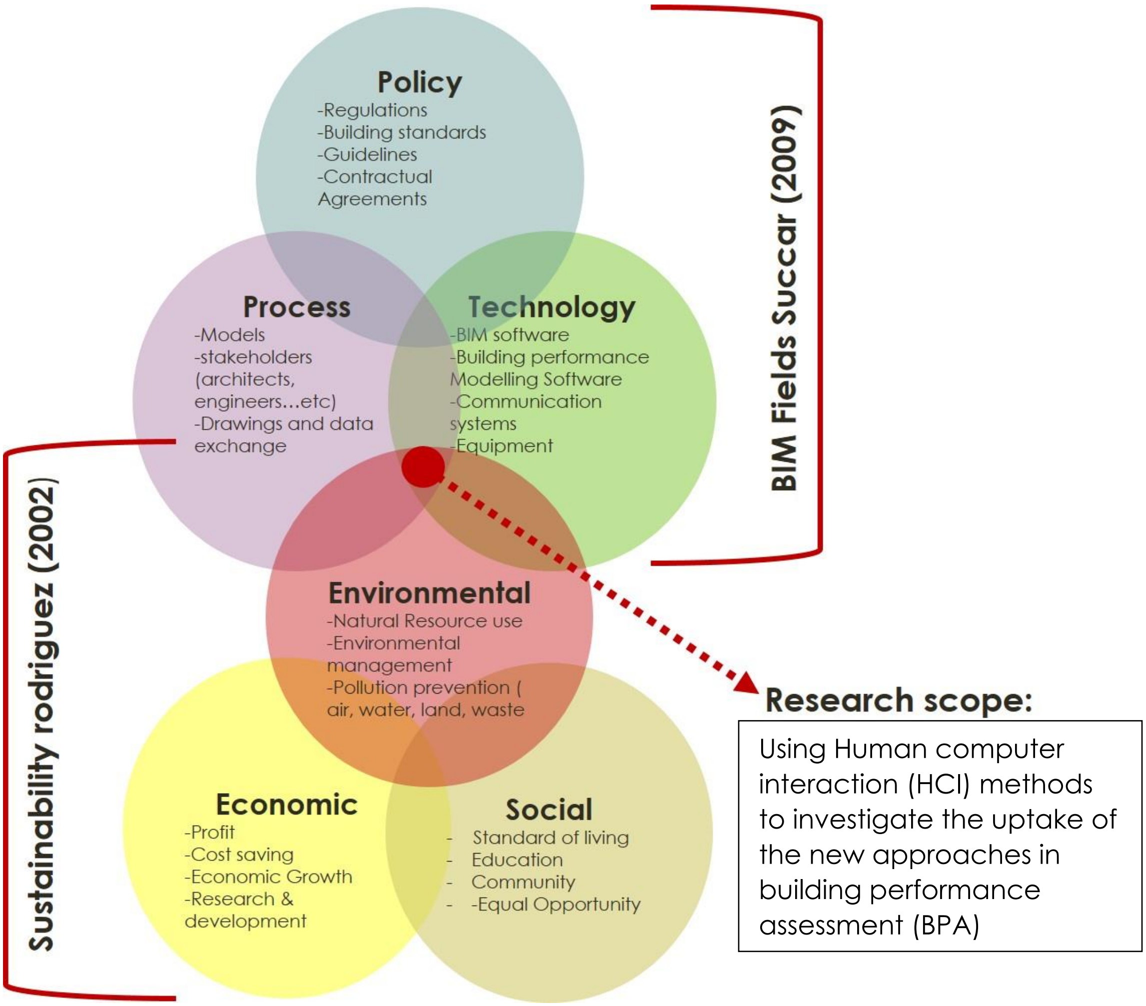

Figure 1.1: Research scope (BIM and sustainability) adapted from a combination of Rodriguez et al. (2002) and Succar (2009)

Scholars have identified the major factors that act as drivers regarding the increase in demand for green rating systems. Those driving forces are: social and end consumer pressure ; the need to increase building performance and reduce life cycle cost; global pressure towards sustainability; governmental pressure regarding compliance; and finally, financial benefits to the owner and property users; as illustrated in detail in table 1.1 (Ahn et al., 2013; Balasubramanian & Shukla, 2017; Darko, Chan, et al., 2017; Darko, Zhang, et al., 2017; Olubunmi et al., 2016; Shazmin et al., 2017)**.** Researchers have also discussed the barriers to deliver sustainable construction at an industry level. Examples of these barriers are market deficiency in knowledgeable practitioners and green suppliers; risk of increase in cost; stakeholders' rigidity regarding change; deviation of the project schedule; immature and inconsistent state; and lack of sources of guidance; as shown in table 1.2(Ahn *et al*., 2013; alasubramanian & Shukla, 2017; Nguyen *et al*., 2017; Wimala *et al*., 2016).

These studies have shown the internal and external influences and motivators that effect change in the industry towards green projects (Ayman *et al*., 2018). The factors that have been discussed in these studies can be categorised into three levels of investigation, relating to: industry level, project level and individual level. This research aims to expound the potentials and gaps in BIM for sustainability at the project level. Technical capabilities with process aspects were the main area of investigation in this research, which are shown in figure 1.2. .

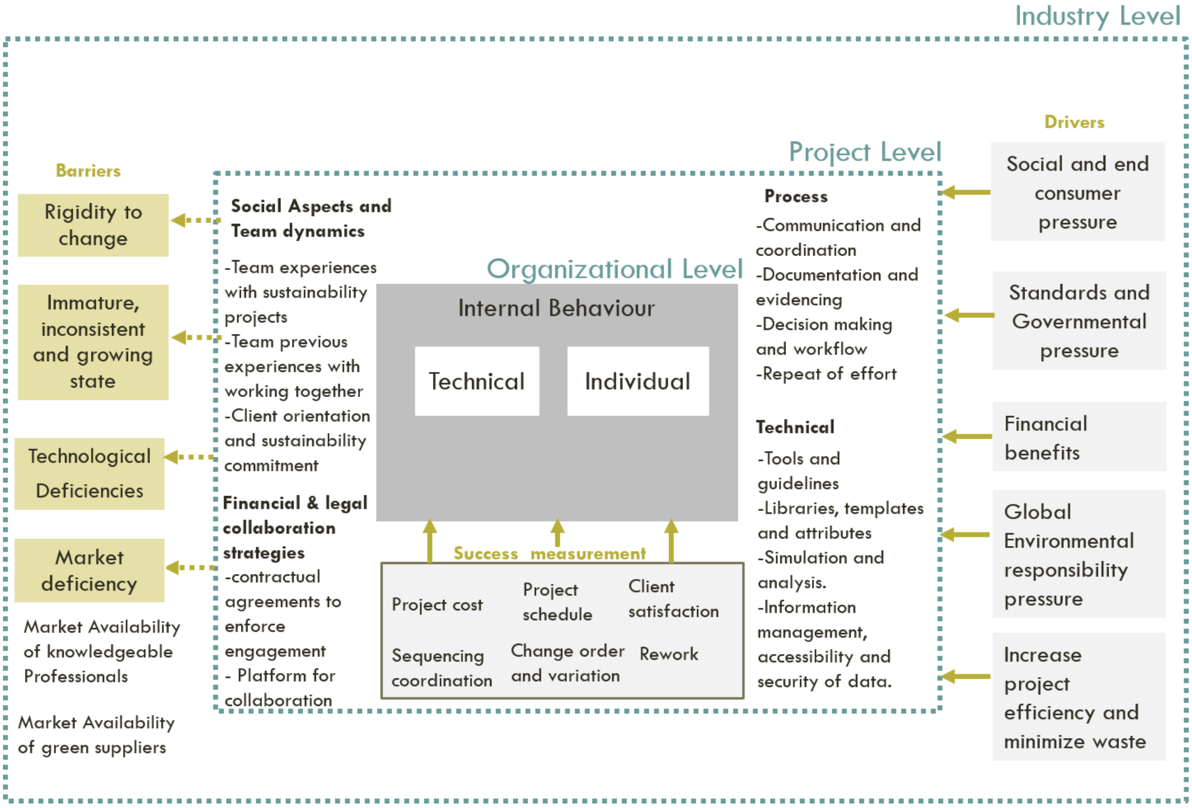

Figure 1.2: Drivers and barriers affecting sustainability demands (Ayman et al., 2019)

In order to define the research scope and narrow down the aspects that the research will address, investigation is required to prioritise the problems in the current approaches and then develop an approach and solution to a certain problem. As shown in figure 1.3, the investigation in this research started with searching in all environmental sustainability

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aspects. Then after the exploration case study, it was narrowed down to operational energy, daylighting and LCA of materials, due to the reported importance of these aspects to design decisions. Due to technical limitation found in integrating operational and daylighting within BIM authorized dynamic platform, further details will be discussed in chapter 4. Therefore, scope is narrowed down to LCA. Then Embodied carbon (EC) is selected as one of major and most famous environmental indicators for LCA of materials. The next section will outline the objectives derived from the main aim of the research.

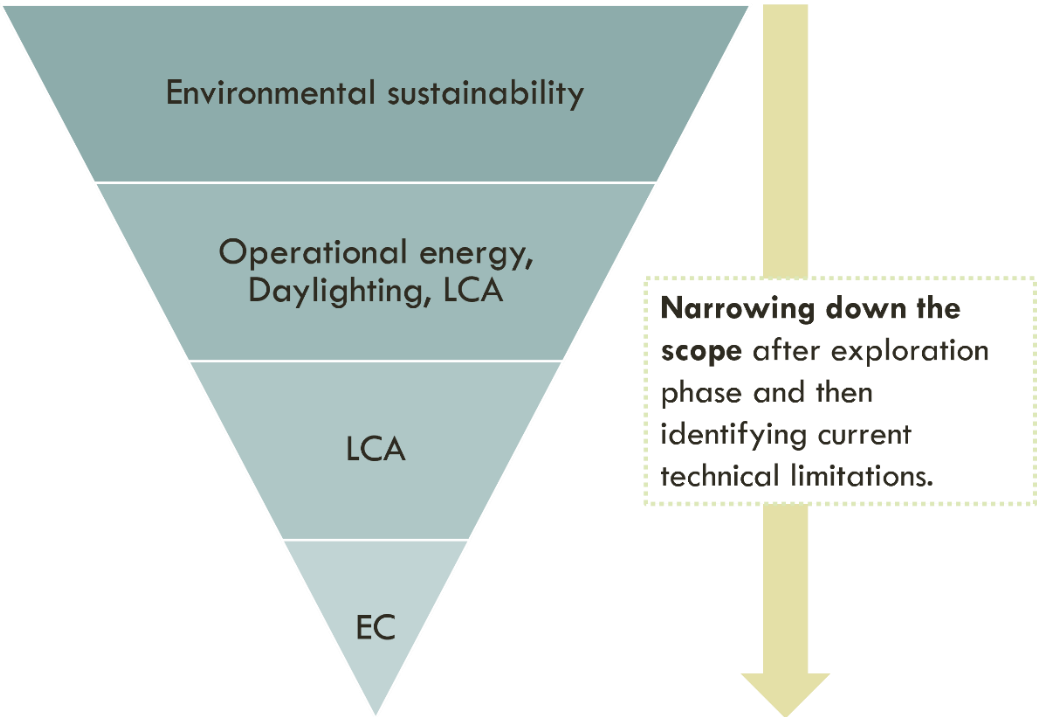

Figure 1.3 Narrowing down the scope of the research

1.3 Aim and objectives

The research aim was to investigate incorporating sustainability aspects through performance-based design using BIM-based sustainability tools, challenges and problems in workflow; then to develop and evaluate a framework for a dynamic integrated process. This was achieved through satisfying the following objectives.

1.3.1 Objectives

1. To carry out a systematic literature review of collaborative design and integrated project delivery within sustainable design, by investigating the sustainable building

design and architecture process, BIM-enabled sustainability and dynamic design environment.

2. To explore and present industry professionals' understandings of BIM-based sustainability and current methods of working, in order to determine the relationships, gaps and barriers of adoption.
3. To identify and review new tools and frameworks using visual programming languages performance simulation platforms specifically to deal with LCA.
4. To propose a framework for a better dynamic design environment to deliver green buildings using a VPL platform to iteratively be able to assess EC throughout the building design process.
5. To test and evaluate the potential usability and acceptance of the new proposed tool and framework among architects using user experience methods.

1.4 Research design

This study used an abductive technique to fulfil the research objectives (iterative process of induction and deduction) (Halecker, 2016). The adopted method was a reiteration of "testing" and "explanation," with the external validity of the study results being checked continuously. The implementation of the "iterative theory building process" will be further discussed in chapter 5 and justification of all research methods will be explained. This part will introduce and summarise the tasks created accordingly to formulate the thesis structure:

Table 1.1 Research design tasks with research objectives

Research objectives	Research design tasks
Objective 1	1. A systematic literature review of the associated books, scientific papers in journals and published conference proceedings that cover potentials and problems in synergy between BIM and sustainability.
Objective 2	2. An exploratory industry case study to identify and understand the problems in current BIM-based sustainability practice.
Objective 3	3. A review of the potentials and limitations of visual programming language applications to assess building sustainability performance specifically to automate LCA.
Objective 4	4. Formulation of a framework and model using VPL in order to automate the LCA process and enable iterative assessment.
Objective 5	5. Design and conduct workshops, questionnaires and interviews with architects in order to validate and evaluate the usability of the model. 13 participants contributed in four workshops plus interviews.
Objective 5	6. Analyse the findings and triangulate them with output from the literature to provide an explanation of how the model offers improvement in current practice.

1.5 Contribution to knowledge

The research provides three segments that contribute to knowledge, through investigation of current state of BIM-enabled suitability project delivery:

1. **Theoretical contribution:**

The main contribution of this research is theoretical. Through interrogating existing research via a systematic literature review, this research constructed an 'analysis map' to 'bridge the gap' and highlight current limitations and successes between BIM and sustainability practices. A novel approach was presented through clustering six areas of future investigation for successful integration: representation; performance simulation; transaction and exchange;

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documentation; automation; and standardisation and guidance. Also, an innovative solution can be found in the flexibility provided in the BIM material library for life cycle assessment (LCA) calculation, which existed in the ability to mix life cycle inventory (LCI) databases and correction factors added to deal with different levels of development of the BIM model.

2. **Methodological contribution:**

Building on the outcomes of the exploratory phase, a model was developed to deal with one of the sustainability aspects: embodied carbon of building materials. A methodological contribution exists in the use of the human computer interaction (HCI) method, usability for evaluation and test. A unique approach was utilised to understand the possible uptake among architects of the innovative rising VPL solutions using the user experience HCI method.

3. **Practical contribution:**

This research contributes to practice by first providing a showcase on application using the built-up scripts and back-end calculation model. It also generates knowledge by providing evaluation and testing of the potential use of new BIM tools by architects using visual programming language scripts to deal with material selection (LCA) iteratively and dynamically.

1.6 Research design and thesis structure

This thesis is divided into eight chapters. The thesis objectives and aims are linked and summarised in figure 1.5, which provides a schematic guide to the thesis organisation. The following section will provide a brief summary of the outcome of each chapter.

Chapter 1: Introduction

This chapter introduces the research background and highlights its importance through justification of the drivers and barriers towards the adoption of BIM-enabled sustainability. The guidance of the research outline is presented along with aim, objectives, and contribution to knowledge.

Chapter 2: Sustainable building design process

This chapter formulates the first part of the literature review. The chapter provides an overview of the existing definitions and goals of SBD implementation and process, with emphasis on choice of building materials. It also reviews the problematic aspects of the different current approaches in performing static and conventional LCA and energy simulation. This chapter seeks to answer the following questions:

- What are drivers and targeted sustainability benchmarks?
- What are green rating schemes, how do they work, and what are their similarities and differences with respect to life cycle assessment?
- What are the previously reported problems in current approaches assessing sustainability? (Energy and material selection.)

Chapter 3: BIM enabled sustainability and dynamic design environment

This chapter contains the second part of the literature review. It outlines the existing definitions of digital plan of work and BIM, and examines the current literature around the potentials and challenges of the BIM-enabled sustainability practices. The main outcome from this chapter is definitions of the elements of integration and the BIM and SBD synergies. It will highlight the literature gap and define the choice of the research investigation and implementation field. It also presents the exploratory case study, in order to investigate the problems in application of BIM-based sustainability.

Chapter 4: Visual programming language and performance-based design

This chapter explains the contribution in the development of visual programming language tools to deal with sustainability aspects during the design phase in a dynamic approach. The difference in conventional methods of assessing design performance for architect usability and new VPL platforms, tools and method will be presented in this chapter. It highlights the benefits of the method and its potentials for the use of architects in order to deal with evaluating sustainability aspects within their designs in a less time-consuming and complex way, as well as its current limitations. Previously proposed frameworks and scripts are reviewed in this chapter. Through the overview of the different approaches to the use of simulation models during the design process, the advantages of the use of VPL use to utilise the distributed model method will be justified. This chapter will be used in order to build the proposed parametric dynamo for LCA model that will be evaluated.

Chapter 5: Research design and methodology

This chapter establishes the philosophical positioning of the research project in terms of its epistemological and theoretical perspective, which guides the strategy and plan of actions described in the methodology and justifies the choices of the methods used. In addition, it describes the research design and phases, discussing the choices regarding data collection, model development, and analysis, alongside the considerations for quality measures taken to assure the validation of the research findings. All the philosophies and principles adopted were selected to suit mixed methods research and human computer interaction (HCI) methods.

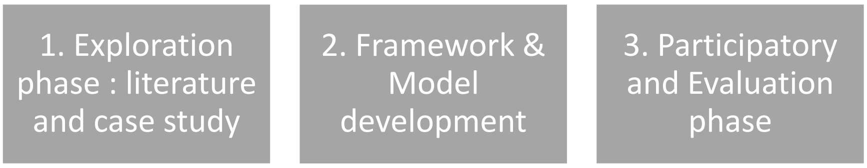

Figure 1.4: research phases

Chapter 6: Development of a framework and show case application

This chapter formulates the development of a dynamic feedback process for sustainable building digital delivery model using VPL. It explains the components of workflow that allow mechanisms for change towards a collaborative and iterative performance process of SBD. It presents the system's architecture for an interactive and dynamic framework to deal with the optimisation of materials in terms of embodied carbon using VPL. This chapter will also define how the framework could be used to support the generation of a BIM object library, embodied carbon dynamic calculation, decision-making, and documentation of database resources.

Chapter 7: User experience analysis

This chapter demonstrates the participatory phase of the research which enriched the reliability and trustworthiness of the research's practical contribution and output by capturing architects' feedback. It first describes the methods used for workshops and interviews with industry practitioners (architects). It then presents the refinement and recommendations for modifications on the model. The discussion presented in this chapter aims to highlight the usability of the model in the design process for architects in terms of adaptability, flexibility, comparison and feedback loops.

Chapter 8: Conclusion and future research

This chapter summarises the main findings of the research and provides insights and reflections on the study journey. The discussion will include reflections on the future potential of the effect of using BIM-based tools and a VPL proposed model on architects' workflow to deal with sustainability aspects. The discussion in this chapter also presents the contribution to knowledge and novelty presented in this thesis. The limitations of the research, along with future study recommendations, are also outlined.

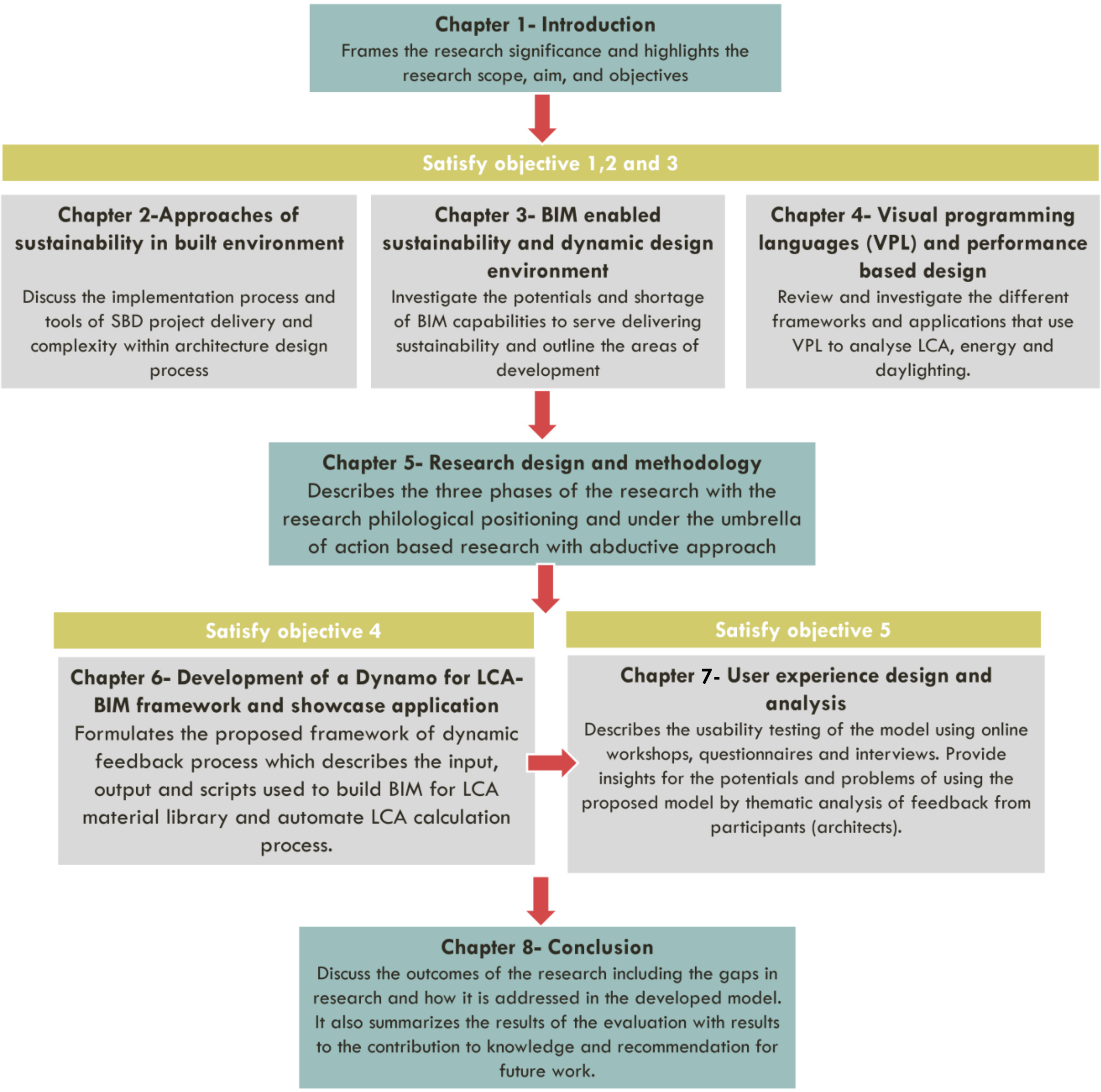

Figure.1.5: Guide to the thesis

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1.7 Summary

The research problem and background have been framed in this chapter, in which the synergy of BIM and sustainability have been highlighted as one of the major interest fields in practice and academia. This chapter provided a justification of the research significance and identified the research scope and area of investigation to achieve the aims and objectives of the study. The research significance was justified by the importance of BIM and digitalisation, and its positive effect on the AEC industry and immature state of integrating sustainability within the existing workflow. Moreover, the contribution to knowledge has been summarised to demonstrate the academic and practical achievement of the research. Finally, the structure of the research has been explained and illustrated along with the objectives. The structure aimed to achieve the objectives by an iterative abduction approach through the following phases: (1) Exploration phase: literature review and case study; (2) Framework & model development; (3) Participatory and evaluation phase.

Chapter 2 : Approaches to sustainability in the built environment

2.1 Introduction

Sustainability in the built environment is the first pillar of this research topic. Therefore, it is important to review how this term evolved, what the different approaches are to achieve it and what gaps and challenges exist in current methods. Hence, this chapter is considered the first part of the literature review that aimed to satisfy the first objective of this research. The structure of the chapter is presented in figure 2.1. It starts by explaining how sustainability as a term and practices within it emerged worldwide and goes on to consider its importance reflected within the AEC industry. Different types of green rating systems are presented as one way of promoting the delivery of sustainable buildings. This is followed by outlining the barriers to delivering sustainable buildings, which highlight that development in digital and technological ways of integrating sustainability in design processes may contribute towards overcoming these barriers. The last part reviews and assesses the different current approaches of simulating sustainability aspects (energy and daylighting, Life cycle assessment (LCA)).

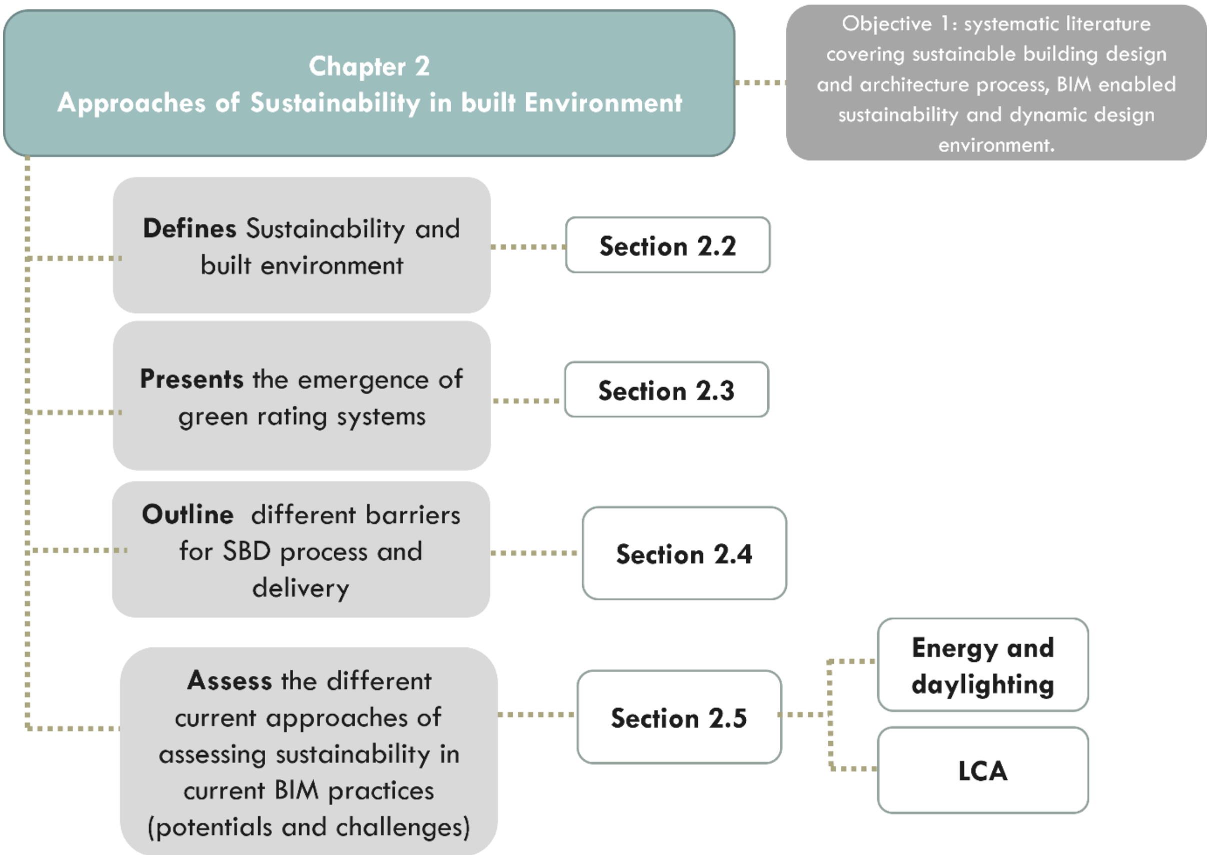

Figure 2.1: Chapter 2 structure

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2.2 Sustainability and the built environment

The Brundtland Commission (MRCGP, 1987) (World Commission on Environment and Development, 1987) acknowledged the notion of sustainability over 30 years ago, and from that time to the present, it has stimulated a debate on how sustainability may be defined, applied, and evaluated. This argument has grown as people have discovered the impact of their actions on ecology and the climate, which impact on human and other animal life on Earth, as well as endangering future generations' ability to meet their requirements. As a result, numerous classifications for sustainable development were developed, although the majority of them focused on the integration of environmental, social, and economic concerns, as mentioned in chapter 1. Sustainability in this thesis is concerned with the environmental aspects of the AEC industry and does not include social and economic aspects. In accordance with international recognition of the danger posed by climate change, a variety of legislation, rating systems and standards have been developed worldwide to improve the performance of the built environment.

As the construction industry is one of the largest in terms of energy consumption and negative environmental effects, sustainability in the built environment became a major concern worldwide and developed countries began to establish councils and schemes to address those issues. Firstly, the creation of the US Green Building Council (USGBC, 2016) in the early 1990s was a significant step forward for the cause. The UK Green Building Council (UKGBC, 2016) was founded in 2007, focusing on environmental issues such as energy efficiency, materials, and water. The UK Government's Carbon Reduction Commitment (CRC) Energy Efficiency Scheme, which was introduced in 2008, and the Energy Act 2011 (HM Government, 2011), whose key provisions are the Green Deal, Energy Company 13 Obligation, and Energy Performance Certificate (EPC), are initiatives to improve building performance (HM Government, 2015). More recently, targets were set by RIBA in a report entitled “RIBA climate challenge 2030” for operational energy use, embodied carbon and water use reduction. These have been validated through engagement with UK professional groups and the Committee on Climate Change. These goals represent a vital first step towards ensuring that the construction industry achieves the considerable reductions required by 2030 in order to have a reasonable chance of achieving net zero carbon for the whole UK building stock by 2050 (RIBA, 2019).

As a result, building sustainability has become a main concern for AEC practitioners, and new ways to integrate sustainability assessment in the design process have become essential. The goal is to minimise the impact of buildings on the environment while improving human comfort and health. Many governments and international organisations have created rating systems as one way to measure sustainable construction to solve this issue. The next section will provide a summarised review of these schemes (Azhar *et al*., 2011).

2.3 Green rating schemes

Sustainable or green rating schemes, also known as environmental assessment methods (EAM), are defined as tools for investigating the existing performance or predicted performance of a 'whole building' and transforming that evaluation into an overall assessment that allows for comparison against other structures (Fowler and Rauch, 2006). The evaluation is usually translated into points gained for each project from a list of criteria set in the rating scheme. Then a certificate can be awarded to the building according to the number of points achieved, scaled to different levels. For example, it may be "Excellent", "Very good", or "Good", although the award names and levels differ from one scheme to another. The most famous examples of these schemes are: Building Research Establishment Environmental Assessment Method (BREEAM) in the UK; Leadership in Energy and Environmental Design (LEED); Passive House Institute Darmstadt (Passivhaus) in Germany; Comprehensive Assessment Scheme for Built Environment Efficiency (CASBEE) in Japan; and Building Environmental Performance Assessment Criteria (BEPAC) in Canada.

These schemes are widely used around the world, with BREEAM and LEED being the most widely utilised (Roderick *et al*., 2009). AEC practitioners currently use these assessment methodologies as frameworks for sustainable building design (SBD); however, they provide little guidance on the important challenges of sustainability during the design process. Furthermore, practitioners use building performance assessment (BPA) technologies to estimate and quantify aspects of sustainability from the beginning of the design process, considerably improving both quality and cost throughout the life cycle of a building. Despite the benefits of these tools and digitalisation, allowing better efficiency of evaluation, cost- and time-related issues are still in the foreground for most stakeholders. The current approaches for BPA for operational energy, daylighting and material life cycle assessment will be reviewed in section 2.5.

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2.4 Barriers to sustainability in construction

2.4.1 Themes of the main barriers to sustainability

To be able to assess the contribution of digital construction and BIM in green project delivery, it is crucial to be aware of the barriers to green construction practices. It is important to know the obstacles that affect the increase in adoption of green practices, and to be able to then evaluate the level of contribution of the synergy between BIM and sustainable design. The benefit of investigating previous research discussing these barriers is that the researcher will be able to determine the areas of improvement needed to overcome some barriers, while at the same time avoiding the claim that integration will solve all the problems in the industry towards green practices. Existing literature on the barriers to delivering sustainable building is focused on current industry deficiency, risk to investments, initial costs, and rigidity regarding change in practices. Numerous research studies have attempted to explain the influence of these obstacles regarding the adoption of green strategies. However, a systematic understanding of how BIM-based practices contribute towards the reduction of the influence of some of these barriers is still lacking, especially regarding the effect of reducing costs by using BIM technologies in the long run; this will be addressed in chapter 3.

Balasubramani (2017) demonstrates the relationship between the drivers and barriers to green practices and the development needed with respect to stakeholders in the industry in terms of core building practices and facilitating green practices. Recommendations are proposed in different studies to overcome barriers by promoting the benefits of developed markets (Wimala, Akmalah and Sururi, 2016; Nguyen *et al.*, 2017). In the literature, researchers have agreed that it is essential to focus improvements on different tracks to overcome green building green building barriers. As mentioned in Hopkins' published paper in 2016, it was argued that possible solutions include: altering perspectives of practices; targeting development of university education; changing policies; and finding ways of funding green building financial incentives. Also, improving methods of green building delivery to overcome process efficiency barriers in terms of extra cost and time could be a motivation for stakeholders to adopt green building practices. This research scope covers the technical challenges in green building project delivery and the contribution of digital tools and BIM to enhance the efficiency and effectiveness of the design process. The next section will discuss the technical challenges of green building delivery.

2.4.2 Technical challenges and problems in green building project delivery

To achieve sustainability, different building performance assessments (BPA) need to take place for design optimisation during project phases. Examples of these assessments include operational energy, thermal comfort, daylight efficiency, and life cycle assessment of materials (Azhar *et al*., 2011). Specialised tools are available to analyse these elements, so as to be able to evidence the predicted performance of the design. These assessments are also needed for evidence to submit either to building regulations or to achieve green building rating certificates for one of the schemes mentioned above. According to MacLeamy in 2008 the impact of alterations on the final design of a building is greatest at reasonable prices during the early stages of design. So in order for the analysis and optimisation process to be successful and inform design decisions, the approach for assessments needs to allow dynamic feedback with the design iterations. Therefore, digital technology of building information modelling (BIM) is integrated in several ways with sustainability simulation tools to allow prediction of the design's sustainability performance.

2.5 SBD process management and design process

Architects are becoming more conscious of the urgent need to incorporate sustainability into their projects, which can cause changes in the design process. Analysis tools and BPA methods play a critical role in integrating sustainability decisions into the process of building design. This section will review the different approaches for assessing energy use and the effect of materials selection on the environmental performance of the building.

2.5.1 Energy and daylighting simulation

Energy simulation is an assessment of the overall building energy performance (BEP) and is known as building energy modelling (BEM). By modelling the geometry of the building and mapping the materials used and the building systems, different analysis outputs can be obtained from software, including predicted operational energy, thermal performance of the fabric (solar gains/losses), daylighting etc. There are various existing BEM tools available for the use of architects and building services engineers (Hyun *et al.*, 2015), in order to help them evaluate the design decisions during the pre-construction design stages and inform building design performance analysis and validation, as shown in table 2.1. The selection of these tools depends on the purpose, which can vary according to the project stage (M A Zanni *et al*., 2013). The purpose can be simplified design alternative comparison or informed and detailed analysis which requires accurate and detailed input variables.

Reeves, Olbina, & Issa (2015) conducted a study that evaluated the criteria which determine uptake by users of these tools. The study empirically evaluated the tools with respect to: interoperability with other BIM modelling platforms; usability in term of ease of use and simplicity; availability of inputs and outputs within the tool; speed; and finally, accuracy. In the UK, a few tools, such as IES-VE, design builder and energy plus engine are approved and compliant for high accuracy, as they are accredited by the UK's National Calculation Method (NCM) (BRE, 2019). However, these tools are reported to be overly complex and non-user friendly, especially for architects, as they require highly detailed input. In addition, they are not compatible with architects' iterative working need to explore multiple alternatives at an early stage in a way that requires manageable input (Yusuf Arayici *et al*., 2018). BEM tools are used in conceptual and design stages in order to:

1. Understand the climate and weather of the project location.
2. Inform the massing and orientation phase.
3. Assess the design and selection of materials for the building fabric.
4. Simulate the energy use of building services.

Design variables and examples of the BEM tools that can be used are summarised in table 2.1. Performance simulation for the selection of building fabric and building services can be approached through a conventional standalone approach or a semi-automated integrated approach (Kamel & Memari, 2018), as shown in figure 2.2 and 2.3.

Table 2.1: Table building performance energy analysis (Zanni, 2016; Reeves et al., 2015)

Design stage	**Design/ Energy variables**	**BEM tool**
Climate and weather	Daylight availability Solar access/intensity Wind direction/intensity Temperature range Humidity	Autodesk vasari Sefaira Autodesk Revit PHPP IES-VE EcoDesigner EDSL TAS Bentley Hevacomp TRNSYS Climate consultant
Massing and orientation	Overshadowing Building height and footprint Irradiance over building's planes Thermal performance Daylight Ventilation	Sefaira Autodesk Revit plug in IES-VE EnergyPlus eQuest PHPP iSBEM
Building fabric	Glazing and shading Daylighting Insulation properties of building skin: Solid and voids (U-Values and G-vlaues) Airtightness (at 50 Pa) Ventilation and free cooling Overheating	IES-VE Sefaira EnergyPlus (engine) PHPP DesignBuilder (operated by energy plus) Open studio (operated by energy plus) EcoDesigner EDSL TAS Bentley Hevacomp TRNSYS EnergyPlus
Building services	Energy consumption Heating, cooling, and hot water Electric load IT and small power consumption Energy source Artificial lighting Occupation schedules	IES-VE Bentley Hevacomp Modelica Sefaira EnergyPlus (engine) DesignBuilder EcoDesigner EDSL TAS TRNSYS Assessment (SWERA) Solar Deployment System (SolarDS) Open studio (operated by energy plus)

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A. *Conventional approach*

The conventional approach is not an integrated approach, so the simulation model and BIM (model) are not connected to each other. The assessor builds up the model on one of the simulation platforms, such as IES-VE, Sefaira, energy plus etc. All the geomaterial, materials, system and occupation properties are modelled and mapped from the architect's model manually, then the simulation takes place and an energy report is sent so the architect can analyse the results. In this case the approach does not benefit from the effort of parametric modelling in the BIM authorising tool, as all geometrical, material and required data are inserted manually. This means that this approach is impractical, inefficient, and does not promote simultaneous analysis with the design iteration.

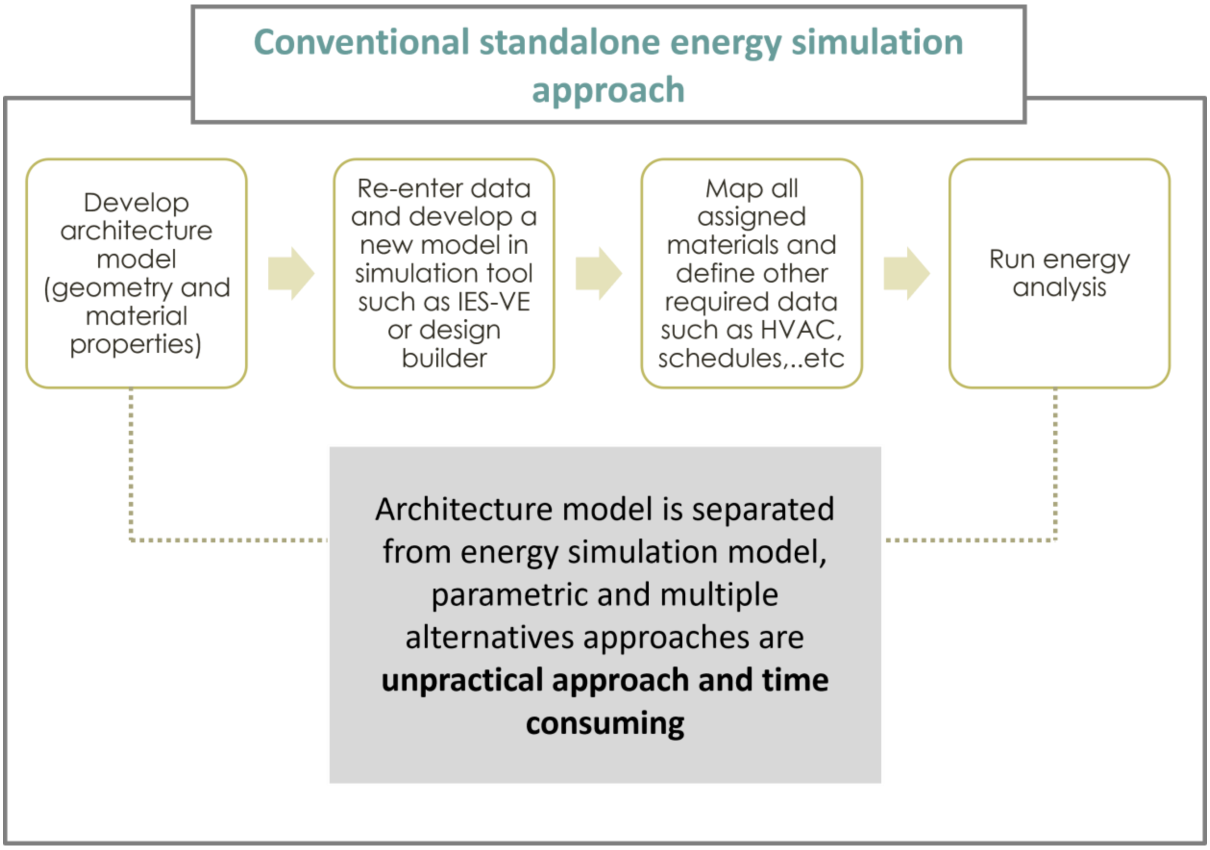

Figure 2.2: Conventional standalone energy simulation approach (Alwan et al., 2021)

B. *Semi-automated, BIM integrated approach*

The integrated approach is semi-automated using open standards such as Green Building XML (gbxml) and Industry Foundation Classes (IFC) (Noack, F. *et al*., 2016). These open extensions

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allow the exchange of the model from the BIM authorising tool, such as Revit, to the simulation tool, such as IES, design builder etc. The aim of developing these extensions is to reduce duplication of effort in modelling by facilitating the transfer of the BIM model between platforms. As shown in figure 2.3, the semi-automated BIM integrated approach is used mainly to transfer geometry from the BIM authorising tool to the simulation tool, which eliminates duplication of effort and time. However, it has been highlighted in several studies that deficiencies still exist in the functional exchange of these models to different platforms to allow multiple iterative trials required for fast and simple optimisation (Yusuf Arayici *et al.*, 2018).

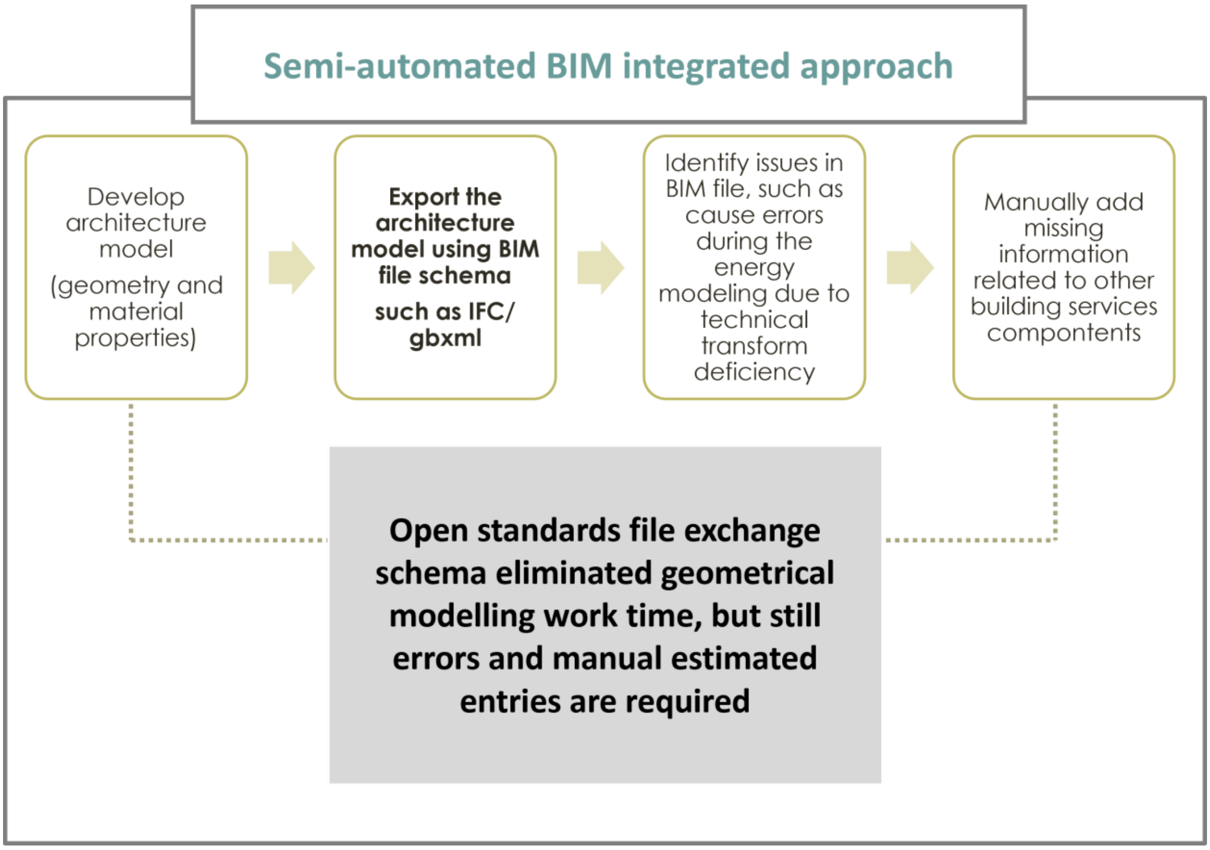

Figure 2.3: Semi-automated BIM integrated approach (Alwan et al., 2021)

It can be argued that both approaches have limitations for practical use in early conceptual design stages and during design development for the purpose of exploring and comparing different alternatives. This can be reasoned by the requirement for manual entry of complicated input variables that have already been estimated by stakeholders in the early stages in the conventional approach. As illustrated in figure 2.1, the workflow for both approaches reflects the effort and time required by the user to compare the energy performance of different design alternatives. These challenges and limitations have motivated the use of simulation and

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parametric approaches on platforms such as Grasshopper plugin for Rhino and Honeybee plugin for EnergyPlus (Shadram & Mukkavaara, 2018), which will be explained further in chapter 4.

2.5.2 Life Cycle Assessment (LCA)

A. Definition and system boundary

Life cycle assessment (LCA) is a methodology for assessing environmental issues comprehensively throughout the whole life cycle of the building process (Naneva *et al.*, 2020). It includes the assessment of whole life cycle of a material in a building, from the extraction and processing of raw materials to the manufacturing of building components, as well as the usage and end-of-life of the building. The LCA technique is standardised in ISO 14040 and ISO 14044, which establish a technique to assess the life cycle of a product as a system. In the building sector, a methodological guide is presented in Standard EN 15978:2011, which is used to guide the quantification of the environmental impacts of buildings. It defines the different system boundaries and building elements that can be included in the scope of the calculation. Figure 2.4 shows that the life stages of a product or material are divided into product stage (A1-A3), construction process stage (A4-A5), use (B1-B7), end-life stage (C1-C4), and finally, benefit and loads beyond (D). The system boundary covers the stages included in the calculation, and it can be, for example, cradle-to-gate which includes A1-A3; or cradle-to-grave which includes A1-A3, A4-A5 and B1-B7, as shown in figure 2.2. It is also important to determine which elements from the building system will be assessed, and they are categorised as illustrated in figure 2.4.

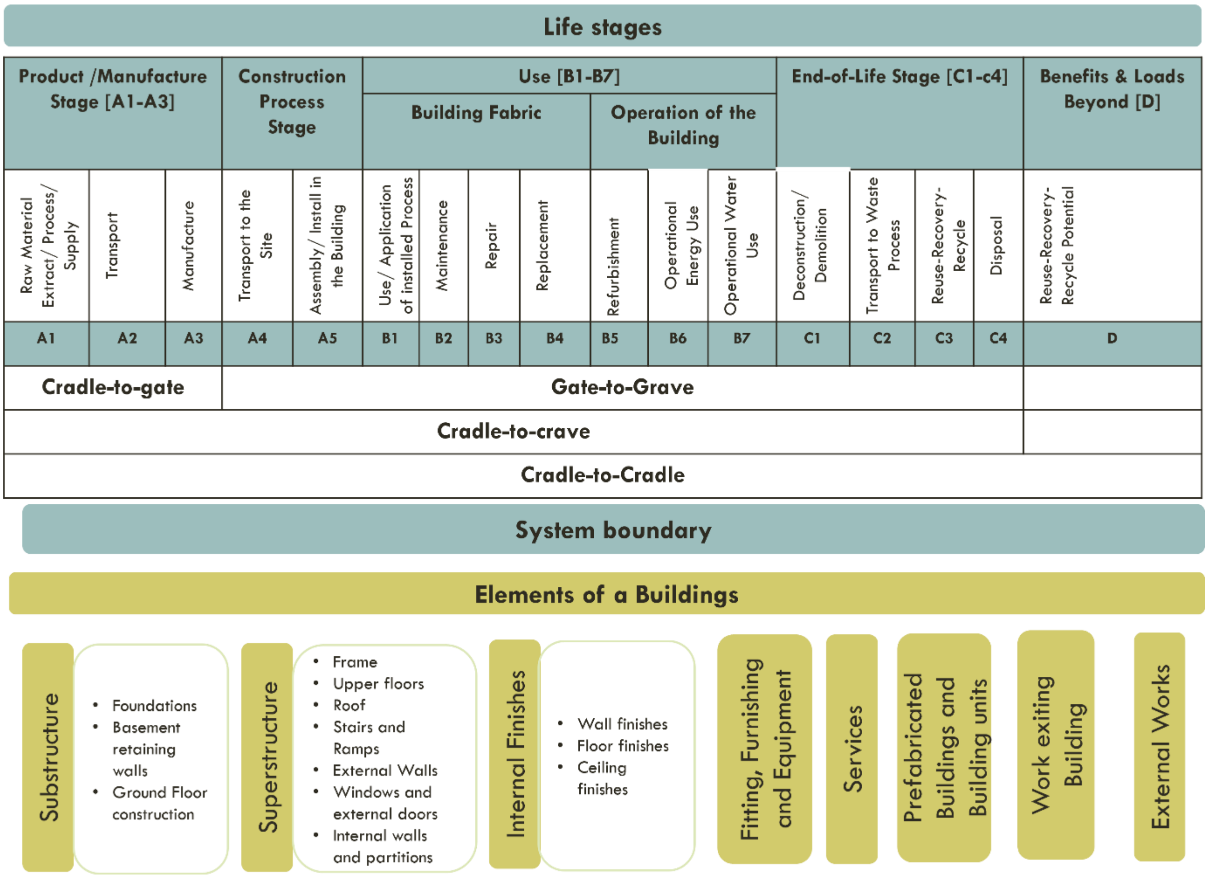

Figure 2.4: LCA system boundaries and elements of a building, based on (Silvestre et al., 2016; Environdec, 2018)

B. *LCA and types of databases*

LCA is considered to be a powerful tool to reduce environmental impacts in the building sector, and it has therefore been reviewed in several studies (Cavalliere *et al*., 2019; Obrecht *et al*., 2020; Roberts *et al*., 2020). According to Russell-Smith and Lepech (2012), it can estimate the environmental impact of buildings over their life span and help people make more sustainable decisions. In industrial production methods incorporating standardised processes, LCA is commonly utilised for environmental evaluation (Braet, 2011). However, when used in the AEC industry, LCA becomes more difficult due to the more complicated processes involved (Ortiz et al., 2009). It is reported in several studies that LCA is complex and demanding in terms of time and effort, due to the considerable amount of information and processing needed. Therefore different approaches to simplifying LCA for buildings have been investigated by researchers. These approaches involve producing a life cycle inventory (LCI) database that contains functional units representing the environmental impact of a material. Also, digital

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integrated approaches have been developed to connect BIM with LCA to allow more efficient processes. To conduct LCA, the bill of quantities of the materials included in the elements of the building chosen to be in the calculation must be calculated by the required unit (area or volume or per unit) and then multiplied by the functional unit. Hence, this process contains a number of challenges, which will be outlined in section D; the approaches of BIM integrated LCA will be reviewed first, in section C.

In order to support LCA calculation, different national life cycle inventory LCI databases have been developed. There are different types of databases: generic, specific, and profile LCA databases (Wastiels & Decuypere, 2019). Generic databases usually contain generic data about a material or component, which is not linked to a particular manufacturer or product. Generic databases can be provided at material level or building element/component level. Examples of material databases include ICE (UK-based), and Gabie database; in this database coefficients (functional unit) are provided per material. An example of a component-based database is Bauteilkatalog, which provides a coefficient per building component. The next type of database is a specific database for environmental product declaration (EPD), which contains LCI data for a specific product provided by manufacturers. BRE provides a collective library in which practitioners can search and find EPDs, named "Greenbooklive". LCA profile is usually a database embedded in a software which is a combination of the LCI of certain materials which forms a profile, such as gypsum board sandwich partitions, which may contain gypsum boards and stainless studs. These calculated profiles make it easier for users to pick the component, instead of calculating each material in the component separately.

C. LCA approaches and tools

Recent studies by Obrecht *et al.* (2020) and Wastiels & Decuypere (2019) have comprehensively categorised the different integrated LCA approaches within the BIM environment. Approaches for integration are categorised into five types, as illustrated in table 2.2. The first type of integration (1) is accomplished by exporting the Quantity take offquantity take off of building materials from the BIM environment into other software or an Excel-based datasheet. This strategy is the most widely used in current practice, according to their observations. The second method (2) involves importing the BIM model in IFC format, which is then manually aligned with established LCA profiles by an LCA practitioner, using a library embedded in the tool. The third option (3) involves processing data from a BIM tool in a BIM viewer, before transferring it to dedicated LCA software. The fourth method (4) involves the use of specifically created plug-ins that allow LCA analysis to be performed within the BIM application. Examples of this software are Tally and One Click LCA. The fifth kind (5) is known as a method for including LCA information (LCI) in the BIM objects that are utilised in the BIM model, rather than attributing it to the building components later in other tools. The LCI database is attached to BIM objects in the parameters of the model. Table 2.3 analyses examples of LCA tools for different tools.

The first strategy depends on quantity take off and uses the BIM model only as quantity take off, then a dedicated LCA software tool or an Excel spreadsheet where LCI is dedicated. Tools (shown in table 2.3) that can be used in this strategy include Athena Impact Estimator, or else databases such as ICE or Gabie can be manually mapped in an Excel sheet; this is considered a conventional approach of LCA. Manual mapping of the database is time-consuming; this approach might not support iterative assessment.

The second strategy depends on exporting IFC from the BIM model and importing it to LCA software. Quantities and structures of elements are automatically imported into the software and are ready to be mapped with the existing LCI library in the tool. This strategy is slightly better than the first approach, as the structure is automatically read by the software, but any updates to the IFC will result in losing previously mapped LCI data. One Click LCA is an example of LCA software that provides this strategy.

The third strategy relies on BIM viewer, where the LCI database is mapped through it. The IFC model is extracted from the BIM model, then BIM viewer is used to assign the material to the LCI library of the tool. In this case it is the same procedure as strategy two, but more visual, as BIM model is viewed and navigation through the model can take place in a 3D environment. An example of this strategy is a BIM viewer, where FDES-profiles (Environmental Product Declarations from the French programme, Inies) are mapped then imported to Elodie software (Chevalier *et al.*, 2010; Wastiels & Decuypere, 2019).

The fourth strategy is the most developed and allows an iterative design process, to be performed in the BIM environment. Examples are Tally (Kieran Timberlake, 2014) and One Click LCA (ONECLICK LCA, 2019.). It depends on plugins within a BIM authorised tool (Revit), as shown in table 2.2. All steps including reading the model structure, mapping, selecting from software library, calculation and visualisation of results take place in the plugin. The LCA results can potentially be shown in the geometric model, offering a rapid picture of the hot spots or most relevant impacts, which is a significant benefit over previous methodologies (Wastiels & Decuypere, 2019). However, one constraint is that only the material database library in the tool can be used, not any specific external LCI.

The fifth approach is constructed through embedding the LCI database in the BIM model by including data attached to BIM objects in the form of parameters (Genova, 2019). This maintains that at any time during the design, the BIM model is associated with the data required for LCA calculation. A further step is needed to complete the workflow by either exporting data to the LCA software or using visual programming languages to automate the calculation and exporting of the LCA results. This approach has been found to have high potential in providing real time LCA assessment and is also flexible. However, an LCI BIM material library still needs to be built first by practitioners, before use. Further and more detailed explanation of this approach can be found in chapter 4.

Table 2.2: Different approaches of LCA (Wastiels & Decuypere, 2019)

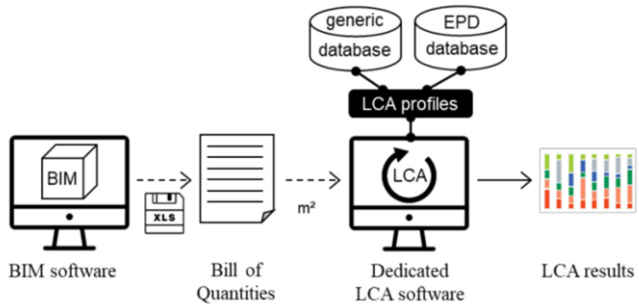
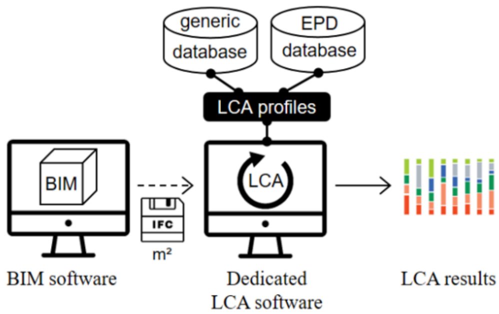
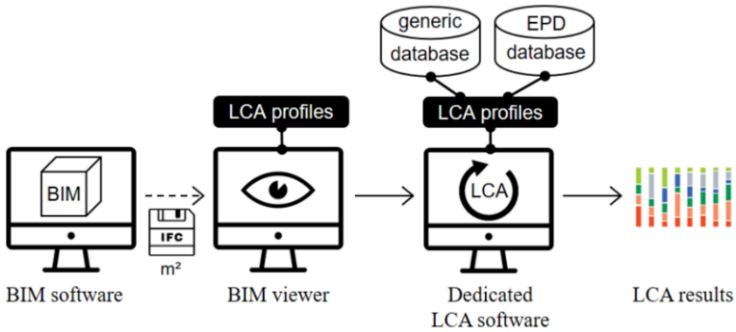
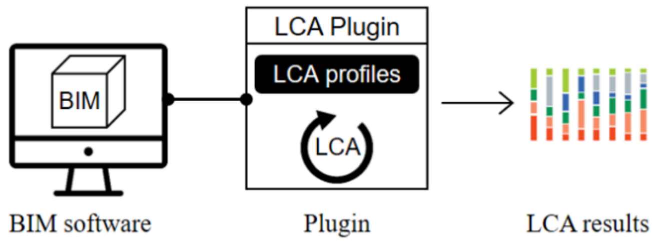
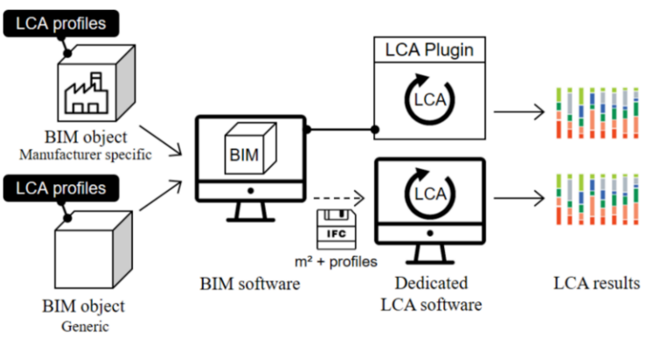
Type 1 **Export BOQ from BIM model to LCA software or Excel file**	
Type 2 **Export IFC to LCA software**	
Type 3 **Use BIM viewer to associate LCA profile**	
Type 4 **Workflow based on use of an LCA plugin for the BIM software**	
Type 5 **BIM objects are enriched with LCA-based information or references**	

Table 2.3: Analysis of examples of LCA tools

Tool	Types	Input required	System boundary and region of database	Interoperability with BIM environment- and complexity
		Within BIM Environment (Type 2,4)		
Tally (Kieran Timberlake, 2014)	**Type 4**	**-Automatic Quantity take-off from model:** Only required to assign the unit of material calculation/ Material take off options (Length, area, volume) -**Automated family identification:** All object are automatically available in the interface according to modelled families. **-Required material mapping** of the existing materials to the material library database in the program.	**Allow cradle to grave system boundary.** - Usually user rely on industry average transportation and construction impact. - Ignores construction details and asks for lump sum value. -Material database used is German database GABi and filtered to North America market and manufacturers.	**Plugin limited only for revit** -It is plug in within Revit architecture or structure model. -Depends on the granularity and detail of BIM model LOD. **-Deal with 3 detailed levels:** schematic design : showing building components weighting. Design option comparison: comparing reports but the after mapping of materials once and executing the results report are available in the BIM model. Complete LCA - **Closed commercial product:** Limited customized development or update for the inventory data and not flexible to other system boundaries.
One click LCA (One Click LCA, 2019.)	**Can be Type 2 and Type 4**	**Import open standard BIM schema file either IFC or gbxml and file additional project information.** Similar to tally.	**Allow cradle to grave system boundary.** -complies with European standards and has template for North American Market as well. -Have different schemes for use in UK and international schemes as well.	**Can be used with wide range of software not limited to one.** -web based interface softaware. (IFC can be plugin in Revit, IES-VE, Graphisoft ArchiCAD, tekla structures….and others. Plugin within revit is recently developed
On separate platform- BIM model can just be used for material take-off (type 1,3)				
Elodie software (Chevalier et al., 2010)	**Type 3**	**Model exported with IFC format from BIM software to a BIM viewer where geometries are mapped with the existing LCA profiles Then this file is assessed by software to do**	-Contains environmental indicators of the NF P01-010 standard -Designed for French context	-Benefit from LCA ready profiles that are generic and EPD specific. -Simplified LCA as profiles are ready to be mapped to geometries in IFC model.

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		calculations and present LCA results		
Athena Impact Estimator (Bowick et al., 2010)	**Type 1**	**Input :** 1. **manual entry of project material take-off** 2. **Assembly information** (geometry, assembly/material choice, loading) 3. **Operational energy information** (annual operating energy) 4. **Building information** (location, life expectancy, occupancy type, floor area, height)	High detailed tool with high range of LCA scoping according to : 1. Object of assessment eg. Core and shell 2. System boundary, Life cycle activities To according include scenario for database -Suitable for Candian and US regions.	-Manual entry of material quantity information and required high experienced LCA individual to complete information module about: product, construction installation, use, end of life. -Very complicated for the use of screening and simplified LCA that is suitable for early design conceptual phases
etoolLCD (Hermon & Higgins, 2015)	**Type 1**	Similar to Athena IE	Similar to Athena IE, but have different schemes for use in UK and international European and US schemes as well	-Manual entry of all Material, Assembly and operational inputs. Have simplified scheme
Ms Excel and data base such as ICE, Gabie, US LCI	**Type 1**	-Manual entry of material quantities that can be -Manual search through data base to get coefficients of the embodied energy values for excel calculations.	**Flexible method** as User can determine the system boundary. Level of complexity is also determined by the user.	-Results are not connected to the BIM model. -Level of complexity is flexible and can be designed to suite the conceptual design stage. -High possibility of errors. --Doesn't allow iterative process as it will be impractical and time consuming. -Reliability is not assured and validation is required.

D. Challenges in LCA

Numerous studies in the last ten years have highlighted the potential of BIM-LCA integration, in addition to the challenges. From the approaches reviewed above, a recent review paper by Nizam *et al.* (2018) provided a critical review of BIM-LCA integration with different approaches, which revealed the challenges of the different methods and approaches to calculating embodied carbon, LCA environmental impact calculation through BIM, and interoperability challenges represented in the exchange of material sustainability data and BIM quantity take off. The next part will discuss these challenges.

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The first challenge identified is the complexity and time-consuming nature of mapping the LCI input data with building material quantities (Soust-Verdaguer *et al.*, 2017). The multiple manual input required to match the sustainability data with the material properties database leads to questions about the practicality of use, due to the long modelling time needed and high susceptibility to errors during transfer. For example, a study by Jarde & Abdulla (2012) assessed the embodied energy and carbon of two houses, one made from mud-brick and the second from cement blocks. The manual calculation presented in the study to estimate the embodied energy and carbon for the two alternatives reflects the high degree of complexity and time required to achieve and compare results, which negatively affects the uptake of this approach by architects in early design.

The second challenge is the lack of interoperability between the BIM model and LCA tools, which limits the role of the BIM model in the framework to an automatic material take-off in type 1. The general method of this approach is illustrated in figure 2.2. Several scholars have attempted to build their proposed methods with this approach. A comprehensive framework was provided by Shadram *et al.* (2016) to estimate embodied energy during building design, with the use of Power pivot – "an Excel add-in which can used to perform powerful data analysis and create sophisticated data models" - as the main data integration platform. In the same vein, Jarde & Abdulla (2012) conducted LCA through BIM by proposing to export IFC from the BIM model and use IFC analyser to prepare quantities required by the LCA tool, which is considered to be a type 2 approach. However, the IFC export file may contain errors, and not all elements are included. Types 4 and 5 are considered the most efficient in overcoming the interoperability problem, as analysis and calculations are carried out within the BIM environment.

The third challenge is determining an adequate granularity and development process for building the BIM model. The development of the BIM model is determined by the level of information (LOI), which describes the associated information to the object in the model and level of detail (LOD), thus determining how much detail is in the geometry drawn in the model. The level of development of the model is connected to the different granularity levels of the databases: some databases provide functional units per materials, components or elements (Obrecht *et al.*, 2020).

Several studies have tackled the issue of the granularity of databases and BIM level of development. Lee *et al*. (2015) proposed a framework for automated LCA within the BIM model without data exchange. This framework utilises parametric modelling and inter-object data relationships which associate embedded impact factors of the materials in the Revit family (∗.rfa) file. After preparing a Revit family for each building element by using a family writer tool, the file is used by the modeller in the BIM authoring tool (Revit). This requires the development of a model of LOD 3 or higher, in addition to the need for a highly skilled modeller to use the developed built-in family. Another method for automating calculation of LCA impact factors without exchange of data is proposed by Jrade & Jalaei (2013). Similar to Lee *et al.* (2015), the framework provided adds a unique keynote i.e. parameter in each Revit material family. Manual preparation of the material library is required before use, by filling keynotes for the potential materials. These studies provide automatic calculation within the BIM environment with no exchange of files between different platforms, although the methods provided are complex and impractical for use in the industry in its current state. This is reasoned by the current lack of a ready-to-use material library, and the requirement for a highly skilled modeller to use the detailed built-in family.

2.7 Summary

This chapter first provided a definition for sustainability in the built environment, then outlined a brief history of how the issue of sustainability gained attention worldwide. This was followed by an explanation of green rating schemes as a mechanism for promoting the delivery of sustainable buildings. Barriers to sustainable construction in general were reviewed, highlighting the lack of technical/technological integration within existing workflows. Therefore, different strategies for assessing and simulating energy and LCA were explored. Various current approaches were discussed, which revealed gaps in literature and practice in utilising BIM capabilities in a way that minimises the need for duplication of time and effort in manual entry or modelling required for simulation and assessment. In addition, problems in ensuring new technologies can work efficiently and effectively while integrating performance-based decisions to deliver suitable buildings have been outlined. These problems do not support iterative performance-based design, as they involve duplication of work, time and effort in processes, errors, complex processes, and the need for repetitive manual entry in order to be able to test design alternatives. In summary, the findings from this chapter contributed to highlighting the current gap in terms of a need for dynamic BIM-based sustainability assessments, and supporting the need to develop a framework and new approaches for maximum utilisation of the capabilities that BIM can provide. The next chapter will review and discuss further BIM capabilities and areas of potential development to enhance integration between BIM and sustainability. It will also present the exploratory case study findings, which acted as a foundation for scoping and guiding the framework and model that will be presented in chapter 6.

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Chapter 3 : BIM enabled sustainability and dynamic design environment

3.1 Introduction

The second pillar of this research is BIM, hence this chapter starts with the definition of digital construction and Building Information Modelling (BIM). Then an alignment of BIM capabilities and design process is discussed. This is followed by explaining BIM enabled sustainability and discussing the change that BIM have created in green project delivery. Through interrogating existing research via a systematic literature review, this chapter takes the original approach of constructing an 'analysis map' to 'bridge the gap' and highlight current limitations and successes between BIM and sustainability practices. For the first time, this research highlights future potential investigation areas, which are argued to be categorized into six clusters: representation; performance simulation; transaction and exchange; documentation; automation; and standardization and guidance. This acted as theoretical contribution to the thesis and it was published in Architecture science review Journal (Ayman et al., 2019). As part of the exploration phase and in order to satisfy objective 2 mentioned in chapter 1, an exploratory case study had been presented in section 37. This case study aims to understand the current state of BIM-enabled sustainability in industry in order to determine relationships, gaps and barriers of adoption. The findings from case study informed the need to explore new methodologies and tools to automate Building performance analysis for dynamic integration within BIM design process. Also, it worked on narrowing down the scope of the research as priority was identified with operational energy, daylighting, and life cycle assessment of the materials assessment being the most important. The structure of the chapter is illustrated in figure 3.1.

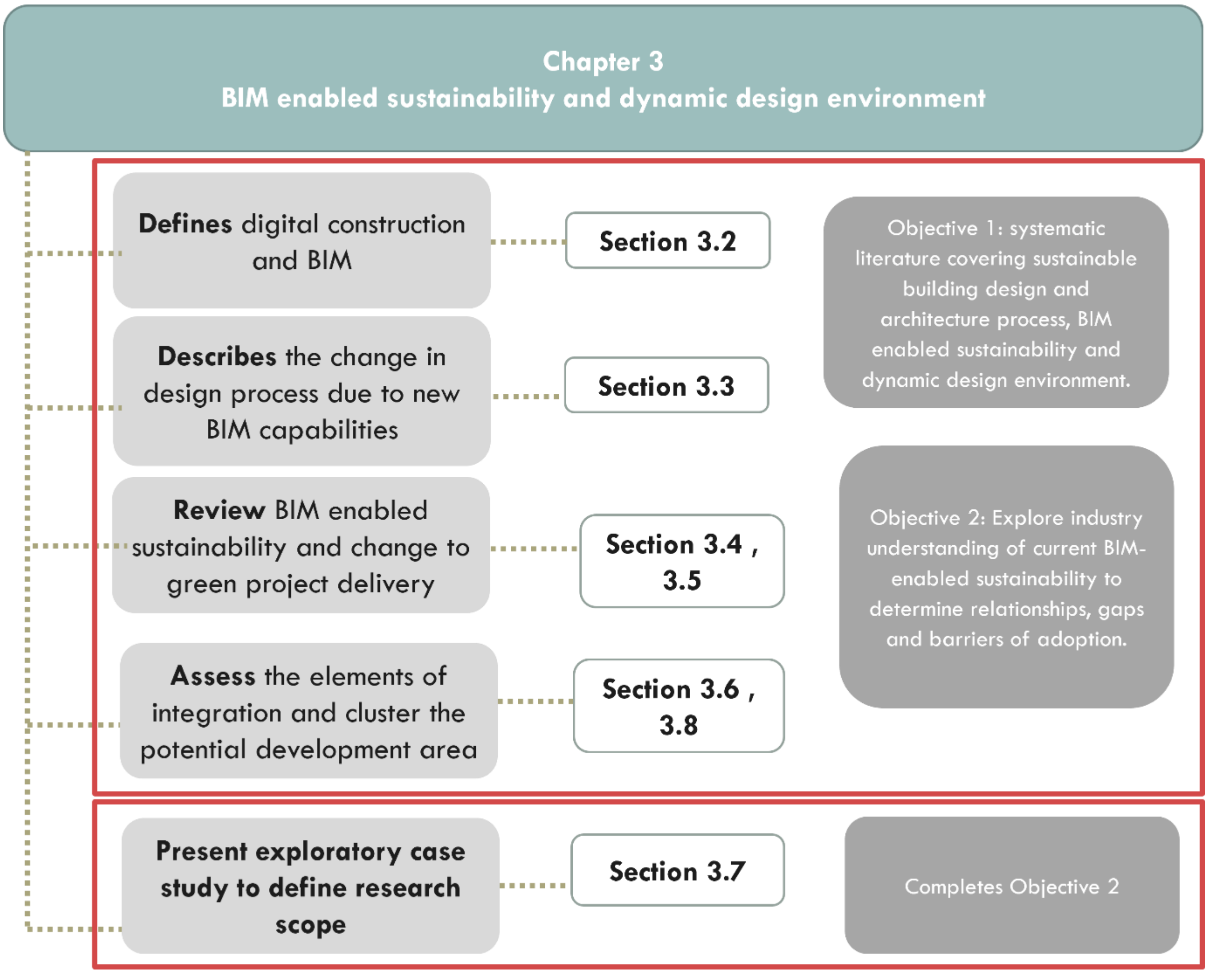

Figure 3.1 Chapter 3 structure

3.2 Digital construction and BIM definitions

Building Information Modelling (BIM) is defined in various ways, which reflects the different understandings of BIM as product, method, or a tool/software. As BIM is not limited to software, it is acknowledged that BIM as defined by the British standards institution is " the use of a shared digital representation of a built asset to facilitate design, construction and operation processes to form a reliable basis for decisions"((BSI), 2018). Also, NBS has defined BIM as "a process for creating and managing information" for a construction project across its entire life cycle. Using a set of relevant technology, a coordinated digital description of every feature of the produced asset is created as part of this procedure. This digital description is expected to consist of a combination of data-rich 3D models and structured data such as product, execution, and handover information. The ISO 19650 and 12006 set of standards are

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the latest agreed definitions of the BIM process and accompanying data formats on a global scale.

Regardless of the definition it can be agreed that it has provided a development of clusters of policies, processes and technologies (Succar, 2009; Eastman, 2011) which have promoted contemporary methods for collaboration within the AEC industry. BIM benefits have been discussed extensively in the last decade (Azhar, 2011; Ghaffarianhoseini et al., 2017; Succar, 2009; Volk et al., 2014). Example of these benefits included early integration of the design models of the multi-disciplines which reduces the frequency of field coordination mistakes; time and cost savings owing to the visualisation of digital models throughout design and construction (Khosrowshahi, 2017).

The next section will discuss the change caused by BIM technologies new capabilities to the design process in context of delivering sustainable projects.

3.3 Design process and BIM capability

The perspective of the BIM change to the design process is discussed through the lens of how the capabilities of BIM technologies are changing the architecture field into leaner practise (Arayici et al., 2011). BIM functionalities provide the designer with new capabilities that can eliminate time consuming tasks of production and collaboration. They also allow margin for iterative analysis through design maturation and development cycles that reinforces the application of the designers' knowledge.

The following section will discuss the literature through the lens of the perceived benefits of BIM as an asset of information. It will develop from the definition used by a pivotal early study in the field by Succar (2009), which divided BIM into three stages: modelling, collaboration and network-based integration. The benefits that BIM capabilities provide in the generation, sharing, management and reuse of information in projects within BIM stages defined by Succar(2009), are listed in table 3.1. Insights on the coverage of these functionalities to serve the delivery of sustainable projects for BIM stage 1 (modelling) and stage 2 (collaboration)are also considered. Table 3.1 categorisesthe BIM technological benefits from previous studies focusing on information use in building design phases and their coverage in the literature related to sustainable delivery. From literature it maps the BIM multi-functionality and

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heterogeneity benefits, and its coverage in serving sustainability practices and green certification processes. BIM stage 1 (modelling) is represented from the perspective of representation and information generation. BIM stage 2 (collaboration) benefits are presented from the perspective of a multidiscipline heterogeneous platform, information and knowledge management, and finally analysis and performance simulation. Each category will be discussed separately in the following section.

Table 3.1 BIM benefits to improve work efficiency and coverage in sustainability context

BIM stage	Benefit	Coverage in sustainability context	Example reference
Stage1: Modelling Representation and information generation	Parametric features: ease remodelling and modification	●	(Fox & Hietanen, 2007) (Azhar, 2011)
	Early visualization and exploration of alternatives	●	(Fox & Hietanen, 2007) (Azhar, 2011)
	Object-based Information for specification and documentation	○	(Eastman, 2011) BIM handbook (Arayici et al., 2011)
	Production: ease of execution, technical drawings and quantity take-off	○	(Eastman,2011) BIM handbook (Arayici et al., 2011)
Stage 2: Collaboration Multidiscipline platform	Coordination and planning of work	○	(Singh et al., 2011)
	Share and data exchange	●	(van Berlo & Krijnen, 2014)
	Data structure for: accuracy and reliability of data (fewer document errors and omissions)	○	(Biswas & Krishnamurti, 2012)
	Model checking and validation: assuring quality of information of different disciplines (consistency-correctness- completeness)	×	(Getuli et al., 2017)
	Compliance checking : regulations and code reviews	○	(Greenwood et al., 2010) (Biswas & Krishnamurti, 2012)
Stage 2: Collaboration Information management: recall and re-use	Progress tracking through model level of development definition	○	(Porwal & Hewage, 2013)
	Information life cycle and re-use	×	(GhaffarianHoseini et al., 2019) (Petrova et al., 2018)
	Standardization and knowledge management.	○	(Zima, 2017)
Stage 2: Collaboration Analysis and simulation	Simulation and performance analysis: operational energy consumption, LCA, daylighting, carbon footprint	●	(Bahar et al., 2013) (Azhar et al., 2011) (Wong & Fan, 2013) (Roudsari, Michelle Pak, Smith, 2013)

● Discussed sufficiently in the context of sustainability practices
× Not discussed in the context of sustainability practices
○ Hardly discussed in the context of sustainability practices

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3.4 BIM enabled sustainability

The synergy between BIM and sustainability is considered to be an area of major interest with extensive attention in the AEC industry (Raouf & Al-Ghamdi, 2018). It was discussed before in literature how BIM technologies and processes could enhance the delivery of environmentally sustainable projects (Azhar *etal* , 2011,. Wong & Zhou, 2015). These studies highlighted the integration and BIM Synergy in terms of facilitating data exchange, providing visualized analysis and simulation of green building attributes such as energy, emissions, material environmental impacts (Alwan 2017, Lu, Wu, Chang, & Li, 2017,). Awareness of the importance of synergy has been raised because of global demand for delivering sustainable projects with increased process efficiency and client satisfaction. The construction sector uses increasingly complex processes and systems, and is characterized to be fragmented, also require multidisciplinary participation, and include multi-systems, which has led to high amounts of waste in the project life cycle (Sarhan ,Pasquire and King, 2017). In the last decade BIM is promoted to enhance dealing with construction sector characteristics mentioned above over conventional ways. BIM's revolutionary technologies are facilitating a proactive decision-making approach by supporting rapid iterative feedback and exchange of performance on changes in design alternatives from early stage rather than limiting just performance testing at the end of design stage (Negendahl, 2015). This have acted as a potential for collaboration platform with which to deal with the construction challenges mentioned above. The next section will discuss specifically how BIM capabilities have affected green project delivery.

3.5 BIM change to green project delivery

3.5.1 Representation and information generation

Representation and information generation are considered a significant advantage for stakeholders, as it saves time and effort using parametric and database storage features for designing and planning documents (Turk, 2016). Digital representation technologies are adopted to serve solutions that improve collaboration and productivity. Representation of building components in 3D form, rapid generation of design and design alternatives, automated generation of drawings and information required, integrity of model and traceability of information changes, rapid evaluation of design alternatives, and object-based exchange are all technical functionalities which caused extensive transformation in the development of AEC practices (Arunkumar, 2018). In the context of sustainability delivery, parametric features, remodelling and realistic visualization functionalities are widely covered in the literature. Ease of technical execution drawings and quantity take-off for covering for sustainability tasks are hardly covered, while object-based information and specification for documentation of sustainability aspects are not addressed sufficiently in previous studies. This suggests that a better understanding of what needs to be presented and a breakdown of the sustainability information that needs to be generated and built up during design processes is still needed.

3.5.2 Collaboration: multidiscipline platform (IFC/xml and gbxml)

Delivery of Sustainability parameters within BIM has largely been derived by compliance requirements in EAM tools; such as LEED and BREEAM, with emphasis on direct impacts daylighting, energy use, impact of materials. This section will use of communication platforms within BIM to how they can assist in delivery of sustainability objectives. In addition BIM-based performance analysis and simulation is the most commonly recognized application of BIM to satisfy sustainability requirements (Azhar & Brown, 2009; Heffernan et al., 2017; Li, 2017).

BIM has enabled a transformation in approaches to collaboration between the project team by providing a multidiscipline platform which allowed stakeholders to model and associate the information required, and to share it with others (Akponeware & Adamu, 2017). The ability to combine different information models from different disciplines reinforced the capability to coordinate building services and systems with the structure and architectural elements, as shown in the benefits mentioned in table 3.1. This reinforced the reduction of uncertainty and provided privilege in planning, estimation and control over new construction projects. This is facilitated by innovation solutions and rapid evolution of Information Communication Technology (ICT) to deal with the increasing complexity of projects in terms of data structure. The use of BIM as a collaborative platform has supported stakeholders to reach project goals at an optimum level. This has been enabled by the ability to exchange virtual information, evaluate performance, and rehearse the effect of decisions on aspects such as cost, time, sustainability, constructability and other factors.

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In order to support multidiscipline collaboration and interoperability among BIM tool adopters, standard form data exchange formats have been developed, including IFC and MVD. BuildingSMART (*BuildingSMART - The Home of BIM*, 2019) established the form of industry foundation classes (IFC) standard as a neural and open standard format to avoid the control of a certain vendor format defined in ISO standard (ISO 16739-1:2018). BuildingSMART also developed model view definition (MVD), which is a standard subset of IFC to define information required in models for a certain purpose. In addition, green building XML schema was developed to facilitate the transfer of BIM models to simulation analytical software tools but was not considered a full data structure of all sustainability elements. These schemas are considered a fundamental ICT requirement in order to apply the benefits of the multidiscipline platform. The BIM development process was positively affected by this major change in enabling interoperability among project participants though the exchange of semantic and geometric building elements, but a mature definition of sustainability factors in those schemas has not yet established. Therefore, practices related to conflict and clash detection for data validation, accuracy and reliability of data to reduce reworking, document errors and omissions still do not include all sustainability parameters, such as materials embodied impact factors on environment required. Scholars have argued that it is necessary to develop parameters in MVD schema in order to deal with sharing and exchange of sustainability aspects and include all the functions mentioned (Maltese et al., 2017a).

3.5.3 Information management: exchange, recall and re-use

In 2018, the first two UK BIM specifications were issued as international standards. They are: BS EN ISO 19650–1:2018 Organization of information about construction works — Information management using building information modelling — Part 1: Concepts; and BS EN ISO 19650-2:2018 Organization of information about construction — Information management using building information modelling — Part 2: Delivery phase of the assets. These standards superseded BS 1192:2007+A2:2016 one principle and PAS 1192-2:2013 on the capital delivery phrase(The British Standards Institution, 2013) are standard specifications for information management in the UK as BIM level 2 protocol; the information life cycle through project phases is described, and information and knowledge management assessment are proposed for re-use. The latest updated contribution is European standard BS EN ISO 19650-1:2018 (British Standards Institution (BSI), 2018), which will replace both BS 1192:2007+A2:2016 and PAS 1192-2:2013. In addition, the release of ISO 15686-4:2014 provided the guidelines that structures the data exchange standard of a facility at handover. Accordingly, BuildingSmart have released standard for data dictionary and minimum information exchange to support delivery of data structure for facility entitled “Construction Operations Building information exchange” (Cobie) using IFC schema. These standards have aided the use of BIM in collaboration using data structures; information management as a standardizing exchange facilitated the recall and re-use of information to develop knowledge management strategies. The information included in the model may vary in order to provide the designer with sufficient elements for decision making, and reduces the risk of omitting any parameters. The information includes geometry and spatial connections associated with properties of building elements such as u-value, fire rating, specification, embodied carbon, finishes, etc. Any parameter can be associated with geometrical information whenever the user finds it advantageous for a particular purpose. This purpose could be documentation, coordination with other stakeholders through information exchange, or calculation and simulation. Building up knowledge contribution with the capability to combine input from different professionals in one model, as mentioned before, enables systematic review of the effect of changes in a project and progress tracking. RIBA (Royal Institute of Building Architects) have developed digital plan of work in 2013that has BIM overlay using definitions in PAS 1192:2013 protocol(BSI, 2013) and linked it to guide of Green overlay (RIBA, 2011) document that outline tasks and information exchange for sustainable project delivery. These protocols provide architects with broad guidelines for process of green BIM, but still Information life cycle, re-use, exchange frameworks, and knowledge management for sustainability delivery purposes are very general and not mature yet.

3.5.4 Analysis and performance simulation

The inherited BIM features: namely the parametric digital representation and link of geometrical, data and informational properties, enabled easier changes to the model and interoperability between BIM modelling software and performance analysis software in the modelling phase. The extra work of repeating the modelling on different simulation platforms is eliminated using gbxml schema, as mentioned before in chapter 2. The tools used are categorized into two phases; firstly, tools that have BIM-inherited features for modelling, and secondly BIM-based analysis tools for calculation. Previous research has addressed the simulation of potential performance, such as energy consumption, lighting analysis, environmental impact of material selection, CFD and ventilation (Wang *et al.*, 2017; Stapleton *et al.*, 2014b). Although a body of literature can be found concerning the use of BIM as a simulation platform, technical challenges in interoperability are still found (Noack, F. et al., 2016) as discussed in chapter 2. It is important to understand the relationship and transformation of data between the tools, and how data are exchanged between BIM authoring tools and dynamic Simulation Accredited Software, in order to determine technical deficiencies in exchange formats. Examples of simulation accredited software; are reviewed in chapter 2, such as IES for operational energy and One click LCA for embodied carbon calculation. Using the results of analysis to evidence performance required by codes, regulations and green rating systems demonstrates an attempt to automate the review process using BIM modelling (Biswas & Krishnamurti, 2012), but validated data structures and processes have not been developed yet.

Alternatively, environmental plugins through visual programming language (VPL); Grasshopper (Grasshopper3d, 2019.) and dynamo (Dynamo BIM, 2019), are rising due to the reported technical deficiency in the standard schema that caused problems in integration of simulation from early design stage, provoked by the limitations of the bidirectional modelling and simulation (Negendahl, 2015). Other plugins, such as ladybug tools (Mackey & Sadeghipour Roudsari, 2018) and topologic are in continuous development to support architects need for fast, iterative and interactive feedback (Aish et al., 2018; Sadeghipour Roudsari, Michelle Pak, Smith, 2013). The development in the VPL approach claim to achieve rapid and flexible analysis that is more sufficient for architects' use than the current gbxml and IFC schema packages (Negendahl, 2015). This will be discussed in depth in chapter 4.

3.6 Elements of integration

From the analysis of the literature that discuss the synergies between BIM and sustainability, it can be concluded that there are three main elements of successful integration. These are The fit between: BIM process and sustainability decisions; BIM technologies and sustainability tasks ; BIM guidelines, people and collaboration strategies with sustainability activities. Research can contribute to one or more area of integration.

The first element of successful integration relates to understanding the fit of sustainability related decisions and tasks into the BIM process and information workflow. Although some studies have attempted to develop BIM-enabled sustainability design process framework

(Zanni *et al.,* 2017), this has not yet been sufficiently defined or verified in depth. Development of this managerial framework should be informed by an understanding of the interactions, roles, tasks, deliverables and decision points of sustainability criteria, in order that they are accommodated in the BIM process. It is also crucial that the transaction of information be defined; understanding of sustainability criteria and how, what information the team needs and why it is needed ,should be translated to the level of development (LOD) required (Lim et al., 2015). Information exchange should be facilitated through the definition of BIM data structures for sustainability. The second element relates to the fit between the BIM technology functionality and sustainability task, including the mapping of tools and software to automate processes, reduce workload, and increase the reliability of predicated performance of the building. It also includes the deficiency in interoperability and data structure definition between BIM modelling tools and building performance analysis programs. In addition, due to the sociotechnical nature of the AEC industry, readiness to accept new tools is an important issue, and frameworks should include the study of both technical issues and team relationships in order to achieve better collaboration (El-Diraby et al., 2017). The third element references BIM-enabled sustainability guidelines in relation to key participants' perspectives and views about the process, to develop the guidelines and standards.

This research scope has chosen to cover the BIM technologies and sustainability tasks fit, which is concerned with the challenges and barriers of stakeholders to integrate current sustainability assessments within BIM workflow.

The next section will present the exploration case study which aims to understand the current state of BIM-enabled sustainability in industry in order to determine relationships, gaps and barriers of adoption.

3.7 Exploratory case study

The summary of the literature review revealed more than one research gap and areas of development as discussed in section 3.7. This attempt to satisfy the first objective of this thesis which is conducting a literature review to cover issues with sustainable building design, architecture process, and BIM enabled sustainability. The review also partially satisfied the second objective to explore industry understanding of current BIM-enabled sustainability in order to determine relationships, gaps and barriers of adoption. But, still it is not enough in to determine the industry understanding of the synergy between BIM and SD. Therefore, a case

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study was required to explore in depth the industry current state. Also, this exploratory case study acted as method to prioritize aspects need to be treated in the scope of the proposed model in this thesis.

The next section outlines the information of the Case study and the strategy of the data gathering and analysis. Further details on the criteria of selection of case study will be explained in chapter 5 section 5.6.1.

3.7.1 Case study brief

The case study that was selected is a National Discovery Centre and hostelin the North east UK upon which construction was completed at the end of 2017. Interviews for the case study were conducted between July 2018 and October 2018; this ensured that the important requirement for using a recent project was met. The gross floor area for the project is around 3000 m2 and the Construction cost is around £9 million.

The targeted BREEAM certification for the project was Excellent, but the final awarded certification was Very Good. BIM modelling was used by architects, Mechanical & Engineering, and structural engineer. NBS Create, a digital specification tool, was used with Uniclass to produce the project specifications, and BREEAM Tracker was used by stakeholders to monitor and manage communications with the BREEAM assessor. These were important aspects of the inclusion criteria for selection, as project data was digitalised and managed in the archival history, allowing observation of the project process and changes in decisions. The information provided for this project by the BREEAM assessor and architect were:

1. Project drawings and specifications.
2. Minutes of meetings at milestones and BREEAM tracker reports.
3. Full package of submitted BREEAM evidence and assessment documents.

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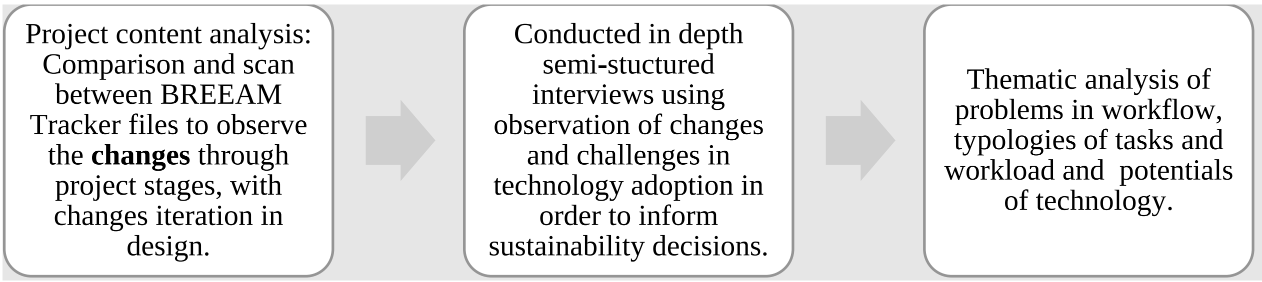

Figure 3.2 The strategy for case study content analysis and formulation of interview questions

Four interviews were conducted, with the BREEAM Assessor, lead architect, architect responsible for BIM execution of models, and BIM manager. The aims of the interviews were:

1. To understand the project circumstances and dynamics.
2. To explore the reasons behind loss of credits.
3. To investigate problems, potentials, and challenges of dealing with sustainability tasks and deficiencies in the process.
4. To explore the utilised BIM capabilities in the project.
5. To prioritise the potential development extracted from the themes of the literature review.

3.7.2 Interviews analysis and findings

The interviews allowed the exploration of the different problems in communication, performance analysis workflow, workload and extra work. The interviews showed how the team used BIM model in the project. The architect emphasized on the use of thermal simulation and daylighting to inform design decisions. Also, feedback from BREEAM assessor was needed to optimize material selection according to BREEAM Material requirements. It was reported that the feedback of the BREEAM assessor was not through BIM model and extra preparation was needed to send the documents required for feedback, Thematic coding to the aspect mentioned is presented in Figure 3.5.

Design decisions and technology use	Stakeholders motivation and individual characteristics	Other problems
1. Task of design high performance fabric and building services: Description of the influence of design decisions on environmental sustainability. 2. Fabric first solution : best solution approaches **Use of simulations to inform design: Thermal modeling inform the design decisions** Collaboration between architect, M&E,	1. Motivation towards attaining sustainability 2. Resistance of M&E for early thermal modeling 3. Performance Analysis on SME scale are not performed by architect as it is time consuming And requires high skill to import input data 4. Architect need to be active to ask about feedback about design.	**1. Documentation and providing evidence (extra workload)** **2. BREEAM assessor feedback is not through model.** **3. Contractual agreement affects project success.** **4. Development of adequate detailed generic libraries and get use parameters still in development.** **5. Non unified classification by all stakeholders** **6. Not all manufactures provided products in a uniclass format.**

Figure 3.3 Thematic coding to aspects mentioned in interviews

The interviews revealed problems related to design decisions and performance analysis. Some sustainability aspects are referred as static (such as use of water efficient sanitary equipment) and some are dynamic which are interdependent of information grabbed from different parties and calculations that affect design decisions. The highlighted aspects that require dynamic and iterative design decisions are: Energy, Materials selection (LCA), and indoor comfort including daylighting. The current workflow and tools are not efficient to explore variety of alternatives due to the:

1. Time consumption of modelling.
2. Complex inputs for architect to do performance analysis.
3. Current simple analyses in Revit are unreliable and based on US use of energy and not flexible to changed.
4. Model transfer is not efficient for multiple runs as M&E doesn’t use Architect’s model to run thermal and energy model.

The architects emphasized the curial role of doing thermal, daylighting and energy analysis to inform their design decisions. It has been found that currently in small and medium sized architecture firms if not requested by the client the estimation of heating/cooling loads, overshadowing studies, optimizing orientation and embodied carbon in material selection are not performed by quantitative methods e.g. using building performance assessment tools uses and at this stage they depend more on rules of thumb and experience of the architect. It is mentioned that it is time consuming and existing tools and easy plug ins are more compliant to US context Not for UK for indicators of energy and cost. The M&E consultants are usually responsible to do simulation analysis and usually resistance is found to do early thermal modelling as it requires high detail in building services information.

M&E consultants do not use the architect model:

1. As they Do not need all the details in the architecture model.
2. As the open standards gbxml and IFC Transfer is still not efficient and multiple of errors occur. (geometry, with transfer problems occur solids and voids)
3. As the manual entries are still required for Materials properties, occupancy, and schedules.

The other analysis is related to the tools available to the architect to evaluate the life cycle assessment of the materials, which indicated the impact of use those materials on environment. Challenges are separately investigated by the researcher in chapters 2 and 3 in order to inform the model development.

3.7.3 Findings informing model development

With the deficiency of the current workflow in BPA reported from stakeholders and need for architect to attain new skills in order to performance analysis, the next phase of research is designed. Visual programming languages VPL platforms in BIM environment are promoted to allow architect to deal with alternatives and analysis iteratively and dynamically. Accordingly, the next phases of the research will describe how model is developed using VPL scripts in order to facilitate dealing with these variables in more Dynamic way. As these tools requires new skills for architect to learn and interact, evaluation phase using user experience methods which is considered one of the human computer interaction methods will be used to test usability of those tools and workflow to integrate performance analysis in design process and deal with them in dynamic way. **This generated the following research question:** Can the use of BIM and visual scripting (automation of tasks) help the architect to have reliable to the performance analysis figure 3.5 to facilitate and inform design decisions within iterative non-linear process?

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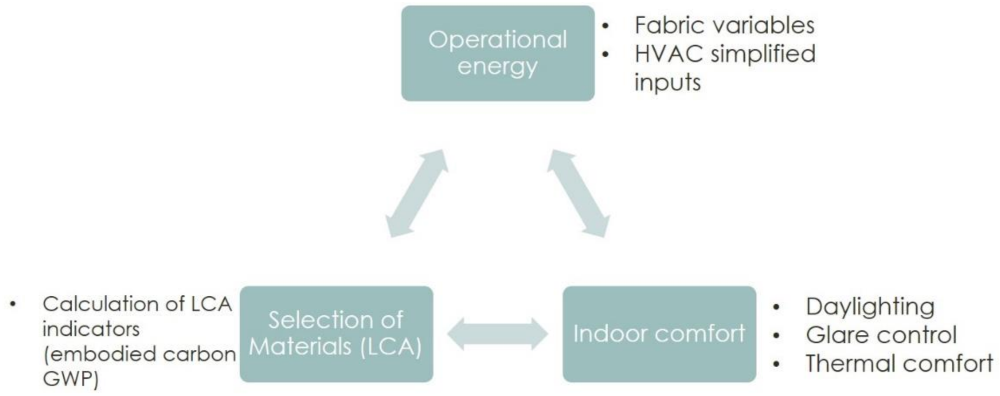

Figure 3.4 Critical dynamic sustainability performance assessments in building design

The findings from the exploration case study and the literature review fed to construct the conceptual model that present the possible future area of development in BIM for green project delivery. The next section will include a discussion of how understanding of these three elements should inform those areas.

3.8 Development areas

The findings of the systematic review and case study led to the conclusion that, although there is great potential for synergies between sustainable practices and integrated project delivery processes, investigation is still required to address deficiencies in the synergies. It is proposed that six areas of development are important for future implications on practice. These six areas have been derived from the systematic analysis of the literature and are listed as follows: representation; performance simulation; transaction and exchange; documentation; automation and standardization; and common guide. Figure 3.5 gives short definitions of the six developing areas. It is also argued that analysis of best practice and knowledge management of the three elements of integration mentioned in the previous section have an essential role in informing the process of integration. The following section discusses each developing area in terms of current state, potentials, and information system and knowledge management required to develop these BIM areas towards delivering green buildings. These development areas need to be investigated in relation to the elements of the sustainability fit within BIM uses and processes in order to determine future directions.

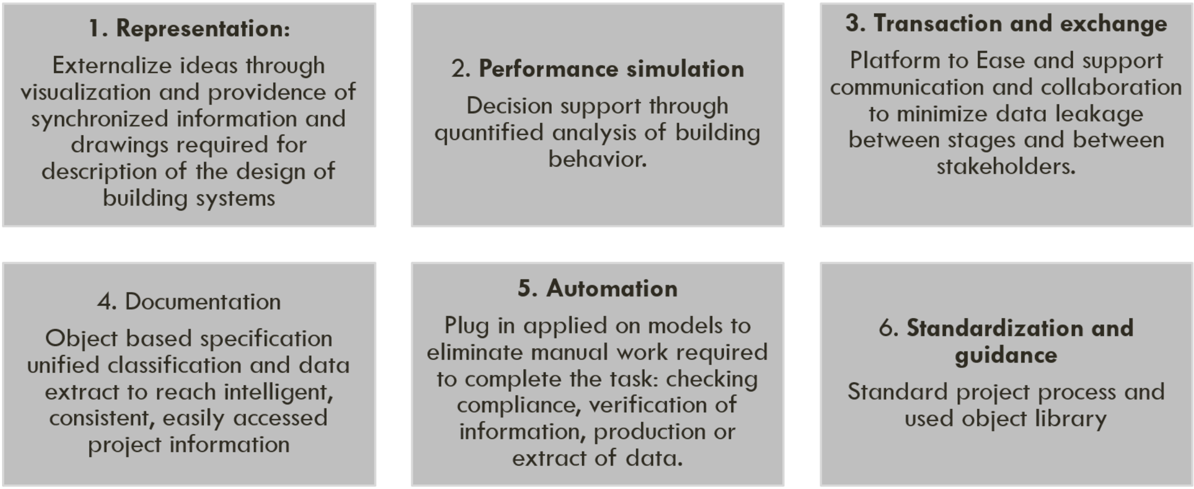

Figure 3.5 Six development areas

3.8.1 Representation

In the previous section, it was highlighted that visualization is one of the most powerful benefits of BIM technologies, and has acted as a major driver in the shift in stakeholder processes to deal with and exchange information on designated elements in buildings. As discussed earlier, better understanding of the designed project and the relationships between the various systems within the building is provided through 3D visualization using BIM tools (Tulubas Gokuc & Arditi, 2017). There are three advantages of representation and visualization between stakeholders listed as follows:

- Realistic representation using different tools to show ideas of designed elements, selected forms, materials, envelope, etc., to serve sustainability targets. Such visualization options have improved the ability to rigorously analyse different alternatives with clients and other stakeholders (Tulubas Gokuc & Arditi, 2017). Sustainable design solutions are easily modelled and changed in the project real-time and this is already common practice in firms which are adopting BIM, which indicates that further development is not a major concern or a critical aspect in enhancing decision making processes regarding sustainability.
- Technical representation: generation of updated and synchronized drawings which illustrate the required information is considered a great advantage compared to the

traditional delivery method of CAD. In order to evidence sustainability decisions in building, a number of technical drawings need to be provided, and these can easily be generated from the model. These could be achieved through the development of project file templates that contain visibility pre-sets on drawing sheets with illustrations and information that fits the required evidence for EAM such as calculated Embodied carbon using LCA.

- Coordination: The ability to visualize building elements within the context of other systems has facilitated the ability to eliminate clash between building systems. Different disciplines use the power of combined models in order to visually identify problems in the relationships between systems. One example of this is specifying mechanical systems, with high performance that will achieve the required sustainability targets, where the specification for the device requires certain room dimensions that are not compliant with in the architecture design. The development of a system which establishes different checking point scenarios would allow benefit to be gained from this advantage within the BIM execution plan.

3.8.2 Performance simulation and decision support

As mentioned before, a large body of studies were found that investigated sustainable design related analysis types in relation to their interoperability with BIM models (Azhar, 2009). Indicators for environmental performance analysis, such as energy and thermal simulation (Bahar et al., 2013), daylighting, value and cost, materials impact analysis and LCA can be simulated on separate specialized tools (Azhar et al., 2011). There is increasing recognition of the value of adopting performance-based design according to simulation results as quantitative evidence of building performance. However, the problems that limit increased adoption of these tools from the early stages are: complexity; increase in cost of process due to the requirement to invest more time and effort; and the reliability of the results (Azhar & Brown, 2009). Although a number of studies are developing ways to benefit from the data created through BIM models and eliminate extra effort caused by duplication of modelling using an IFC format, challenges and problems are still observed and recognized in interoperability (Arayici et al., 2018). The research focus in this area is derived from the use of the IFC gbxml BIM model to be imported into all other simulation programs, avoiding problems in geometry

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disorder and data loss, which all require technical interoperability solutions. The inspection through knowledge information management and use of best practice to ascertain the timing and number of simulations are required to inform design decisions, and the level of development of the model with suitable estimations in order to reach reliable results. As mentioned before. the new approach of simulation using VPL; grasshopper and dynamo, are developing because the method provides a potential to overcome challenges and problems in gbxml IFC exchange schemes which are: interoperability, usability and customization, precision and validity and model speed which provides more dynamic integration of simulation models (Negendahl, 2015). As this platform has shown a high potential in providing a dynamic and iterative way for assessing sustainability performance of the building design, it is selected to be investigated and tested in this thesis.

3.8.3 Transaction and exchange

BIM technologies act as a platform for collaboration by enabling easy exchange of related graphical and non-graphical information (Singh et al., 2011). As discussed in section 3.3, many applications in the BIM functionality were derived from the ability to exchange, combine and check BIM models of different disciplines in order to maintain an optimum decision making process, with minimum requirement for changes in later stages (Biswas & Krishnamurti, 2012). Research approaches were developed focusing on deficiencies in the process of exchange of sustainability aspects within the BIM environment, such as data sharing (Biswas & Krishnamurti, 2012), BIM execution planning for green buildings (Wu et al., 2015), process map and exchange requirement (Baeza Salgueiro & Ferries, 2015), and data schema and workflow structure (Maltese et al., 2017b). However, limited studies were found on developing collective ways of building up data, monitoring the progress of information completeness, checking compliance and extracting information related to sustainability and assessment method requirements within BIM models. In order to reach sufficient exchange of sustainable aspects within a BIM model, it is necessary to set the attributes and parameters which are needed to describe the desired level of information, and then develop a system for monitoring its degree of completeness and compliance. IFC and MVD are agreed standardised method for information exchange for use within the building sector, as mentioned before. It can be observed from the literature and practice that the development of defined MVD and BIM execution plan for delivering sustainable projects is still lacking (Volk et al., 2014). A clear definition of transaction and exchange of sustainability aspects within BIM environment might encourage key participants' engagement leading to successful collaboration. It is therefore suggested that a system for building up data/information, tracking and monitoring progress visually, checking compliance of the information model with regard to the assessment requirements, and extracting the relevant data would ensure enhanced benefit from BIM exchange capability.

Another potential research direction concerns the need to define how to develop better BIM structures for sustainability data, as this is considered a prerequisite to all integration applications. One challenge is to develop a data structure that supports sustainability in the ways the literature review has revealed. It is argued by the process of developing a schema that fully deals with geometric and semantic information (attributes and function) pertaining to all elements about the building is not achievable because it is an endless process (Pinheiro et al., 2018). Nevertheless, it is possible to initiate a framework of sufficient definition to translate sustainability requirements into information objects in a schema (MVD), and then develop it further using built up knowledge about the building systems. This should support the aim of reducing the amount of information about the building that is not digitally linked to the model.

3.8.4 Documentation

The literature regarding problems with EAM processes revealed that the tasks of documentation and evidencing for environmental assessment methods are considered a source of additional effort because they are separated from the work process (Alwan et al., 2015). Extra time and effort are required to evidence the sustainability information within a project, therefore multiple studies found with attempt to automat this process in order to ensure that the data is generated within the project stages (Ilhan and Yaman, 2016;Jalaei and Jrade, 2015). BIM models are considered information assets; researchers have given attention to the development of systematic procedures to enable these models to contribute to reducing the amount of effort, cost and time in order to produce the required documentation for EAMs. Tracking of documentation is usually done through a separate system which is not linked to the built up information in the BIM models; for example, Tracker Plus software (*Tracker Plus*, 2019) for LEED and BREEAM certification. Therefore, taking responsibility for categorizing the type of documentation that is needed, and from whom and when it is required, is necessary

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so that a digitalized documentation system that is linked to the current BIM process can be fully developed. The system for documentation should allow the project team to build up data, monitor progress, check compliance, and extract information within BIM process. More investigation is required to augment how data structure model can be used by project team to define required sets of data sharing for sustainable project (Biswas & Krishnamurti, 2012). Previous studies have attempt to provide framework that utilize Cobie for data sharing and information management for LEED assessments (Biswas & Krishnamurti, 2012), but still studies have to sufficiently cover this aspect.

3.8.5 Automation

The evolution of automating activities and tasks in the construction industry has arisen from the need to work effectively by using the tool's capabilities to inform decisions and minimise the time and effort required to complete work. The second part of the literature review showed that applications of automation in previous studies have tended to focus on generating models that estimate EAM credit points achieved for design assessment and real time feedback (Han et al., 2017; Ilhan & Yaman, 2016), partial automation of materials category documentation (Ilhan & Yaman, 2016), proposed automated certification processes (Jalaei & Jrade, 2015), and cloud BIM models for automated online certification (Wu & Issa, 2012). It may be argued that automation investigation areas have a direct connection to documentation and transaction and exchange tasks to improve communication, inform design, and reduce workload of certification process activities. However, it is still unknown whether these applications would increase efficiency of the work process or not; further development is necessary to enable them to reach a more mature state. It may be argued that such maturity could be achieved through knowledge management and best practice investigations to generate a database within the framework that can deal with building system decision process complexities. However, in order to be able to ensure the reliability of the results of these automated systems, it is important to be able to trust the quality, completeness and validity of the information in the model. Therefore, it is vital to generate rule sets for intelligent model checking of relationships between systems, constraints, and classification, in order to assure that input data is compliant with standards and regulations. It is suggested that insufficient attention has been given to this issue in previous applications.

3.8.6 Standardization and guidance

Standard and guide providence, as discussed in the benefits of collaborative project delivery, is considered one of the advantages of BIM implementation. This concept can be understood with reference to two directions. The first is that the production of standards and protocols defines processes, execution plans, and responsibilities to facilitate BIM adoption and the use of overlapping green assessment methods. In this way guidance is provided for technical and non-technical procedures regulating new processes and roles. Secondly, in generating comprehensive object libraries, templates and schemas that are not vendor-oriented, the process acts as a standard and guide for classification of model data and data organization in order to structure the project life cycle. Standard vocabulary is still a challenge when building, sharing and exporting consistent data, but it is potentially one of the main pillars on which to motivate integrated process.

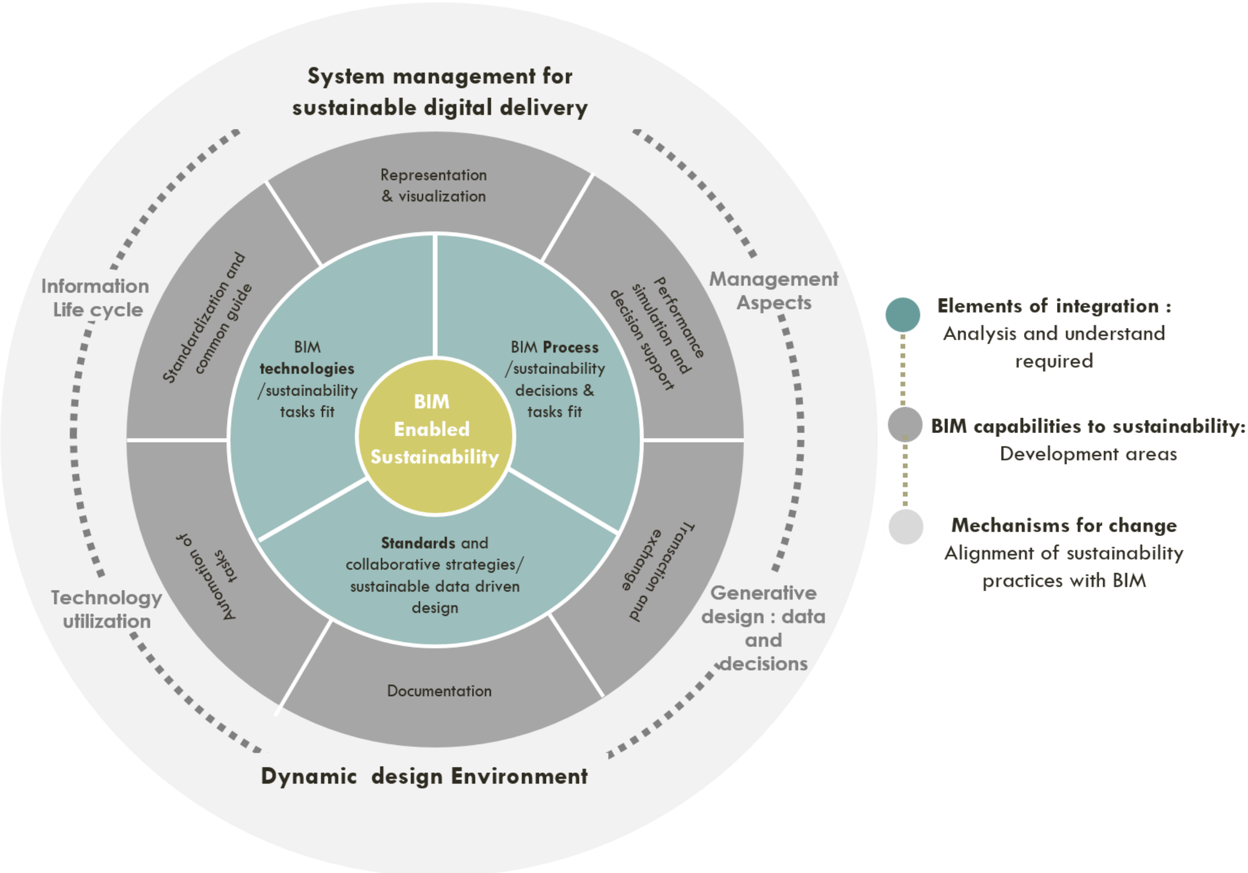

Figure 3.6 Conceptual model for literature recommendation to future research contribution.

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3.9 Summary

The focus of this chapter was to understand how BIM capabilities can serve sustainable project delivery. Global recognition of the valuable perceived benefits of BIM was highlighted, in terms of technical and managerial capabilities to improve efficiency of information generation and knowledge management for different sustainability decision-making purposes. The review provided insights into the diverse contexts of BIM-enabled sustainability applications, information generation and use within construction industry. It was revealed that investigation of the elements of integration formulated within the literature should inform the development of BIM use in the following areas: representation; performance simulation; transaction and exchange; documentation; automation; and standardization and guidance. These elements of integration should be attained through in-depth understanding and definition of the fit between sustainability activities and tasks in relation to the BIM process, BIM technologies and guidelines, people and collaboration strategies. Understanding of the analysis of the element of integration should be reflected in the required development areas in order to amplify the implications of BIM-enabled sustainability in terms of increasing the efficiency of work. This motivates both research and practice towards developing and testing new strategies to address these deficiencies.

This chapter also addressed the limitation of the BIM technologies to deal with environmental sustainability aspects in more dynamic frameworks, which attempt to provide the stakeholders the ability to reduce effort, time and errors on traditional tasks. These developments aim to allow margin for designers' and engineers' knowledge interpretation. This finding is supported by both literature review and exploratory case study. Also, this chapter presented a summary of exploratory case study from industry that aimed to provide insights towards the problems in using BIM model to attain sustainability and gaps in applications, that fed the conceptual model presented in section 3.8. The findings from the case study highlighted the need for developing new strategy to allow the architect to deal with multi-optimization of the design by assessing daylighting, operational energy and LCA of the materials selected iteratively with design alternatives. Therefore, the next chapter will review the potential use of Visual programming languages (VPL) to automate these processes to be able to develop a model and framework for the use of architects.

With respect to the conceptual model presented in section 3.8, the scope of the next chapters is illustrated in figure 3.7 by highlighting in red the only areas that will be included in the following research phases.

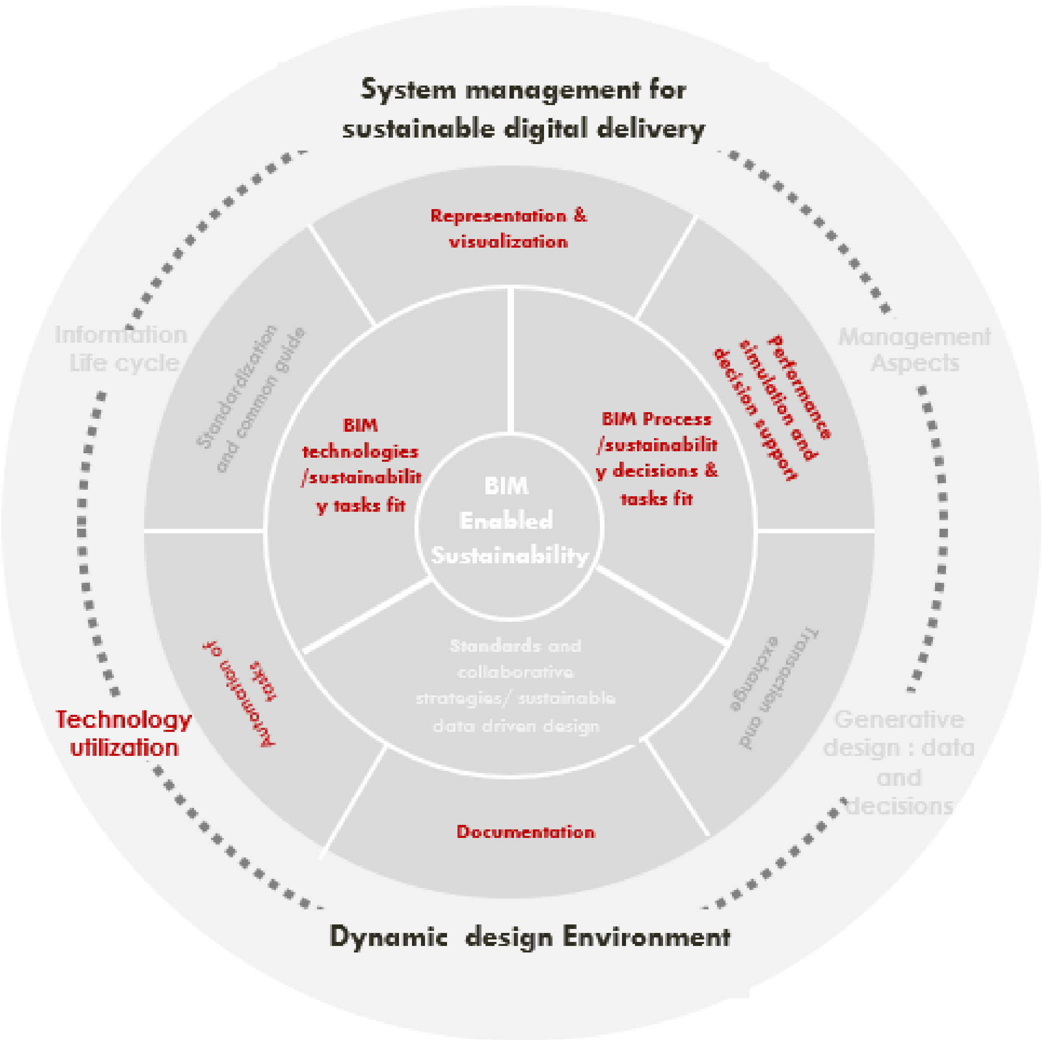

Figure 3.7 The scope of this study with respect to the conceptual model

Chapter 4 : Visual programming language (VPL) and performance-based design

4.1 Introduction

Visual programming language (VPL) is a technique in programming that allows software designers to develop a programme using graphical elements instead of textual languages. This method offers an easier and quicker learning process for non-programmers. Although it has been widely implemented in other disciplines, it has only recently been applied and grown in importance in the AEC industry (Kensek, 2015). The workflow with VPL within a BIM authorised tool is a technique under development which tries to overcome the problems of interoperability (movement of data from one programme to another). The interoperability occurs because of the separation between design and simulation tools as mentioned in previous chapters (Kensek, 2015; Stapleton et al., 2014). Currently, the two available platforms that serve the architecture context are Grasshopper(in conjunction with Rhino) and Dynamo, (for the use with Revit). These techniques allow the architect to work directly with the required performance analysis simultaneously with design workflow; however, this is still relatively new to the building industry. As previously mentioned in chapter one, the framework proposed in this research will employ the use of the Dynamo-Revit platform. A review of previous work involving VPL and performance-based design is included in this chapter. Also, after reviewing both Dynamo and Grasshopper applications, this chapter will focus on the issues around the use of Grasshopper and the need to change between systems which could lead to data loss, which will highlight why Dynamo was implemented in this research.

This chapter will demonstrate the importance of the use of the VPL tool in architecture to act as a driver for architects to learn to use such tools. It will then review current applications of VPL and performance-based design, in comparison with conventional static methods. The benefits, potentials and limitations of the use of these methods will be outlined. Lastly, the previously developed frameworks and approaches for conducting life cycle assessments of buildings using VPL will be investigated and analysed, as the main scope of this study.

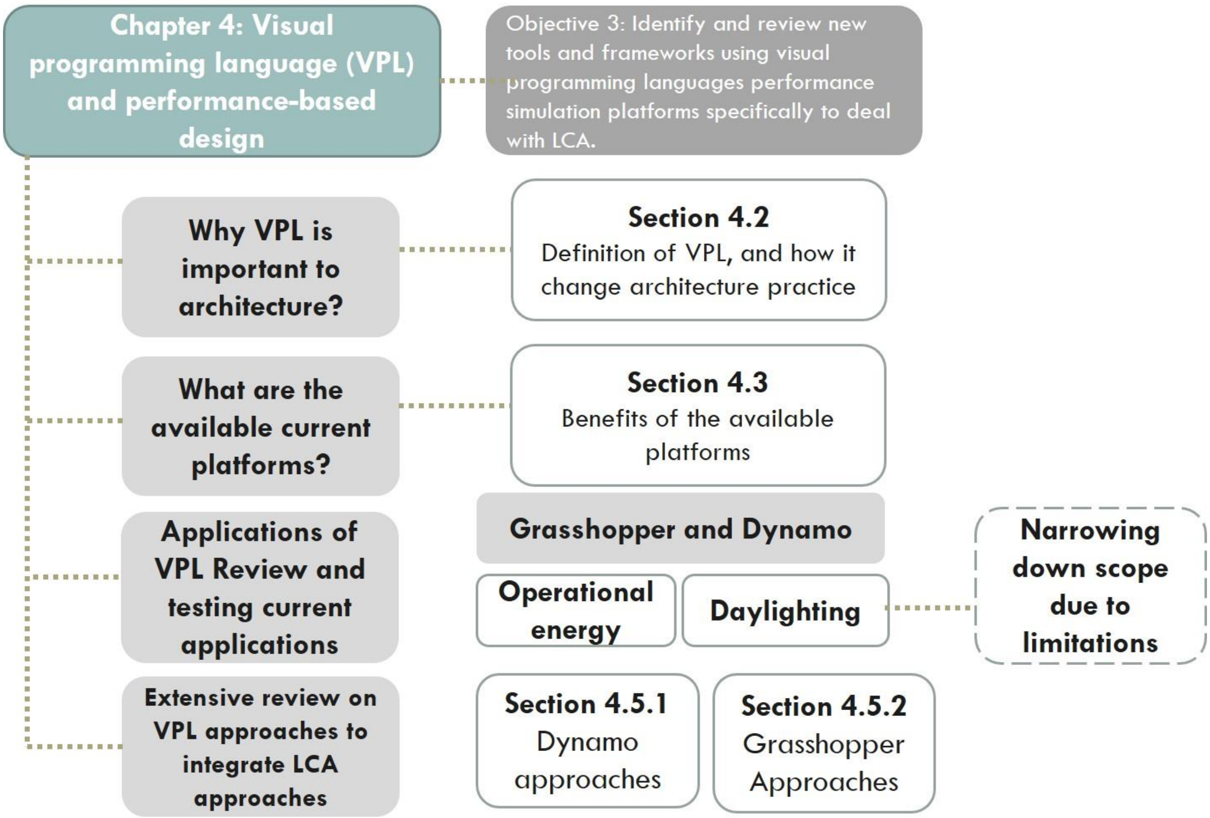

Figure 4.1: Chapter 4 structure

4.2 VPL in architecture practice

In VPL, text code written by programmers - as in Java, C++, Python, etc. - is replaced by a graphical representation similar to a flowchart. Prepacked 'nodes' and 'batteries' are used with connection wires in order to form the script (Ruiz, 2020), as shown in figures 4.2 and 4.3. This methodology attempts to accelerate the potential of non-programmers to learn and use VPL scripts. The concept of VPL in AEC practice started to be used in the past ten years as it leverages the potential of parametric modelling, automation of tasks and performance based design (Kensek, 2015).

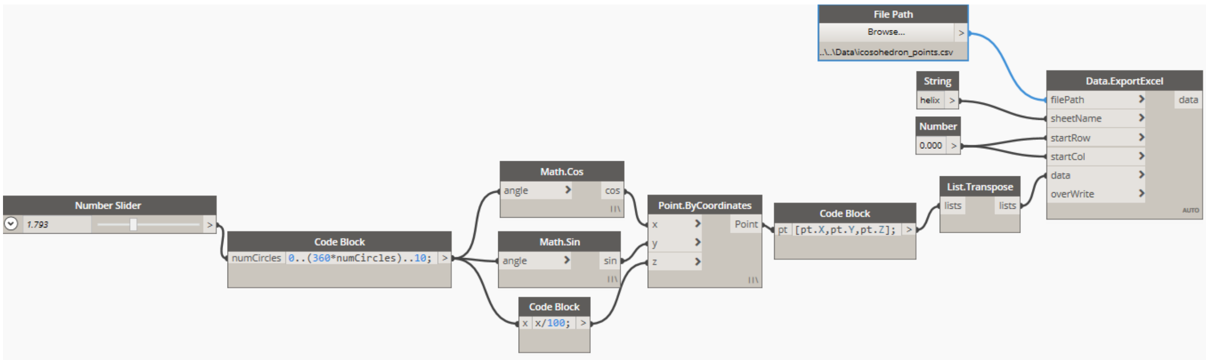

Figure 4.2: Dynamo programme workflow (sample Dynamo file ImportExport data to Excel)

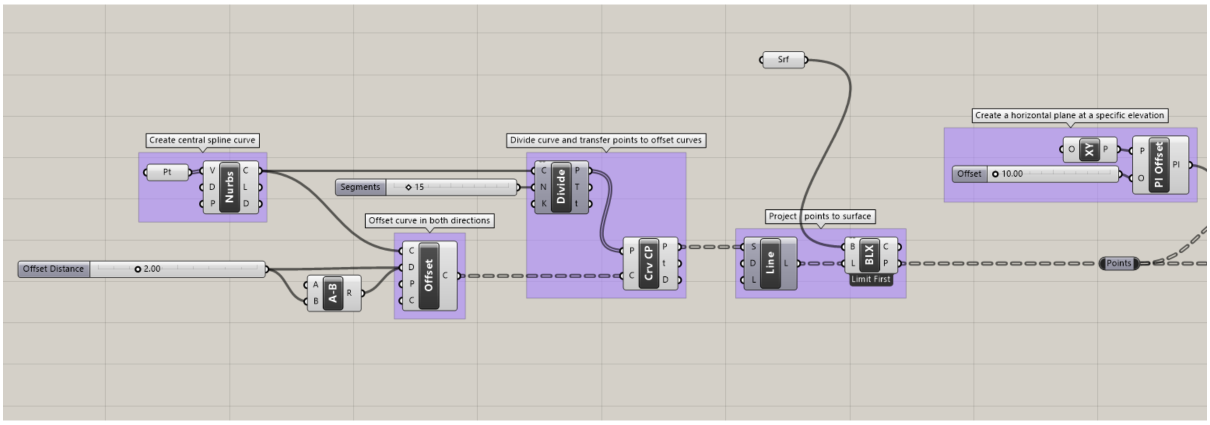

Figure 4.3 Grasshopper programme workflow (sample Grasshopper file create curve)

As discussed in chapter two, architectural decision making needs to be iterative; the heterogenic nature of the design process makes it impossible to satisfy all needs and functionalities in one standard software (Ruiz, 2020). However, with VPL, designers have the opportunity to customise the software around their own needs, preferences and working modes, which motivates innovation. The VPL approach provides flexibility and at the same time, real time feedback loops (Rahmani Asl et al., 2014), which provides designers with additional capabilities that were previously limited to programmers. In addition, liberating the designer from repetitive tasks and time consuming activities provides more free time for the designer to spend optimising the design (Burry, 2013). However, this requires architecture firms to have the vision to allow and enable some designers to change from being passive users of the software, into active users and toolmakers using VPL. The advantages that VPL provides in enhancing productivity and experimentation work as a catalyst to the change happening in the industry towards using scripting for digital design and performance-based design (Seghier et al., 2017).

This section reviews the emergence of VPL in architecture industry, how it serves the change happening in the design process, and the potential for increasing the learning curve of VPL as a future required skill for the designer. The following section will review the applications of VPL on different performance simulation.

4.3 VPL current platforms and software in AEC

In the last decade, the visual programming language concept has been used to develop the use of algorithmic modelling tools in BIM platforms. The most recognised and developed modelling tools are Grasshopper (in conjunction with Rhino) and Dynamo (for use with Revit).. There are also two other tools, which may be less familiar due to limited exploration and development; they are Marionette, which is available from Vectorworks, and Generative Components, available as a plugin within Bentley (Wahbeh, 2017). This section will outline the advantages of using the most diffused and used platforms in digital construction, Dynamo and Grasshopper3D. Their innovative capabilities will be emphasised in the following section in order to highlight their effect on the industry. Of the two tools, greater emphasis will be concentrated on Dynamo, as it is the tool used in the proposed model of this research.

4.3.1 Dynamo

Dynamo is a visual programming open source tool that is used to automate and improve digital building workflow, developed by Autodesk in 2011. It is paired with Autodesk Revit to provide building practitioners with a platform that allows them to construct the required functions using a graphical user interface (GUI) (Seghier et al., 2017). It provides access to Revit application programming interface (API) and extends the power of Revit. Dynamo applies the concept described earlier with reference to VPL, by allowing the user to build algorithms by creating relationships between pre-packed nodes, instead of writing textual code from scratch. This visually oriented strategy makes programming suites more accessible to building practitioners, such as architects, designers and engineers (Kilkelly, 2018).

Dynamo is a VPL tool that allows the user to manipulate data using nodes and wires in the Dynamo workspace, as shown in figure 4.2. The nodes are made up of scripts that have been assigned a task, which might be as simple as storing a number in a list, or as sophisticated as constructing intricate geometry. Python is the scripting language used to create the codes. Most nodes, with a few exceptions, are made up of five components (Skolan et al., 2016), as shown in figure 4.4.

1. Node name.
2. Main body. Right-clicking here brings up options for the entire node.
3. In and out ports where wires are connected.
4. Data preview, which allows you to see the node's primary results in advance.
5. Lacing icon for specifying the lacing option for the matching list.

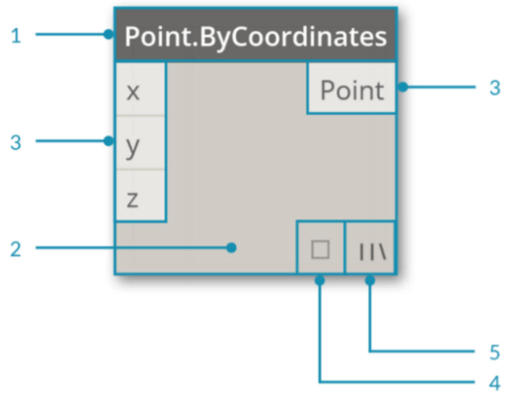

Figure 4.4: Anatomy of Dynamo nodes (Skolan et al., 2016)

A new functionality added to Dynamo - Dynamo Player – has led to an increase in the number of users for Dynamo, as it means that not all users have to code the algorithm (front end users). In such cases, back end users do not have to write Dynamo scripts, but are able to run ready developed scripts simply by using a one button click to provide this function (Seghier et al., 2017).

Dynamo has been shown to be a powerful tool in manipulating the parameters within the BIM authoring tool, Revit, offering an extra degree of associativity and opening up new possibilities for cross-platform and cross-discipline collaboration (Seghier et al., 2017). The use of Dynamo with Revit has added an extra level of ability to control and manage different data types, including parameter values, family geometry, and family placement (Seghier et al., 2017). The user can import, export and map data with Excel sheets, and alter existing elements in Revit. It is also possible to create new elements with required logic or rules. Furthermore, the same Dynamo script may be used on several projects, which is beneficial as it reduces the need for repetitive and time consuming tasks (Kilkelly, 2018).

Dynamo is used in several ways in digital construction workflow. Incorporating the use of Dynamo in daily workflow has been promoted to benefit users in multiple ways (Kilkelly, 2018), listed as follows:

- Automation of repetitive tasks.
- Access to building data.
- Generative geometric exploration.
- Performance testing.

The first feature that Dynamo offers is the automation of repetitive and time consuming tasks, which can transform daily tasks, enabling them to be performed more easily and efficiently in one click. For example, Dynamo users have developed scripts for automating ways of creating sheets, changing text, re-numbering the sequence of sheets, etc. (Kilkelly, 2018). This feature was utilised in the framework, as will be demonstrated in chapter 6, to automate the steps of the workflow, such as creating new materials from the Excel sheet, and creating new project parameters on elemental and material levels; these tasks are considered time consuming if performed in the traditional way through Revit.

The digital paradigm of building information modelling articulates the importance of linking geometrical and non-geometrical data, and having the ability to inspect, modify and coordinate them through parametric object based modelling (Wahbeh, 2017). The second beneficial feature of Dynamo is the access it allows to building data from the parameters attached to elements. This feature has improved control of this data and allowed modifications to be made in a much easier and faster process. Users in Dynamo can construct a “two-way link” between the Revit model and Excel. Dynamo graphs/script can be created to export any specific data from the Revit model to Excel, and Dynamo script can be used to read and import data from Excel into the parameters inside the Revit model, thus providing a very powerful feature. One recent study applied this approach in Dynamo to classify and manipulate non-geometrical metadata of BIM elements, in order to improve the use of this information in the operation and facility management phase (Khaja et al., 2016). This innovative capability is utilised in this research framework in order to import and export material data and calculated data, and link them to the design of the model; this is explained in detail in chapter 6.

Dynamo has been promoted as a powerful design tool in generative design (GD), algorithmic design (AD) and parametric design (PD) (Caetano et al., 2020). Caetano et al. (2020) emphasised specific definitions and differences between GD, AD and PD, but in this context, a general definition of GD is preferred. GD is a 'design paradigm that employs algorithmic descriptions' and encodes the designers' numerical variables, thus generating numerous solutions in order to optimise a design problem (Caetano et al., 2020). GD is utilised in architecture design to generate hundreds of geometrical solutions that can be very complex to design in the traditional way (Wahbeh, 2017). The designer role here is changed from being a creator of the geometry, to being a creator of rules that automate the generation of a variety of designs linked to the desired criteria (Stals et al., 2018). There is huge interest in this approach to design that Dynamo has provided, to support generative and parametric geometrical exploration (Wang et al., 2021). This feature was not utilised in the scope of exploration in this research but, in the context of highlighting the capabilities of Dynamo, it is crucial that it is mentioned.

The final category of new Dynamo capabilities that is provided to the BIM platform is real time performance testing of building design. The approach of integrating building model and performance simulation was initiated and has been found to be more mature in the platforms of Grasshopper and Rhino (Konis & Kensek, 2016); however, several studies have explored Dynamo and Revit platform performance in this area, such as: thermal performance assessment (Seghier et al., 2017); energy efficiency and daylighting (Asl et al., 2011; Baker, 2017); life cycle assessment (Hollberg et al., 2020; Hollberg & Ruth, 2016); and structural analysis (Makris et al., 2016). In addition, other specific relationships have been studied, such as Overall Value of Thermal Transfer Value (OTTV) and Concrete Usage Index (CUI) assessment (Seghier, 2019). Although there has been an increase in such studies in the last decade, comprehensive and extensive explorations of Dynamo and performance simulation frameworks and models are still lacking. Further hands on exploration is needed in academia and practice in order to consolidate workflows and expand applicability and functionality (Kensek, 2015). The next section will overview the other important platform, Grasshopper.

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4.3.2 Grasshopper

The first version of Grasshopper3D was released in 2007 as an add-in on Rhino software, as an open source plugin, and it is now one of the leading VPL tools in the AEC industry (Kensek, 2015; Seghier et al., 2017). Although Grasshopper is not used in this study framework, it is mentioned specifically because it has a substantial set of tools available, and very active community based users. In the context of performance based design and application, the Grasshopper/Rhino environment is more developed than Dynamo/Revit context. However, it cannot be integrated in building information modelling workflow as it is only used in Rhino 3D, which lacks the characteristic of parametric object modelling (Kensek, 2015). Grasshopper is not included in the development of the proposed model, since it is not a BIM authorizing tool and the exchange between the two platforms (Revit and Rhino) causes data loss, which makes the workflow inefficient. Nevertheless, the literature for Grasshopper applications is important to show the possible future opportunities of VPL performance analysis if it is integrated with a BIM authorized platform as Revit, as attempt by Rhino inside Revit plugin.

Grasshopper functionality has grown extensively with the evolution of the third-party plugins/ packages that allow the synchronisation of environmental simulations with parametric design (Konis & Kensek, 2016). This is achieved through linking environmental simulation components and external engines within the Grasshopper interface. The external developers of these components are attempting to automate environmental calculations and link them to the modelling design without having to move the model to export them to another software. Examples of environmental studies include: weather data visualisation; energy simulation; daylighting; material LCA optimisation; and other multiple energy and building material impact optimisation. A sample of the most recognisable and commonly used tools are Ladybug and DHour for analysing and visualising weather data; Ladybug + Honeybee and ArchSim and Gerilla, that link to the EnergyPlus engine; Bombyx and Tortuga for LCA of materials; and DIVA and Honeybee for daylighting. There are other component plugins, such as Octopus, Galapagos, Heliotrope-Solar, and Geo, which are used in Grasshopper for environmental design analysis and optimisation. All of these components are used to assess buildings from an early design phase, and some can be used for detailed and more complex and accurate simulations in design development, in addition to more detailed design phases. As yet, these plugins are not widely used, possibly because they require a new set of skills to be learned by the architects, from modelling to using and developing scripts (Luis et al., 2020), although limited studies have been found on the usability of those tools and factors affecting their rate of adoption.

The Grasshopper3D/Rhino community and developers are working on maturing and advancing simulation sophistication and complexity, which is rapidly escalating the use of this platform. Some developers of the same components, such as Ladybug and Honeybee (Roudsari et al., 2013) are attempting to integrate the same functionality in Revit/Dynamo, but as yet the results are not stable, with errors and problems with slow running performance. This is reported to be due to the limitations of Revit API. Despite the fact that the Grasshopper/Rhino platform currently has more discrete and developed environment than Dynamo/Revit in environmental studies, it lacks the existence of parametric objects which can be used as a BIM modelling tool (Kensek, 2015). Therefore, developers are seeking to find links between Revit, Rhino and Grasshopper; such as the Rhino.Inside Revit beta version (*Rhino.Inside®.Revit*, 2021); however, application studies on its usability are as yet lacking.

The next section will review applications of performance-based design using VPL in order to highlight potential for use and outline the gaps that require more investigation and research.

4.4 Applications of VPL and performance-based design

The exploration case study discussed in chapter three reveals the connection and relationship between design decisions and reported building performance with regard to operational energy, daylighting and embodied carbon (material selection). This section will present earlier studies covering applications of VPL in relation to assessment of these three aspects of environmental performance.

Several previous studies have attempt to apply VPL to analyse building performance aspects such as energy, daylighting, materials, and optimisation, as mentioned in section 4.3.1. However, there is still a lack of a comprehensive framework and workflow for analysing and optimising building sustainability performance. This section will review the previous studies and applications that utilised VPL to integrate sustainability assessment in BIM workflow.

4.4.1 Operational energy and daylighting

With regard to energy simulation and daylighting, Grasshopper has a strong set of tools available, as well as active users and developers (Kensek, 2015). Grasshopper's functionality has evolved greatly since its beginning, mainly involving the creation of third-party plugins, as mentioned in section 4.3.2. These environmental simulation components allow for solar studies, links into energy engines, and optimisation such as EnergyPlus, OpenStudio, Radiance and Daysim. External developers have established a number of components for a variety of purposes; for example, many have created plugins to automate environmental calculations, such as weather data visualisation, daylight and energy simulation, optimisation, and other functions connected to energy simulation.

As mentioned before, a few examples of tools are ArchSim, Gerilla, and Ladybug + Honeybee, all of which link to EnergyPlus; DHour for visualising weather files; DIVA and Octopus (Konis & Kensek, 2016) for daylight and energy modelling; Heliotrope for sun angles; and Mr. Comfy for thermal and climate data visualisation (Kensek, 2015). Numerous studies have utilised those applications, which indicates that the Rhino Grasshopper ecosystem is continuing to expand in size and sophistication.

On the other hand, limited environmental applications have been developed on the other platform, Revit Dynamo. There have been few attempts by developers to provide plugins in the Dynamo-Revit platform. The most famous example is the version for Honeybee and Ladybug that has been provided for Dynamo, but users have reported that it is not stable and that they have suffered from software crashing (Dynamo.Forum, 2020). This study is more concerned with using the Revit route, because practitioners consider it to be the main BIM authorising tool. Therefore, the following sections will investigate the simulation plugins available in Dynamo.

4.4.2 Honeybee test in Dynamo

During this study a test took place to investigate the performance of plugins in Dynamo. Unfortunately, the testing of Honeybee on Dynamo resulted in multiple errors in collecting geometry from the model and performing simulation required. The testing procedure was as follows: firstly, the sample files and “recipe” of scripts provided were downloaded and tested to validate that the system worked. After a few trials, the sample file for Honeybee for a grid

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based daylighting simulation ran successfully, as shown in figure 4.5. Following this, the same script was run on another test model; however, the script was not able to collect the geometry, as shown in figure 4.6.

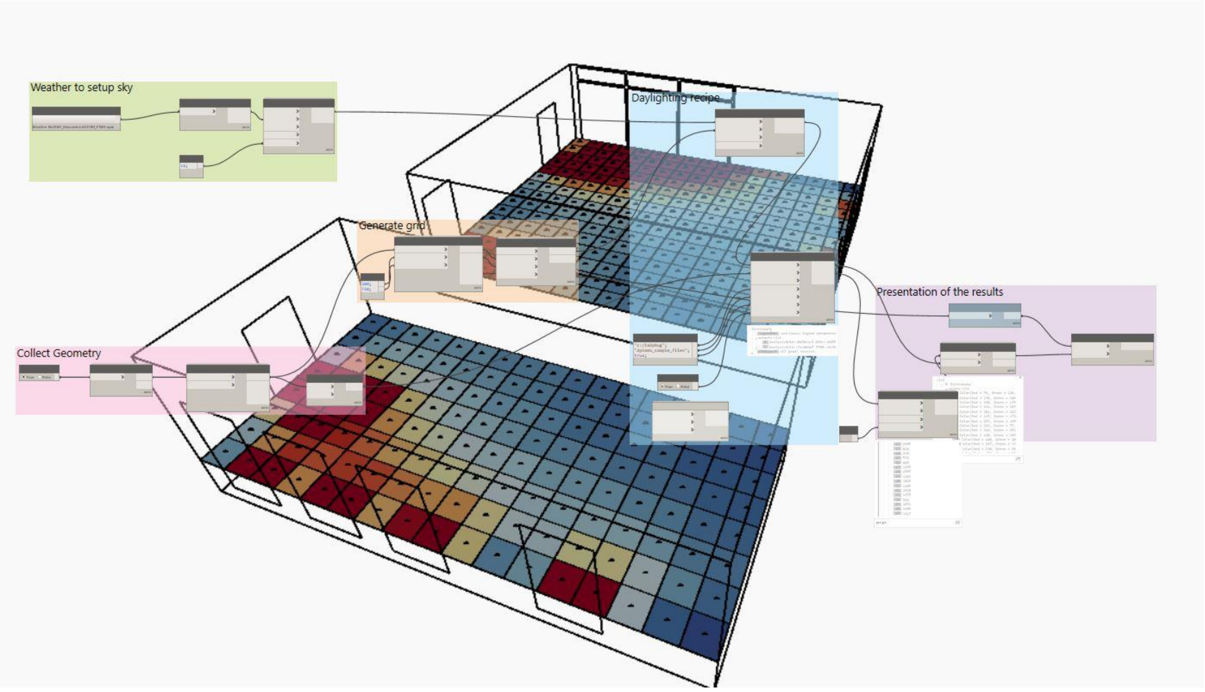

Figure 4.5: Sample file outcome from Honeybee daylighting simulation inside Dynamo

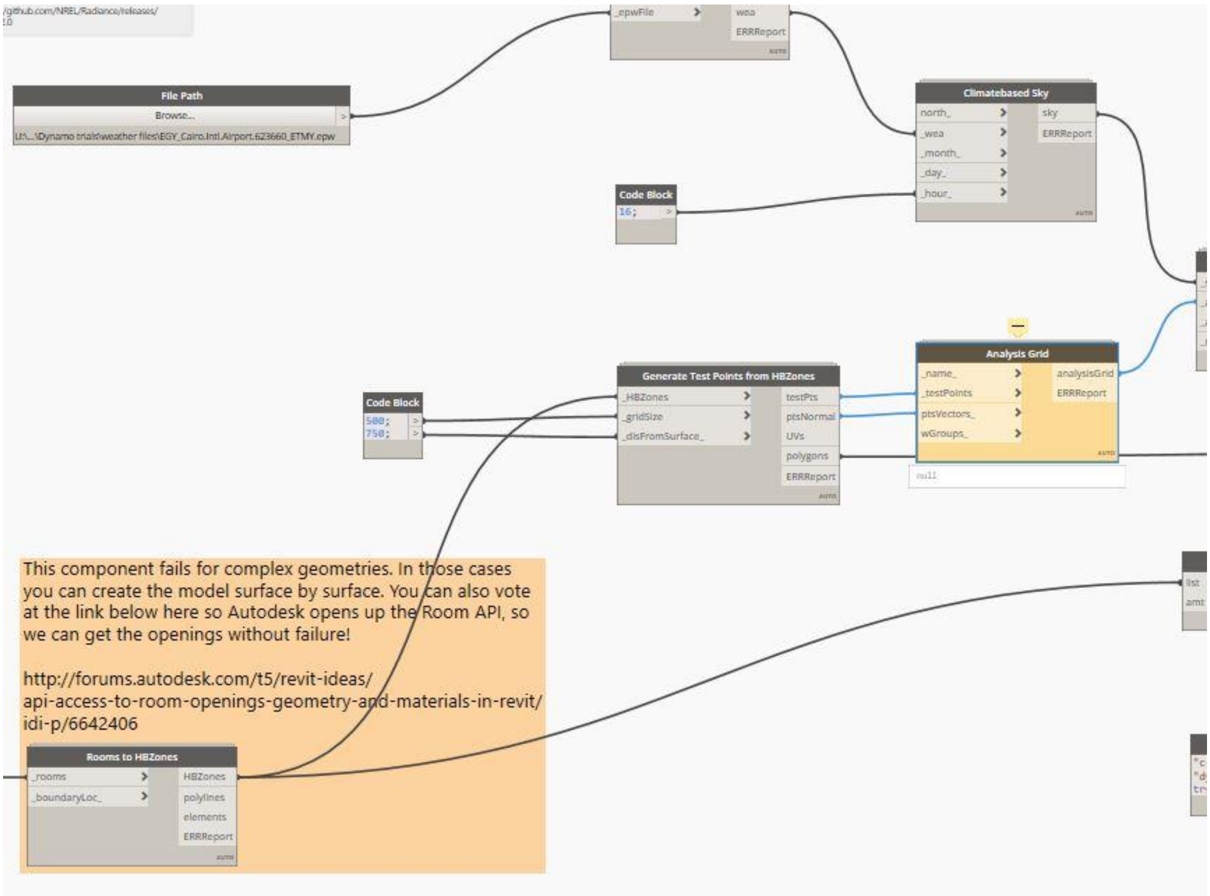

Figure 4.6: Honeybee in Dynamo error in collecting geometry

These errors occurred because Revit geometry is different from Rhino, and they use different approaches in building the model. The key difference is that Rhino is a surface modelling 3D programme, whereas Revit is based on parametric elements like walls, doors, floors, and bespoke components, known as families (Kensek, 2015). A window, for example, includes linked parameters such as width, height, sill height and manufacturer, among others, and new parameters can also be added. Dynamo not only allows users to create 3D geometry in the Dynamo environment ("graph"), but it also allows them to examine and update the values of a family's parameters in the Revit modelling environment. However, this approach acts as barrier as the model is not as lightweight as surface modelling in Rhino. For simulation purposes the Revit model needs to be converted to a surface model in order to be able to apply simulation on it. This is implemented through creating “rooms” in the Revit model. The main problem reported by programmers is that Revit’s Application Programming Interface (API) does not allow easy or direct accessibility to the room information. Programmers are still working to enhance the integration of their applications in Revit through Dynamo, but the current performance of these plugins is very slow, and simulation is unsuccessful in most cases (Github, 2021).

4.4.3 Other operational and daylighting approaches in Dynamo

The main problem outlined in the above section concerns the barriers to creating a lightweight surface model, where the simulation engine nodes in Dynamo can deal with it. This issue was tackled by Topologic developers. Topologic is a software modelling package that can be used within Dynamo or Grasshopper, that allows non-manifold topology (NMT) to be used to create hierarchical and topological representations of architectural spaces, structures, and artefacts (Aish, R. et al., 2018). Topologic is a core library with plugins for visual data flow programming (VDFP) applications and parametric modelling platforms. It is designed to enable architects to engage with it to undertake architectural design and analysis activities using these tools. The purpose of Topologic is to create a lightweight representation of a building as an exterior envelope, as well as the subdivision of the enclosed interior into discrete spaces and zones, utilising zero-thickness internal surfaces. Topologic allows the user to utilise cellular spaces and surfaces with topological data to do various analyses. The input data requirements for energy analysis simulation software have been found to be well matched for such a lightweight and consistent representation.

The library contains nodes that allow the user to construct their geometry using the parametric approach with connected topology. It also contains a number of nodes that allow energy simulations by connecting EnergyPlus (Chatzivasileiadi et al., 2021). This approach showed high potential for architects performing energy simulations to overcome barriers of interoperability between BIM and building performance simulation tools. It also highlighted that performing simulations on lightweight models can minimise problems with crashing and slow process speeds. However, this approach is limited to use by architects with high skills levels in creating geometries by scripting a parametric model; thus, it is not suitable for the workflow of creating a BIM model in Revit.

Another approach was introduced in an academic study in which a non-dominated sorting generic algorithm was used to improve daylighting and energy efficiency (Rahmani Asl et al., 2014). The Thornton Tomasetti CORE Studio's "Energy Analysis for Dynamo" package was released to connect Revit’s conceptual modelling environment with many of Green Building Studio's (GBS) fundamental features within Dynamo. Technically, conceptual masses are not

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controlled by parameters in the same way that fully detailed building model components are in Revit. This means that Dynamo only connects to GBS, therefore any complex adjustments or viewing of results must still be done in GBS. Due to the limitations of this application and its link to Green Building Studio only, simulation could only be performed on conceptual models, and there has been no uptake or further development in later years.

The results of the investigation that took place in this section are supported by an earlier study by Kensek (2015), who reported several limitations of the Revit-Dynamo platform. From the results of the literature review and the trial performed with Honeybee, as described above, it can be concluded that energy simulation packages for Dynamo are as yet not very stable or mature, and still need more development.

4.4.4 Research scoping due to technical limitation

Rhino, together with its visual scripting platform, Grasshopper, and various native and non-native plugins, excels in parametric model analysis and solution production. But it falls short in BIM and documentation, necessitating significant effort for proper project documentation (Kim & Lee, 2017). Meanwhile, Revit is the most extensively used BIM software in practice, which succeeds at documentation and tracking the necessary information, and is therefore the main dependent source of a central BIM model. Nevertheless, it lacks the power of generating evaluation through analysing real time energy and daylighting simulations in parametric models, as stated above. Any practical real time parametric simulation should be able to deal with models generated from Revit to avoid needless duplication of work in modelling design changes and testing alternatives. Unfortunately, the literature review has revealed that within BIM workflow application, a smooth interoperability with Revit Dynamo coupled with operational energy and daylighting simulation are still unstable and needs more development.

Due to the multiple challenges and limitations presented and reviewed in this section, a decision was made in this research study to narrow down the scope in order to focus on incorporating LCA only into the proposed model. The next section will describe in detail the previous VPL approaches that have been proposed in attempts to integrate dynamic LCA assessment into the BIM design process.

4.5 LCA VPL approaches

As discussed in chapter 2, LCA is a commonly used methodology for quantifying and reducing upstream and downstream environmental impacts throughout the life cycle of buildings (Budig et al., 2021). Recently, LCA has been increasingly used to optimise material selection, but time, cost and other aspects mentioned before have acted as barrier for most stakeholders (Nwodo & Anumba, 2019). Multiple studies have amplified the importance of enabling iterative and early LCA assessment via an easy to use LCA tool (Safari & Azarijafari, 2021). The most recent studies have attempt to use VPLs such as Grasshopper and Dynamo to integrate LCA methods into BIM from an early design stage (Hollberg et al., 2020; Kamari, 2021).

4.5.1 Dynamic LCA in Dynamo

Recently, few scholars have developed tools and frameworks using Dynamo as a VPL platform to link the process of LCA calculation into the BIM design environment (Bueno et al., 2018; GENOVA, 2018; Tsikos & Negendahl, 2017). They are considered to be the first scholars to start developing tools using Dynamo as a VPL platform in order to automate the LCA process in the BIM environment. All of these studies used the same idea of creating parameters inside a BIM template file in order to link to the selected LCI database that contains the functional unit of the environmental indicator. In this way, the Revit material or component library, with a permanent link to LCI, is achieved within the BIM environment. Through this link, VPL scripts are used to automate calculation and the visualisation process of LCA. The next section will review these pivotal studies.

Bueno et al. (2018) proposed to automate the insertion and extraction of LCI database using ReCiPe 2008 methodology (Goedkoop et al., 2009) to calculate midpoint impact categories. The script's function is to insert the prepared indicators' values per component into the parameters created manually to accommodate these values by family name. Then another script is responsible for multiplying the quantity of the indictor and exporting it to an Excel sheet.

An earlier study by Tsikos & Negendahl (2017) presented the same idea of using Dynamo to connect the LCI database of material, which contains the environmental impact functional unit; then scripts are used to calculate LCA and extract results.

Genova (2018) proposed a novel approach in automating all the steps required to create a BIM template that contains LCI. This framework provides more detailed and mature steps to

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automate the LCA process using VPL. The database used in this model is the KBOB (Koordinationskonferenz der Bau-undLiegenschaftsorgane der öffentlichen Bauherren) LCI material database. All results of LCA are stored and saved within the BIM environment. The scripts proposed cover the automation of all steps of the LCA process, from BIM template preparation to LCI data interstation, then to calculation, extraction and visualisation of LCA results.

Building on the above studies, Naneva et al. (2020) provides the concept of a dynamic tool for LCI using a combination of the Swiss databases: KBOB, Eco-bau, and IPB (Interessengemeinschaft privater professioneller Bauherren). The idea of combining these different databases serves the implantation and use of this tool at different phases of the design, as they fit with different BIM levels of development (LOD). The Swiss material and component databases acted as strength point and base for the generation of the tool to provide a new process structure for LCA integration in the BIM process. This tool uses Dynamo into Revit to connect the material functional unit values to the BIM model. The parametric tool automates all of the steps required to create a dynamic LCA - LCA parameter generation, calculation, and verification - as well as producing an LCA report. LCA environmental indicators are calculated, validated, and filtered for evaluation and visualisation through the LCA parameter (environmental indicators). After that, the results are exported as an LCA report. The novel approach in this study is the combination of Swiss databases at different LODs to serve different stages of design.

The studies discussed in this section have demonstrated the applicability of developing Dynamo scripts in Revit to automate the LCA process in order to overcome the barriers of traditional calculation. The studies reviewed utilise Swiss databases; however, suitable combinations of databases that can be implemented in the UK are still lacking.

4.5.2 Dynamic LCA Grasshopper Rhino

On the Grasshopper Rhino platform, Bombyx, Tortuga and CAALA are the most famous packages for automating LCA, with all of them using a similar approach (Apellániz et al., 2021). The most recognised application for LCA is Bombyx (Basic et al., 2019). Bombyx is a plugin that can be downloaded in Grasshopper. This plugin provides designers with the ability to map all geometries in Rhino 3D against the existing Swiss material library. The 3D model is light, single layered, and simple. The user has to map the single layer which represents the element into multiple materials using components from the Bombyx plugin. For example, the wall is modelled as single plane and then defined as materials, including bricks, mortar, insulation, etc. The benefits of the Bombyx approach is that it provides flexible environment for LCA assessment with lightweight single layered 3D model, with an embedded ready material library from a Swiss database. However, users have to be knowledgeable at building scripts in Grasshopper, as all mapping materials will occur inside the script. There is also a problem for Revit users, who have to use an intermediate plugin Rhino inside Revit, which is still under testing in a beta version, and unstable. Although the tool provides high potential for providing an easier and simplified approach for LCA assessment, this means parametric modelling cannot be achieved, because any changes in design are not automatically updated or recognised by the tool. Besides this, use is limited to the Swiss material library KBOB database only.

Another approach has recently been introduced by One Click LCA, a commercial software for automating LCA. This involves a plugin introduced for Rhino and Grasshopper in order to integrate LCA with parametric design using VPL (Apellániz et al., 2021). It provides two plugins for Rhino where the user manually maps the building elements with the provided library using the user interface provided, which is similar to the CAALA approach. Another plugin is provided for Grasshopper, where the user needs to have more advanced skills in order to deal with the nodes provided to link the geometry by the database using built up script, which is similar to Bombyx and Tortuga. This approach has high potential for visualising results on the model, in addition to implementing multi-objective optimisation, such as price, using other available plugins, such as Octopus (Apellániz et al., 2021). However, these functionalities cannot be implemented with Revit workflow, for reasons mentioned above.
Although Grasshopper has shown a stronger state in the applications of performance based design, it can not be adopted in this research model due to the change between the BIM authorized tool (Revit) and Rhino lead to data loss. Therefore, dynamo was implemented in this study.

4.6 Conclusion

This chapter discussed the different applications of VPL to serve performance-based design. In the last decade architects and researchers have shown strong interest in using and developing tools using VPL. It has been proven to be a powerful tool to create customised and flexible algorithms, enabling users to automate repeated tasks with real time feedback, which allows the dynamic workflow needed in the industry, as addressed in chapters 2 and 3. Rhino, coupled with its visual scripting platform, Grasshopper, has shown powerful capabilities in parametric model analysis and solution production, but workflow within the BIM environment is not yet smooth, due to the loss of data in exchange between the two systems. On the other hand, literature and hands on testing have revealed that simulation plugins are still unstable and very slow on Revit-Dynamo platform, which is considered the main BIM authorising tool. However, potential was found for Revit-Dynamo to automate the LCA process and integrate it within BIM workflow.

None of the studies reviewed in the literature have gone beyond the step of developing the tool using VPL. Consequently, there is a gap in knowledge relating to perspectives on the use of these tools by architects. In addition, the literature has revealed that a VPL model using Dynamo and a material database that suits the UK context is still lacking. Therefore, the following chapters will discuss how this research will address the gaps outlined above by utilising VPL platform Dynamo to formulate an automated BIM integrated LCA framework, then testing its usability.

Chapter 5 Research design and methodology

This chapter describes the steps taken in developing a methodological approach during the research. The aim of this chapter is to define the logical sequence of the research design, which connects the research question and its nature to the research strategy and techniques used, and the empirical data collected. Research design here refers to the methods used to collect, analyse, and answer the research questions raised, and provides a framework for conducting research (Knight & Ruddock, 2008). The following sections start by discussing in detail the underpinning philosophical positioning and reasoning approach. Following this, it will define the research principles which inform the chosen strategy, methods, and techniques of data collection and analysis. After the selection of the relevant techniques, the research phases are presented in the research design section, followed by a summary of the research choices expressed in research design layers. The chapter structure is illustrated in figure 5.1.

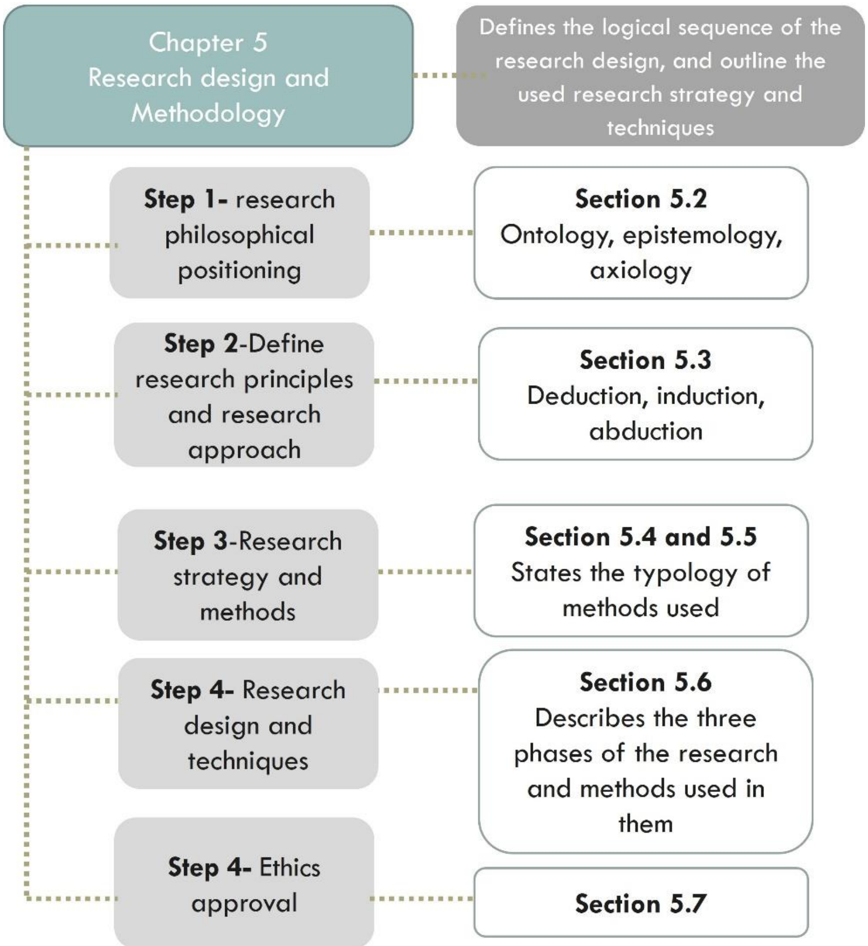

Figure 5.1: Chapter 5 structure

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5.1 Research design introduction

This chapter follows the nesting concept of the methodological elements defined by Saunders, Lewis and Thornhill (2012), shown in figure 5.1. The diagram represents the different layers of the research onion, which presents a hierarchy of factors the researcher should consider in order to construct and define the research design and process. In the following sections the research design and process, from defining the research philosophy up to decisions made regarding data generation, collection and analysis techniques, will be based on this understanding of the research onion (Saunders, Lewis, et al., 2012).

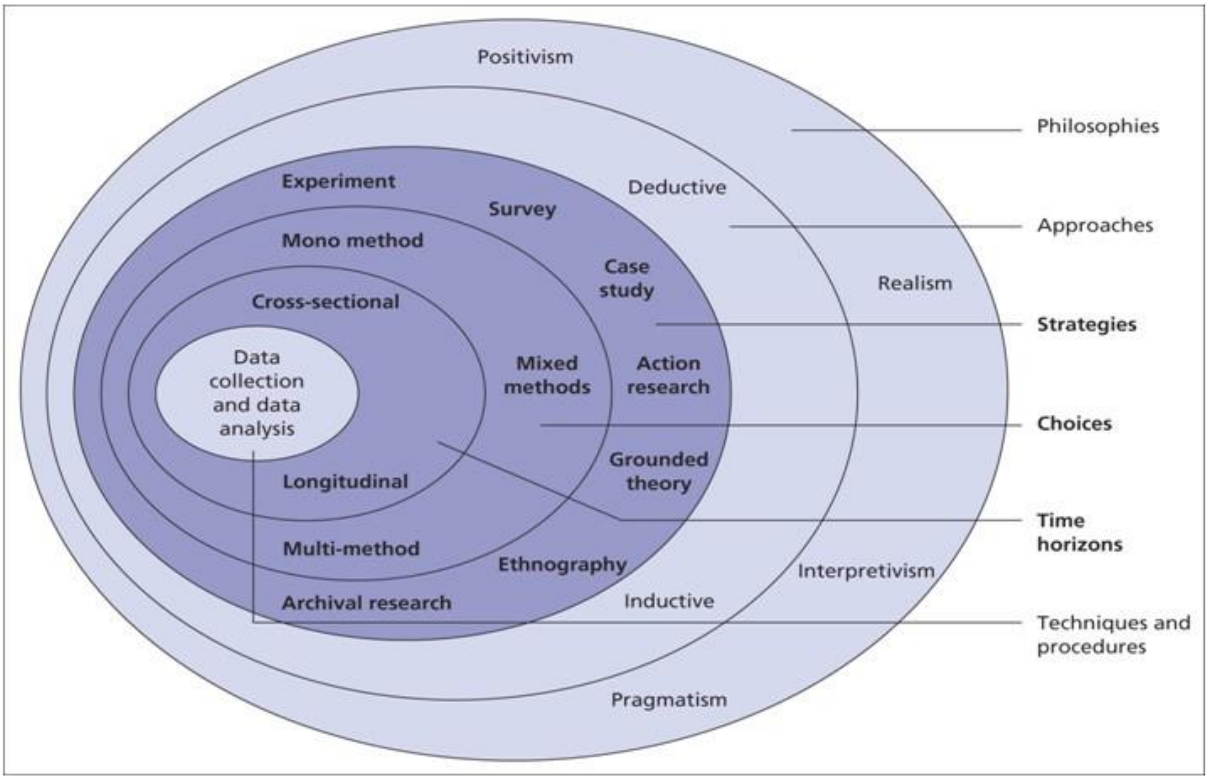

Figure 5.2 Research onion - adaptation of the nesting of methodological elements (based on Saunders, Lewis and Thornhill, 2012)

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5.2 Research philosophy positioning

5.2.1 Ontology, epistemology, axiology

The research philosophies spectrum, often referred to as a paradigm, describes the set of beliefs and assumptions chosen by the researcher to reflect their vision with respect to the social reality of the study. It is considered to be the first layer of research, as it provides a base for the relevant strategy, research methodology and data collection and analysis techniques.

Zanni (2016) summarises the research philosophy, as presented in the theory of knowledge in table 5.1 this summary has been sourced from group of piles in the theory of knowledge. This summary defines the different existing paradigms as:

"Ontological, (objectivism, relativism, nominalism), epistemological (positivism, realism or pragmatism, and constructivism or interpretivism), and axiological (value neutral, value driven)".

This section justifies the research positioning within the philosophical spectrum, guided by the summary developed by Zanni (2016).

Table 5.5.1 Philosophical spectrum (adapted from Zanni, 2016)

	Paradigm		
Ontology (reality)	**Objectivism** (objects exist independent of perception)	**Relativism** (truth is dependent of consensus between viewpoints)	**Nominalism** (truth is dependent on the individual's perspective)
Epistemology (knowledge)	**Positivism** (explains causality - closed systems)	**Realism or Pragmatism** (no commitment towards a single system)	**Constructivism or Interpretivism** (studies individuals' social realities – open systems)
Axiology (values)	**Value-free or Value-neutral** (independent from influences)	**Value-laden or Value-driven** (influenced by social, ethical, and political values)	
Reasoning (logic)	**Deduction** (theory-testing, general to specific)	**Abduction** (combination)	**Induction** (theory-building, specific to general)
Methods (techniques and procedures)	**Quantitative** (can be measured)	**Mixed methods** (multi-methodology, complementarism)	**Qualitative** (based on description)

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5.2.2 Ontology

Ontology is concerned with the, *"nature of reality or being"* (Saunders, Lewis, et al., 2012). In order to define the position of the researcher ontologically, the way the world operates has to be assumed according to the researcher's perspective.

In social sciences, on the Objectivism side, social entities exist in reality, and truth is independent of social actors/individuals (Saunders, Lewis, et al., 2012). Opposed to Objectivism is Nominalism, which advocates that the truth is dependent on the actor or individual's perspective. Meanwhile, Relativism suggests that reality varies from person to person and is subjective (Guba & Lincoln, 1994). Relativism supports the idea that truth is reached through agreement between different points of view; therefore, what is acknowledged as truth can differ from place to place and time to time.

This research agrees that integrating BIM technologies to achieve sustainable design decisions is dependent upon how stakeholders/users perceive a phenomenon (which accounts for individual perspective). Therefore, the problems reported in the first phase interview, and the interviewees' perspective with regard to the usability of the proposed model, are dependent upon the context. Also, results can vary in different periods of technology adaptation, which accounts for time. If this research is placed in different era the perspective of the individuals towards the adoption of technology will be vary, especially in the exploration and validation phase. So this research is dependent on how individual perceive a phenomena (usability of the model and framework). On the other hand, objectivism exist in the formulation of the proposed model in phase two, as it either success of failure in automating the targeted calculation. For these reasons, the researcher acknowledged that this research is not committed to a certain system of philosophy to allow flexible choices of methods that is suitable for each phase.

5.2.3 Epistemology

Epistemology defines what is *"considered accepted knowledge"* from the researcher's point of view (Saunders, Lewis, et al., 2012). It is also concerned with the procedure of questioning facts during research. It is considered the branch of philosophy which deals with the *"sources of knowledge",* and is specifically concerned with the nature, possibilities, sources and limitations of knowledge (Hallebone & Priest, 2009).

The four epistemological research philosophies are: Positivism, Realism, Interpretivism and Pragmatism. In each direction the researcher has their own view regarding what is considered

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as acceptable knowledge (Saunders, Lewis, et al., 2012). At one end is Positivism, which considers only observable phenomena extracted from facts and creditable data that is driven by natural laws (Bell et al., 2018). This is usually the approach of scientists, and it mainly serves theory-testing quantitative research, for example lab-based experiment research. In contrast, at the other end is Constructivism/Interpretivism – an approach often implemented in social sciences and management related research – referring to the perception that individuals' point of view constructs reality, and reality varies (Bell et al., 2018). Therefore, reality and our knowledge of it are highly dependent on context, time and participant perceptions, which are in turn interpreted through the researcher's vision of reality. In these typologies of research, the researcher performs in-depth analysis of what participants are saying with a focus on extracting the truth behind the details, which can result in subjective and open-ended meanings. In terms of method choices, a pure quantitative researcher will most likely advocate a Positivist perspective, while a pure qualitative in-depth researcher is likely to be a champion of a Constructivist, or else Interpretivist paradigm.

Another school of philosophy has grouped Pragmatism and Realism as paradigms that have no single commitment to a system of philosophy, founded upon the belief that flexible choices of methods can be used (Saunders, Lewis, et al., 2012). Their perspective towards Positivism is that it is rigid, highly structured and overly deterministic (with restricted room for choices), while Interpretivism is viewed as highly relevant and subjective. They believe it is possible and appropriate to overcome both sets of limitations through adoption of multiple methods (Olsen, 2004). For both Realism and Pragmatism, the research problem itself is seen as the main focus, and the adoption of single or multiple methods is based on which ones would best serve the specific needs of each stage or incident.

For Pragmatists, the practical consequences of the research findings are the most important aspect in the research (Saunders, Lewis, et al., 2012), and it is considered that acceptable knowledge can be sourced from both *"observable phenomena"* and *"subjective meaning"*, according to what is most relevant to the research questions.

From an epistemological point of view, the researcher acknowledged that a Pragmatic paradigm perspective best served the research typology. This was justified because of the researcher's belief that mixed methods should be adopted in order for the study to result in practical findings, meaning that the data collection and validation processes were determined according to what best suited the occasion. The Pragmatic perspective does not commit to a single system where participation is a key to solving the complexities of the problems addressed, closely aligns with the researcher perspective to conduct multiphase research with mixed methods . Moreover, a Pragmatic view allows flexibility of approach, as it means the research can be designed with an abduction approach, which lies between theory building (inductive approach) and theory testing (deductive approach); this will be explained in detail in section 5.2.

5.2.4 Axiology

Axiology is the third segment of research philosophy, and it is concerned with the nature of value and its role in revealing reality or truth. It is classified as either *"value-free/neutral,"* or *value-driven/laden"* (Saunders, Lewis, et al., 2012). Thus it is concerned with individual values - ethical, social, political - that could influence the research procedure and findings.

The researcher acknowledges that values contributed a large part in interpreting the results. The participants' perspectives in problem definition (in phase 1) and then in evaluating the proposed model (phase 3) ensured that a value-neutral approach could not be implemented, as each participant's background, experiences and values were likely to affect their reporting of the problems and their evaluation of the usability of the proposed model. In addition, it is claimed that value-free knowledge does not exist, as at the very least, the values of the researcher will have a relative effect. Consequently, being aware of the influence of these values and articulating the link between the findings and participants' background and values is particularly important to strengthen the research (Joseph & Kendler, 2005). In order to control, as much as possible, the biases in value-driven research and reach rational and credible results, justification and recording need to take place. An attempt was made to control researcher bias by keeping a record of the outcome of each stage and reflecting on how it guided the next stage, including critical discussion with supervisors and other faculty members in research groups. This was implemented throughout the research process, and justification for choices was critically discussed at each stage.

5.3 Reasoning approach

5.2.1 Deduction, induction, abduction

The second layer in the research onion, as shown in figure 5.2, is concerned with determining the suitable logic for conducting the research. In this section the approaches that were implemented in the research will be discussed. There are three approaches to reasoning; the two traditional approaches are induction and deduction, along with a more innovative approach, abduction. Induction is considered a *"bottom-up"* approach/logic, in which the researcher tries to move from a specific observation to a generalised theory, hence it is a theory creation logic, as shown in figure 5.4 (Kennedy & Thornberg, 2018). In contrast, using deduction, which is a *"top-down"* approach, the researcher starts with a theory, then forms a hypothesis and tests it, leading to either confirmation or rejection, so it is considered a theory testing logic, as illustrated in figure 5.3 (Kennedy & Thornberg, 2018). Deductive reasoning is criticised in particular for a lack of clarity in terms of how to choose which theories to test by generating hypotheses. Inductive reasoning, on the other hand, has been challenged since *"no amount of empirical facts can always enable theory-building"* (Saunders, Lewis, et al., 2012). Abductive reasoning, as a third option, addresses these flaws by adopting a pragmatist viewpoint, as mentioned in section 5.2.1.

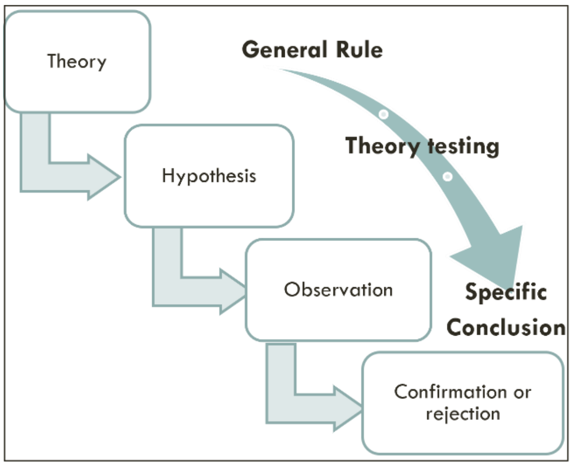

Figure 5.3 Deductive "top-down" logic (Dudovskiy, 2018)

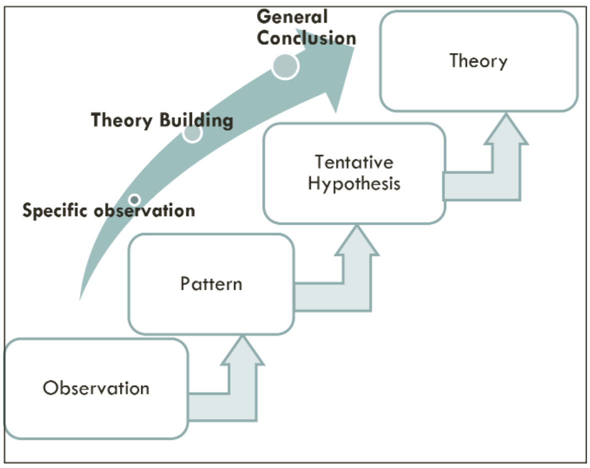

Figure 5.4 Inductive "bottom-up" logic (Dudovskiy, 2018)

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In the built environment, when it comes to theory testing or building within the framework of a particular study, researchers are increasingly challenged by the need to combine diverse research methodologies. As a result, researchers are naturally divided into two camps: deductive and inductive, as well as a hybrid of the two. The abductive approach appears to have overcome the limitations inherited in induction and deduction. This logic allows the researcher to move back and forth between theory and data to generate new theories or amend existing theories (Halecker, 2016).

5.3.2 Abduction

As mentioned in previous epistemology section, the abductive approach was judged to be the most suitable logic to be adopted in this research. Studies have discussed this logic as a crucial component of Pragmatic based research. When it comes to theory testing or building within the context of a study, researchers are increasingly faced with the challenge of combining diverse research methodologies. As a result, researchers are naturally divided into two camps: deductive and inductive, as well as a hybrid approach. The abductive approach appears to have overcome this dilemma. They agree that this method allows the researcher to move 'back and forth' between theory and evidence in order to produce new or better ideas (Awuzie & Mcdermott, 2017). There is evidence that the 'back and forth' approach, as opposed to a linear process, better enables the researcher to expand their understanding of theory and empirical data (Dubois & Gadde, 2002).

From the perspective of this research project, the iterative approach provided by using abduction logic was needed between phase two, which was model development, and phase three, which was validation using usability testing. Also, as the topic was not supported by a strong theoretical base, induction logic could be utilised in the first phase of the research in order to formulate and scope a base for model and framework development. This approach was selected by the researcher with the intention to lead to new insights and discover new aspects in adopting BIM technologies to enhance sustainable decision making through design.

In order to reach a conceptual overview of the research abductive approach, Halecker's 2016 process for the cycle of action and learning was adopted, as illustrated in figure 5.3, and used as a base to develop the research process, as summarised in figure 5.4.Therefore, as illustrated in figure 5.4, the research process is designed as follows: first, in order to identify a narrowed down area of concern, data about a phenomenon is gathered from observations of a practical problem or an explorative pre-study (Kova´cs & Spens, 2005). This is considered to be the first phase in the research, supported by theoretical knowledge from the literature review and experience. After that, a specific problem is determined by the researcher, to work on in the next phase. Accordingly, a preliminary conceptual framework is developed in the second phase to attempt to solve the problem deduced in the first phase in practice. Using a testing method – usability experience testing in the current study - the framework is modified and refined via real world/fieldwork (practice), through validation in phase three. Analysis and interpretation take place in the third phase in order to draw insights from practitioners about potential use and the challenges of adopting the proposed framework.

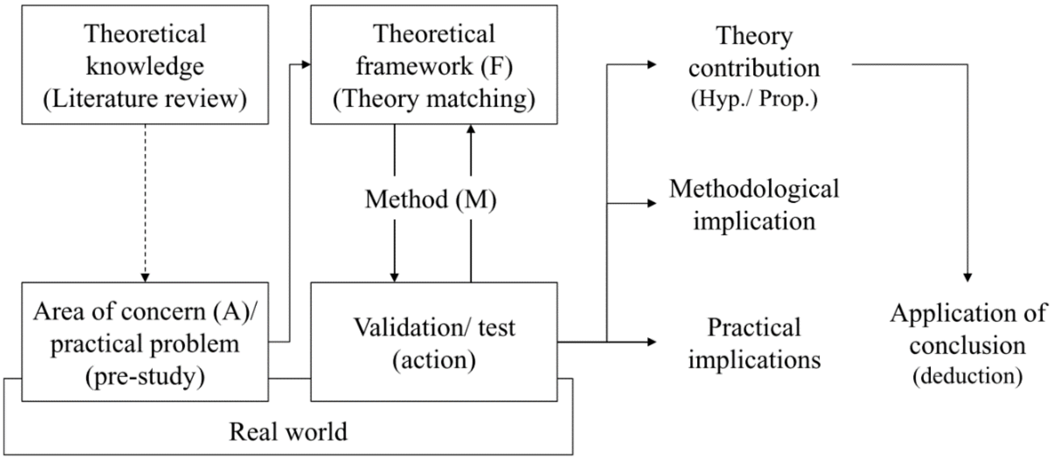

Figure 5.5Conceptual overview of the abductive approach (Halecker, 2016)

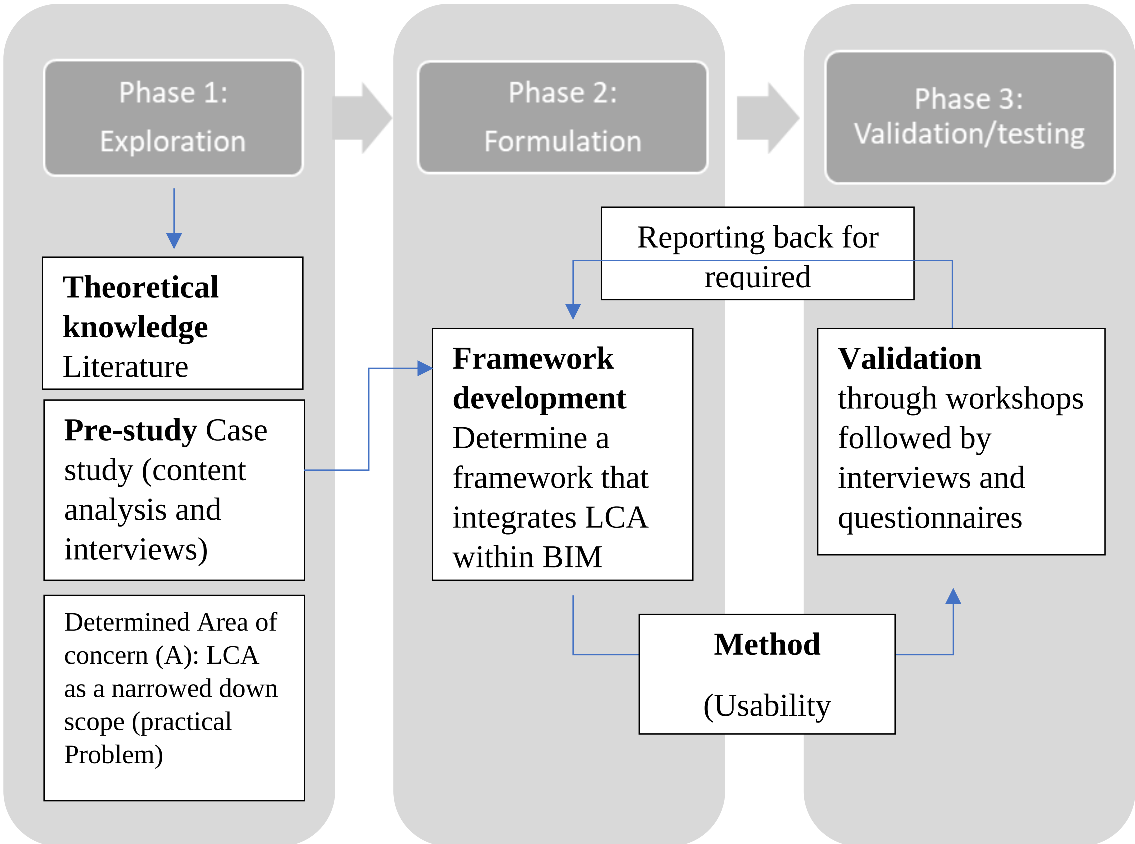

Figure 5.6 Research design process with adoption of abductive approach

5.4: Research strategy

Following the layers defined by the research onion, and after peeling away the approach choice, the next layer revealed is research strategies. This layer emphasises how to address the research

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question, where the researcher decides to adopt one or more strategies within the research design. Examples of the strategies that might be adopted within research designs, as shown in figure 5.1, are ethnography, experimental, case study, action research, grounded theory, and survey. The research strategy is usually tied to the researcher's philosophical worldview, and cannot be segregated from the principles of the followed paradigm (Saunders, Brist, et al., 2012). For example, survey and experiment research are usually strategies that are associated with Positivist research, while ethnography and case study strategies are often linked to Interpretivism and Realism (Saunders, Brist, et al., 2012). This does not mean Positivistic research cannot adopt a case study, or Interpretivism cannot use a survey.

This research aimed to explore the challenges and problems of incorporating sustainability aspects through performance-based design using BIM based sustainability tools. To do so, it focused on developing a framework and testing the integration of one aspect - material selection with embodied carbon optimisation - in delivering sustainable design. This research question aimed to capture a problem in current practice and provide a solution that could be tested and evaluated by practitioners. Therefore, a case study was adopted in the exploratory phase, and then questionnaires and interviews were used in the model and framework testing, as they were arguably the most suitable and appropriate to serve the practical nature of this study. As the framework was to contain a software tool (Dynamo within Revit), human computer interaction principles would be used to evaluate the usability of the model; this will be discussed in detail in section 5.6.3.

5.5 Research methods

After identifying the research strategy discussed in previous section, justification of the adequacy of the methods chosen for data collection and analysis will be provided in this section.

Research methods are defined as the specific procedures and techniques used in order to collect and analyse data. According to Knight and Ruddock (2008), qualitative, quantitative, and mixed methods are the three categories of research methods. One of the strength points of the pragmatic epistemological view is the ability to use mixed methods in research design (Saunders, Lewis, and Thornhill, 2012). Mixed methods were implemented in this research, combining both qualitative and quantitative methods. The research mainly depended on qualitative data and analysis, but quantitative methods were used in the validation phase in order to support the qualitative insights produced from the qualitative data. This indicates that this research implemented a partially integrated mixed methods approach, as mixed methods were only applied in one stage. In the validation phase, the mixed method used is known as a concurrent mixed method, where one methodology is used to support the other in one phase, enabling concurrent triangulation of data (Saunders, Lewis, and Thornhill, 2012). It is possible to achieve richer and more extensive results by adopting triangulation, as the results of one approach are mutually corroborated by the results of the other method, which helps to control bias and increases the reliability of the findings.

The following section will discuss the role of qualitative and quantitative methods in this research.

5.5.1 Qualitative methods

Qualitative methods are based on the Constructivist perspective, and are used to investigate and comprehend the meaning that individuals or groups assign to a social or human issue (Knight & Ruddock, 2008). Qualitative methods are used to understand a phenomenon better as the data is derived from peoples' perspectives. They seek to answer the questions of 'why' and 'how' things happen. Therefore, analysis can result in the discovery of new variables and relationships between realities and may inductively build up understanding of experiences. This study was mainly dependent on qualitative methods for data collection and analysis. This was first implemented in the systematic literature review (presented in chapters 2, 3 and 4), then in the exploratory initial case study involving interviews with three participants), and finally in the validation usability workshops and interviews (involving six workshops and 13 participants).

5.5.2 Quantitative methods

Objectivism is the root for quantitative methods (Saunders, Lewis, and Thornhill, 2012). It is an approach that is based on measurement and/or counting, in which researcher collects and analyses numerical data. This research implemented a quantitative approach in the last phase of the research, validation, in which questionnaires were administered after the usability workshop. The questionnaire was designed to capture the participants' perspectives on and evaluation of the system features, effectiveness of the process, and ease of use of the proposed framework. It first asked questions about the participant experience and profile; then participants' agreement with various statements was tested using a five-point Likert scale, where responses ranging from 'strongly agree' to 'strongly disagree' could be given (check

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Appendix 5). This method was selected by the researcher in order to facilitate the validation of the proposed framework without any interference from the researcher, in order to assure transparency. The outcome was used to evidence and support conclusions arising from thematic coding and analysis of the semi-structured interviews. This procedure achieved concurrent triangulation of data, as explained in the above section.

The next section will synthesise chronologically how the research methods selected by the researcher formed the research design.

5.6 Research design and techniques

As mentioned in the introduction, the phrase research design refers in general terms to the methods through which data is collected, analysed, and used to answer the research questions asked, as well as providing a framework for conducting the study (Knight & Ruddock, 2008).

In this section the methods and techniques used in this research will be linked to the objectives and research questions, in addition to the research phases, as shown in figure 5.7. It will provide a sequential explanation of the decisions taken by the researcher during the research process. It will also describe in detail the phases of the research, and how data generation and analysis were undertaken. Using the *"iterative theory building process"* (Drongelen, 2001), an abductive approach was adopted in this research through a three phase design using content analysis, case study analysis, framework and model development, and participatory user experience evaluation for validation.

The following subsections will describe the role of each phase in the research and the techniques used to collect, analyse, and interpret data. It will also demonstrate how the phases were interdependent on each other in forming the research outcomes, as summarized in figure 5.7. Timeline for the research phases is illustrated in figure 5.8, which provide the chronological sequence of the research phases and tasks to give a temporal context to the work.

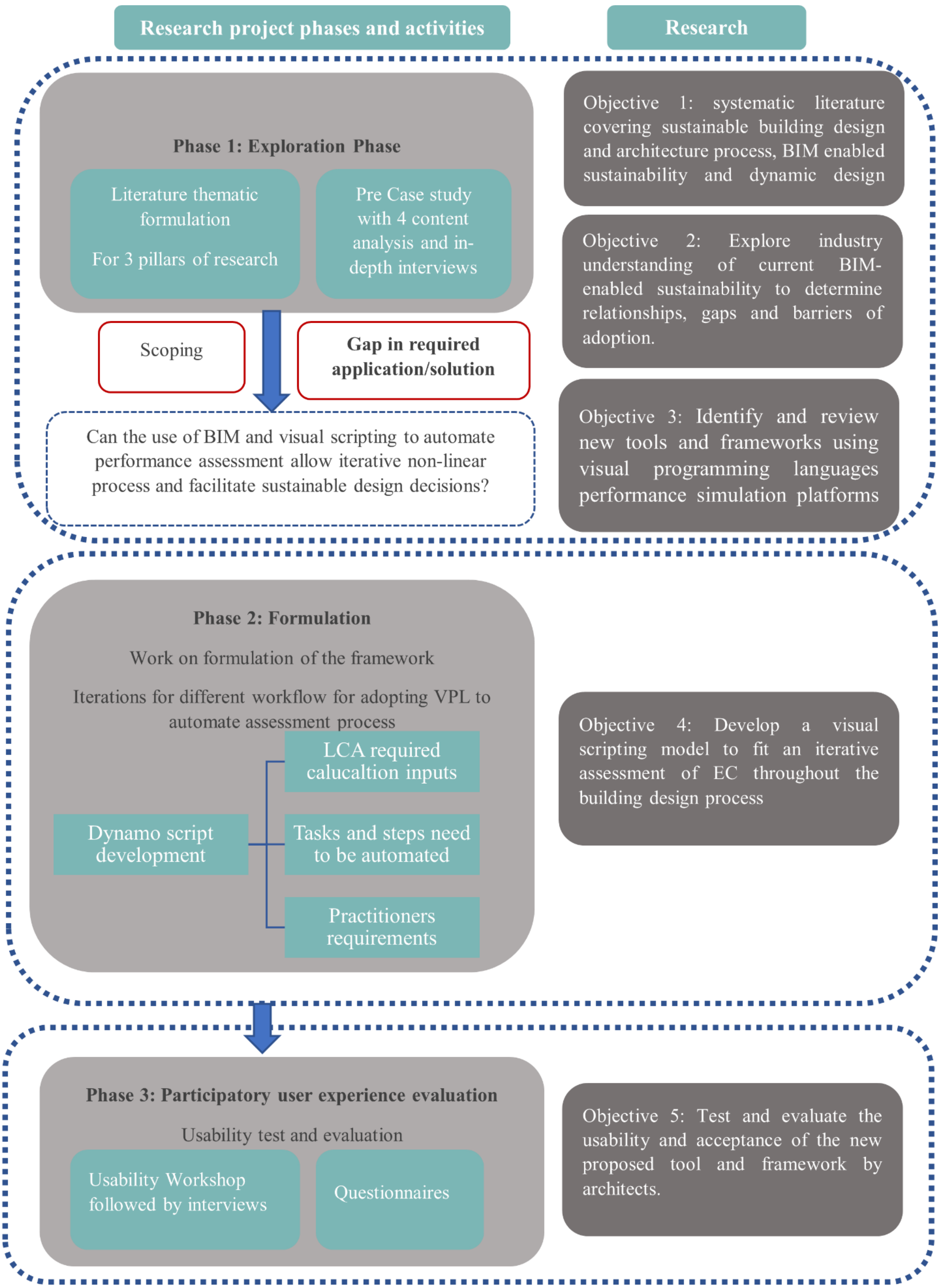

Figure 5.7 Research phases and activities mapped with research objectives

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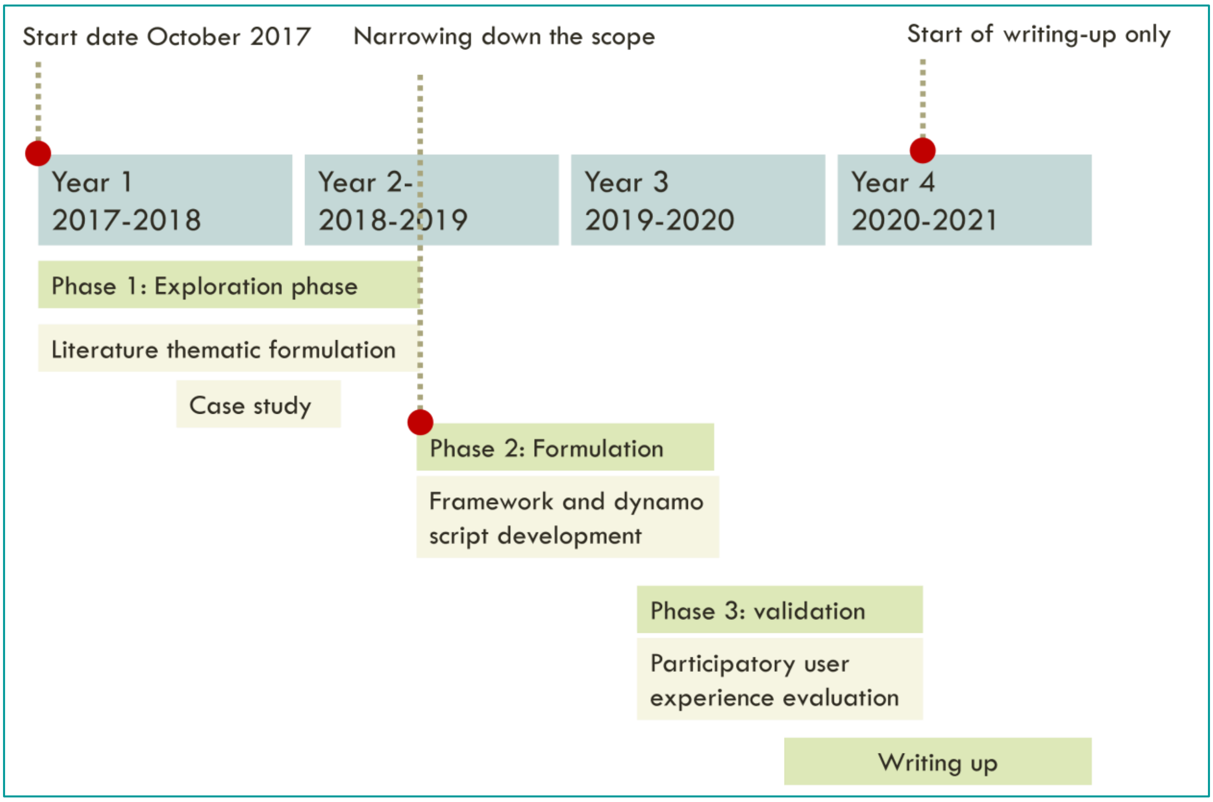

Figure 5.8 Research timeline showing chronological sequence of the research tasks

5.6.1 Phase 1: Exploratory stage

The first stage of the research was an exploratory stage, which took place to investigate the current development areas with regard to sustainability integration with the BIM process. Understanding of researcher potentials and problems relating to BIM-enabled SBD was developed in this phase. It also enabled better understanding of the challenges of the different tasks, including qualitative and quantitative performance analysis, that contribute to the decision making process and proof of requirement (documentation and evidencing) for delivering sustainable buildings. It satisfied objectives 1, 2 and 3, as shown in figure 5.7, and was composed of two parts, a literature review and a pre-case study, which will be explained in the next section.

Phase 1.1: Literature review

The literature review was the first step in research process and was considered an inductive one. It is presented in chapters 2, 3 and 4. It allowed the researcher to develop excellent knowledge and a deeper understanding about the three main pillars of the study: sustainability in architecture and design processes; Building Information Modelling (BIM); and visual programming languages and building performance assessment. Inductive content analysis assisted with developing the theoretical framework and enabled themes to be generated which provided investigation points regarding the potential of technological integration in delivering BIM enabled sustainable design. Content analysis was implemented in the discussion and presentation of the literature survey, which was considered an appropriate approach for unstructured data. In this phase the literature was classified into categories which were clustered into different research fields of development. This is considered to be an approach in theory building that counts as theoretical contribution to knowledge.

The gaps in knowledge, highlighted in the summary of each chapter, motivated the investigation and development in the following stages. Deficiencies were found in the literature in the determination of potentials and barriers towards adapting BIM technology, and dynamic solutions for solving inefficient workflow in sustainable decision making. In addition, development of and usability evaluation for VPL frameworks that allow iterative design assessment have not yet been fully established in the AEC industry. It was therefore decided to conduct a case study as a pre-study to investigate the problems of workflow in practice and work, as a guide for scoping the proposed framework as a solution. This will be discussed in the following section.

Phase 1.2: Case study and thematic analysis

Using a case study in the first phase of the research project allowed the subject to be studied in its natural setting (Myers et al., 2011). The exploration phase satisfied objectives 2 and 3 of the research, as mentioned in chapter 1. Using a case study for the purpose of exploration often combines observation and interview methods in order to capture the required data; this can be a useful approach when the research boundaries are not clear at the start. The key characteristics of the case study are that it allows the researcher to study *"why"* and *"how"* questions, therefore it is a suitable method to provide insight into complex natural settings and processes (Knight & Ruddock, 2008). The next part will describe the exploratory case study in terms of the process applied in data collection and analysis.

Case study description

A plan was made to conduct one case study with one architecture firm. The criteria for selection of the case study were set to serve the aims of the exploration phase of this study. It was decided that the project had to comply with the following conditions:

Table 5.2 Pre-case study criteria for selection

Criteria	**Requirement**	**Reason for the requirement**
Scale of the project	Medium to large scale project	Targeted level of complexity
Scale of architecture firm	Small and Medium Enterprises	The structure and number of employees usually do not allow a specialised sustainability team
Typology	Non-residential building e.g. educational, cultural centre, office building	Other different considerations of sustainability are required
Data of construction and stage	Completed between 2015-2018 or in operation or planned to be by the end of 2018	To decrease the possibility of project members forgetting the circumstances of the project
Sustainability requirement	High criteria are set in the following aspects of energy, materials categories	In order to serve the scope of the research
	If certification targeted: LEED minimum Gold (BD+C) or BREEAM (new construction) Very Good	Not necessary, but if certification were targeted this could be minimum requirement
Tools and software use	BIM model used at any stage of building delivery and simulation analysis (software) for evaluation	To investigate the use of digital tools and challenges of iterative performance assessments
Project documentation	Client/project team are willing to provide access to use project records and communication exchange	Required for observation of the decision making process with regard to sustainability assessment

In the process of participant recruitment, architectural firms that complied with the inclusion criteria outlined in table 5.2 were approached via email. Three architecture firms met the criteria and were recommended by the research supervisors' contacts. In the end, one firm which had a suitable project for a case study was willing to contribute to the research. A recommended protocol was followed to ensure professional communications in order to maximise the response rate (Rowley, 2012). This protocol guided the manner of communication, which included: 1) the researcher placement (including university and course of study); 2) the purpose for conducting the research; 3) a project brief document which was well presented and easy to read, in order to capture participants' interest; 4) a clear account of the required data and time; 5) the benefits for the interviewee; 6) use of data protocol, consent to record interviews and assurance of confidentiality; and 7) provision of the researcher's details. Accordingly, the project brief and consent forms were sent by email to the participants and are attached in appendix 4.

The analysis as discussed worked as foundation for informing the next phase of the research. The case study revealed that there is need to develop framework and tools for the architect to deal with BPA (operational energy, daylighting, and LCA for embodied carbon) dynamically with design. The case study analysis and findings were discussed in detail in chapter 3.

5.6.2 Phase 2: Framework and model development

The main objective of this phase was to develop a framework to support performance design feedback and testing using VPL within the BIM environment. In phase one of the research, challenges of simulation and integrating performance analysis into the design process were explored and highlighted. A gap in knowledge revealed from the literature was that the development of VPL assisted framework and evaluation of its usability among architects is still lacking.

As discussed in chapter 3, the case study revealed that architects' work on operational, daylighting and building material election requires simultaneous embodied carbon estimation in order to optimise the design. Barriers in the tools available for the use of architects, in addition to the workflow issue of having other stakeholders (M&E and BREEAM assessor) assessing architects' design does not allow early iterative and performance-based design. Therefore, the initial proposed framework aimed to work on the three important design variables.

Based on the findings from phase 1, the research scope, problems and strategies were framed more clearly. VPL is one of BIM approaches to support mechanisms for change for sustainable digital delivery and the dynamic design environment, as explained in chapter 4. The next part will explain how the model would be developed to support iterative performance testing by the architects during design.

A. Experimenting with VPL platforms

In order to reach a decision concerning which platform and tools would be used in the framework, different approaches were tested. As discussed in chapter 4, the most recognised platforms for VPL and environmental performance testing are Revit Dynamo and Rhino Grasshopper. The literature review highlighted that the applications and tools within Grasshopper are much more stable and mature than those in Dynamo. However, within the BIM environment, Revit is the most used tool in design and design development. One of the challenges and barriers of not integrating performance testing in architects' workflow is the duplication of effort required in modelling, and not using the same model built in Revit to perform the simulation. Therefore, a decision was made to try the experiment using the Revit model. The period of experimentation within this study took place between May 2019 and October 2019, along with other research activities.

There were two possible approaches: to use Dynamo as a VPL and experiment with the developed tools, such as Honeybee and Topologic, or to test the transfer of the Revit model into Rhino and do the simulation on the platform that is tested and validated without errors and less bugs. Both platforms have been explored with successful applications for embodied carbon assessment. Unfortunately, however, the process of experimenting with the two approaches failed to reach a smooth daylighting and energy simulation.

The challenges of both approaches are outlined as follows. In the Dynamo platform, up to now there are two developed tools: Honeybee and Topologic, as explained in chapter 4. The Honeybee custom nodes for daylighting and operational energy simulation showed a very restricted way of reading geometries. There were two methods for building the script. The first method of geometry collection only operated with a simple two rooms model; if any other model was attempted, it crashed and did not work. Meanwhile, the other method required overly complex mapping of the geometries and surfaces to the materials, which ended up being an impractical approach. This problem was confirmed and reported by the tool developers; these problems are present due to limitations and restrictions in Revit API.

The second tool on the Revit Dynamo platform for operational energy that was explored was Topologic custom nodes, as explained in chapter 4. Topologic utilises OpenStudio as an engine for simulation, but limitations were found as it only worked if model geometries were built up with the parametric logic (geometry developed through Dynamo). The parametric logic aims to build up lightweight models consisting of edges, surfaces, nodes, cells, and cell complexes. This required a new set of skills for building up a parametric model and did not deal with current workflow for the architect. In my opinion, it did not allow an iterative process as it did not read the existing geometry developed in the Revit model.

As the Revit Dynamo platform had been unsuccessful, the other approach of model transfer from Revit to Rhino Grasshopper was explored. It was claimed that transfer of GBXML (open green building interoperability standard) facilitated the transfer of 3D buildings from Revit to Rhino and could be run smoothly. In order to overcome the limitations of the Revit API, Honeybee developers have created a component that deals with collection of Revit geometry in Rhino using GBXML. However, this approach was attempted and still had shortcomings, e.g. geometries were not clean, complex or curved shapes were not supported, and energy data such as HVAC schedules or materials were not captured.

Due to the time constraints of the research study, unstable solutions of existing tools, and the need for complex coding skills to solve the challenges mentioned above, a decision was made to narrow down the scope into providing a VPL framework that dealt only with the calculation of embodied carbon in order to inform material selection. Further investigations and improvements are recommended to be covered in future studies, in order to empower architects' decision making and complete the decision loop. The next section will discuss the formulation of the LCA framework within the BIM environment, which was chosen to be the Revit-Dynamo platform.

B. Framework formulation

As mentioned in chapter 4, applications have been developed by previous studies in this area to create a dynamic approach within the BIM environment to deal with LCA calculations. Despite this, the literature review showed that applications which adopt UK-suitable databases, enable benchmarking, and tackle most of the automation of tasks, are still lacking. Therefore,

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this section will describe the chronological steps followed in order to formulate a framework to allow architects to use the LCA iteratively to inform their design decisions, as summarised in figure 5.9.

The first step was to define the scope of the LCA, system boundary, inventory database, methodology of impact factor calculation and justification of assumptions and ignored factors. The second step was allowing the architects and structural engineers to construct a logic/ontology for a material library with a back end calculation model that needed to be calculated and embedded into the architectural BIM file template. The third step was to develop scripts that automated the functions needed. The fourth and last step was to be able to analyse the data and compare it to the benchmarks. This framework allowed exploration of alternatives of the design, with any changes in the model being automatically reflected in the results, eliminating the time and effort required.

The script logic was developed based on the work presented in previous studies (Bueno, Pereira and Fabricio, 2018; Hollberg, Genova and Habert, 2020; and Genova, 2019). The aim was to construct VPL scripts in order to automate all of the following steps of the process:

1. To create a material library that suits various stages and LODs.
2. To import the life cycle inventory database (LCI) coefficient values in a material library with the BIM library.
3. To link the model quantities with the LCI values and calculate the total LCA values.
4. To export the calculated values for analysis on Excel sheets.
5. To be able to compare the values with UK benchmarks.

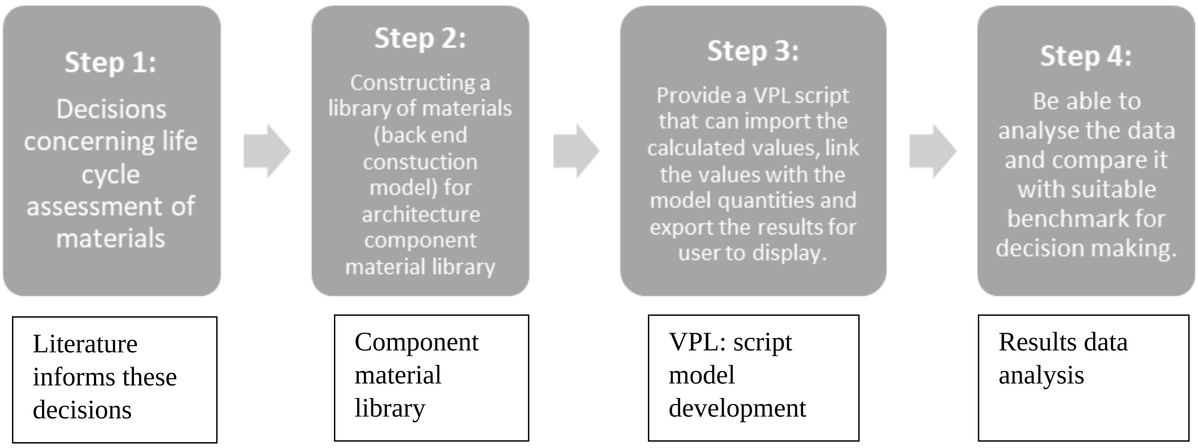

Figure 5.9 Methodology of building dynamic LCA model

In order to satisfy these aims, and before constructing the visual scripts in Dynamo a knowledge and decisions need to be formulated first. Accordingly, a data matrix plan was prepared to follow while constructing the framework (presented in table 5.3), which will be explained more extensively in chapter 6. The next section will describe the last phase of the research, which was the participatory and evaluation phase.

Table 5.5: Data planning matrix

	What do I want to know?
LCA	1. How will integration be achieved? 2. What inventory databases will be used? 3. What LCA boundary will be included? 4. What impact factors (indicators) will be used in the calculation script? 5. What is the methodology for calculation (indicators)? 6. What are the assumptions and the neglected factors in the calculation? (Transportation to the site, material RSP RSL) 7. How will the material library be used at different LODs? 8. Will the database provide coefficients on an element level or material level? 9. What architectural and structural elements will be included in the calculation model and how will it be categorised? 10. What benchmark will be used?
Dynamo script	1. What are the steps required to automate the calculation process? 2. What element/component/material library will be used in the BIM template? 3. What is the logic of back-end calculation of the model and the front end user input/output results? 4. How will the user run the model and what are the different methods of engagement?

5.6.3 Phase 3: participatory and evaluation phase

This phase was designed with the premise of state of the art for user experience methods, as considered under the umbrella of human computer interaction (HCI) (Blandford et al., 2016). HCI were used in order to address issues related to interaction design: inform the design by investigating user needs and evaluate novel or existing designs of system, tool or websites. As mentioned before, the VPL simulation and performance analysis were promoted to allow architects to test their designs iteratively and dynamically through the project timeline. However, these workflows and tools are new to the architecture industry and require a new set of skills to be acquired by staff, so this phase of research contributed to understanding the factors affecting engagement with these technologies.

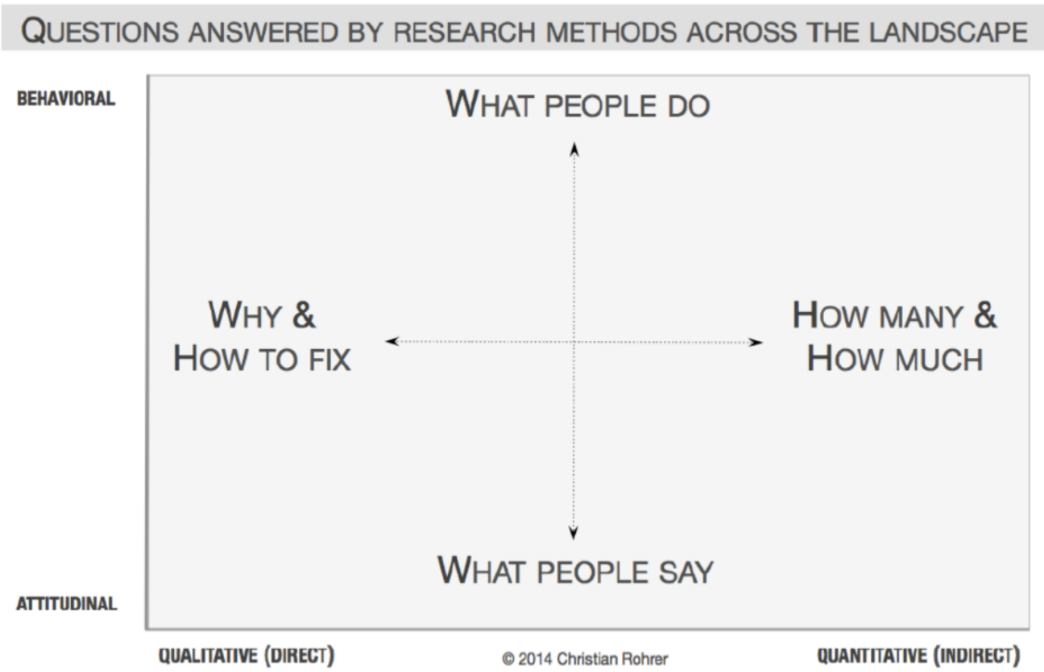

Figure 5.10 Questions answered by research methods (Rohrer, 2014)

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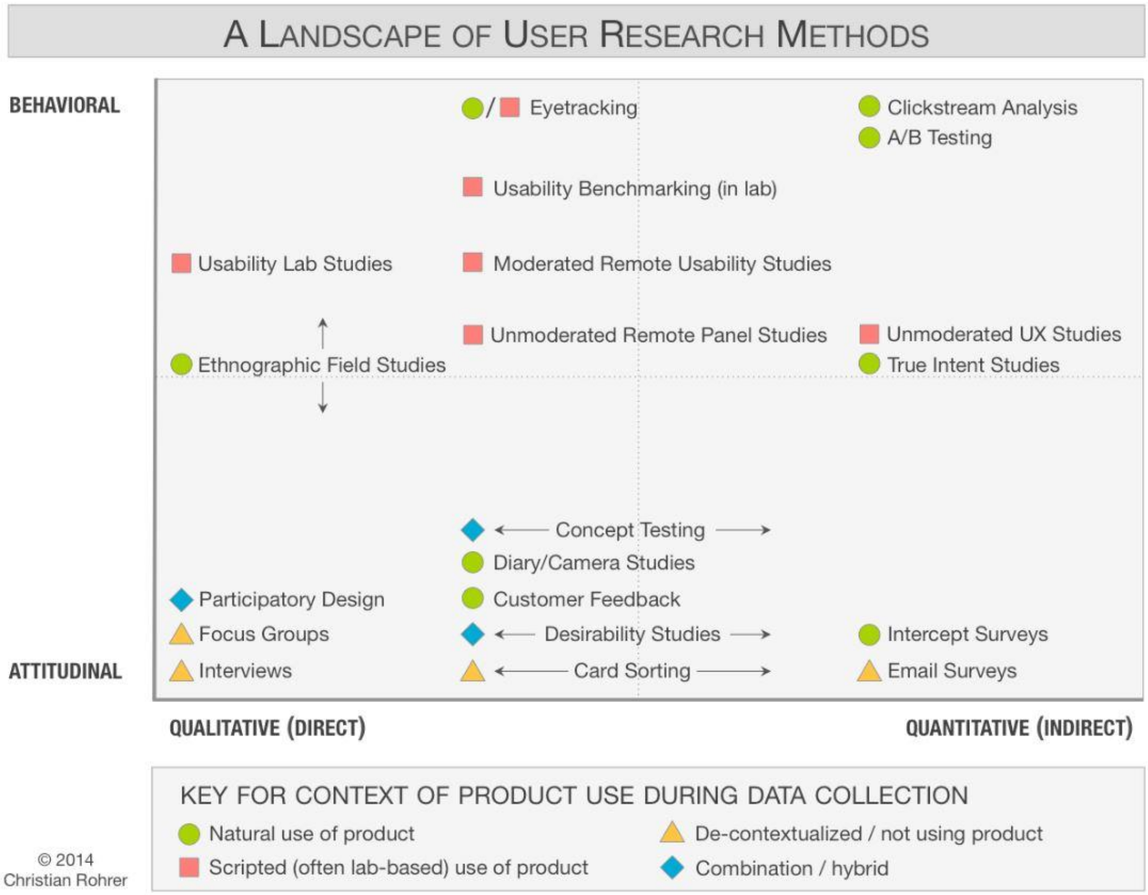

Figure 5.11 A landscape of user research methods (Rohrer, 2014)

This phase aimed to describe and explain the uptake and use of this model by architects, rather than just hypothesis testing, therefore qualitative approaches were more suitable than quantitative approaches, which may be limited only to answer, *"how many"* and *"to what extent"* type questions. Also, in order to achieve triangulation of data and support the qualitative evaluation, quantitative questionnaires were used to avoid bias and weakness caused by the subjectivity of mono qualitative methods.

As shown in figure 5.9, a variety of techniques are used to gather data in research designed to adopt attitudinal techniques by exploring *"what people say"* rather than behavioural techniques which focus on *"what people do"*, along with limitations in terms of the research time and the availability of participants. Firstly, a showcase of the workflow of using the scripts was demonstrated in order to evaluate the sustainability targets. Qualitative data was gathered by arranging a series of workshops where the researcher introduced the use of the scripts and workflow, then allowed the participants to evaluate and share their thoughts on use and

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adoption through semi-structured interviews. Interviews focused on the feedback from architects on three main aspects: system related, process related, and skills related aspects, as shown in figure 5.12. The targeted participants were: architects in SMEs with no experience with VPL; architects with experience with VPL; and students at M Arch level with experience with VPL. A detailed description of the usability test procedure and results will be given in chapter 7.

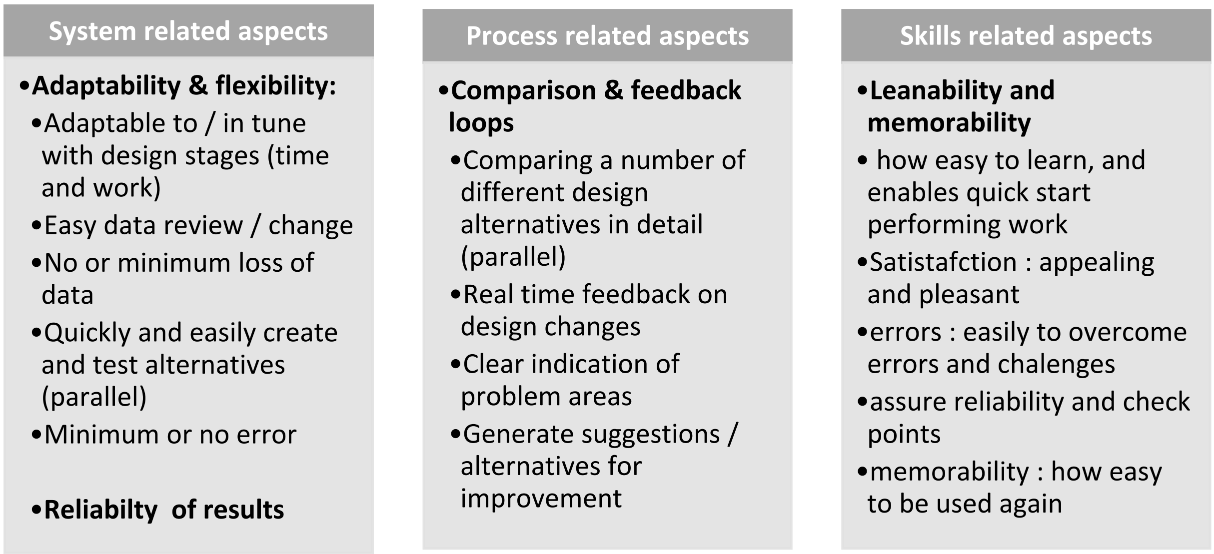

Figure 5.12 Interview evaluation themes

5.7 Ethical approval

In order to conduct this PhD research, it was compulsory to obtain ethical approval from the Faculty Research Ethics Committee (FREC) in the Faculty of Engineering and Environment at Northumbria University. An ethics application was submitted twice during the timeline of the research. The first one was granted at the beginning of the project with the submission of the project approval which included the research design and activities. The second application was submitted as an update before conducting the last phase, which was the validation, as changes were made to the planned work in order to adapt to pandemic circumstances. The validation was initially planned as a face-to face workshop and interviews; but they were switched to take place online instead to avoid gathering due to Covid-19.

This study was considered to be a medium level risk study, as it involved human participants from industry. In the two ethics applications, the research design activities were reviewed by Northumbria Ethics board, including: recruitment method, consent forms for interviews and questionnaires, and collection and storage methods. While recruiting participants, first an invitation to participate was sent by email explaining the nature of the research, the project brief and the role of participants (see Appendix 4). Consent was sought in advance of participation in any research activities (e.g. interview or questionnaire) and participants were made aware of their right to withdraw at any time from the study if they wanted to do so. In all forms of participant involvement, the participant's identity, name and firm name were kept anonymous. All interviews, workshop recordings, and questionnaire data files were kept confidential and were securely stored for the period of the research only, and then destroyed after the final submission.

5.8 Summary of research design

This chapter has presented the research design and the researcher's methodological choices for this PhD study. It began by justifying the choice of Relativism as ontological perspective and the Pragmatic epistemology which set the philosophical foundation for the research. It went on to rationalise the choice of an abductive approach that served the typology of the study as it allowed an iterative theory building and testing process, which shaped the three phases of the study. Following this, the implementation of human computer interaction methods principles was advocated for adoption in the study, informing the data collection and analysis methods. The data collection and analysis methods were demonstrated, including a case study with semi-structured interviews; and workshops followed by semi-structured interviews and questionnaires, with regard to the research phases and objectives. In the process of presenting the sequential process of the study in this chapter, credibility and trustworthiness have been rationalised through the quality control criteria that were applied in each step. Finally, ethics considerations have been highlighted to ensure confidentiality and protection of participants' information. In table 5.4 a summary is provided of the research design discussed in this chapter, along with summary of the justifications.

Through following the implemented methodological approach presented in this chapter, the next chapters 6 and 7 will represent the main data collection process for model development and the validation process. A task planning matrix is presented in table 5.5.

Table 5.3 Research design summary

	Choice and positioning	Summary of justification
Philosophy	Pragmatic	Truth exists through agreement of different viewpoints (from individuals) but can differ from place to place and time to time. No fixed commitment to a certain system of philosophy to allow flexible choices of methods.
Choices reasoning	Abductive	Allowing iterative process between theory building (inductive) and theory testing (deductive)
Strategy	Explorative Case study- human computer interaction for testing	Strategy that focuses on the practical consequences of the findings, need iterative process in the development and seeks validation from practitioners.
Methodological choice approaches	Mixed methods	Depends on qualitative data, supported by quantitative data to apply concurrent triangulation of data to strengthen the study.
Data collection methods	Case study, semi-structured interviews, workshops, questionnaires	Collection methods that engage practitioners and seek answers and insights with solution to a problem in the industry.
Data analysis methods	Content analysis, thematic analysis, quantitative graphical representation (insights)	Analysis methods objective is to explain the phenomena (problem, process, solution), support from quantitative analysis to overcome weakness of subjectivity of qualitative interpretations.

Table 5.4: Research tasks and outcomes summary

Phase	Tasks	Outcomes
Phase one	Literature review In-depth semi-structured interview applied on a case study.	Thematic coding highlighted required areas of integration with design process.
Phase two	Model development	Framework and Dynamo script model developed for integration
Phase three	Validation workshop (Prepare workshop material with showcase and guide videos and steps for user trials)	Usability evaluation report for the model

Chapter 6 : Development of a Dynamo for LCA-BIM framework and showcase application

6.1 Introduction

This chapter provides an overview of the second phase in this study, which is the formulation of a framework utilising Dynamo integrated with Revit automated life cycle assessment (LCA) to calculate embodied carbon (EC) in a BIM environment. The chapter is structured as illustrated in figure 6.1. Firstly, a brief summary of the challenges of conventional and static methods in EC assessment will be outlined in section 6.2. Secondly, the scope of LCA calculation will be defined including system boundary, included indicator, and assumptions. Then the following sections will explain the framework concept with respect to the integration elements and requirements. Finally, the last step will include more details about the formulation of the script and different levels of users' interference.

This chapter presents the development of a framework and VPL model that aim to overcome the challenges of dealing with LCA assessments as a tool for informing material design decisions, in order to satisfy objective 4 of this research. The sections are designed to answer all of the questions formulated from the literature, which were presented in table 6.3 as a data planning matrix in chapter 5.

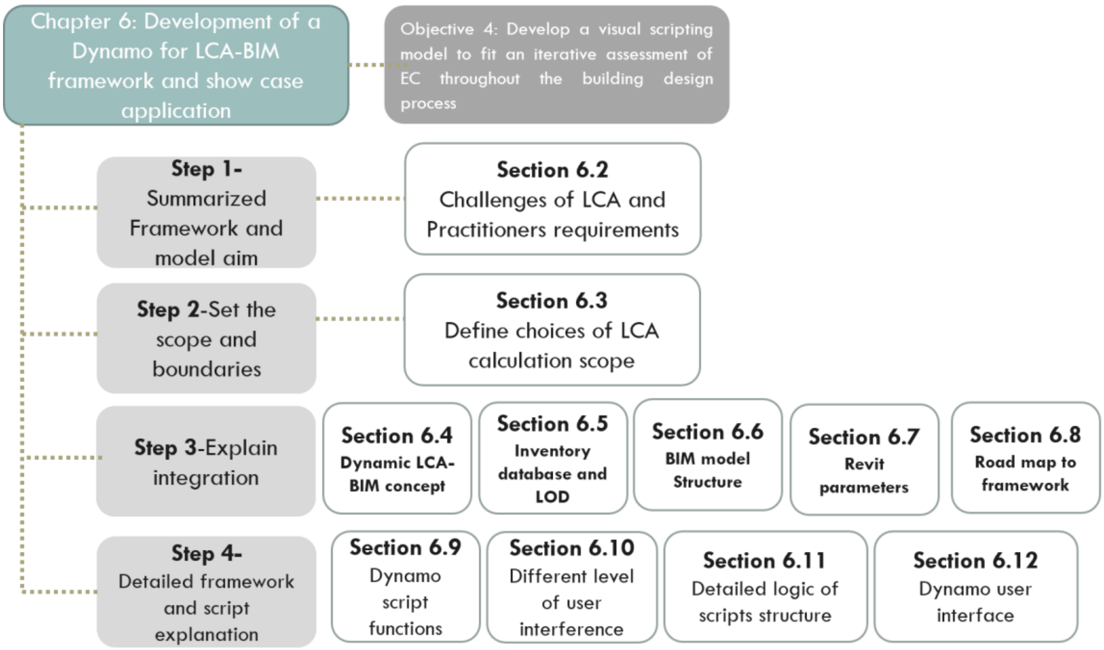

Figure 6.1 Chapter 6 structure

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6.2 Purpose of the framework and model aim

LCA is a useful method for determining the entire influence of building materials on a building's life cycle. As mentioned before, the time-consuming nature of assessment and the challenges highlighted in the literature motivated the development of new ways to incorporate LCA into BIM workflows. In chapters 3 and 4, the different approaches of BIM-LCA integration have been explained extensively.

Challenges and limitations of static and conventional approaches have been addressed in chapter 3, which overarched the advantages of incorporating LCA into BIM platforms. The benefits of combining LCA with BIM in the design and building process are numerous. Using building information models in conjunction with an LCA approach can save time and improve the application of building environmental performance from the start, and will allow multiple assessments throughout the design stages. The use of data from the BIM model will allow for a more accurate LCA evaluation. Manual re-input or missing data entry during the LCA approach can be avoided if data sources are identified.

According to the findings from the literature review about the challenges of LCA integration in the design process, potential of incorporating LCA-BIM and opportunity of VPL approaches, the proposed model will be designed. The aim of this model is to achieve the following:

1. Real-time LCA assessment.
2. Time efficient process (eliminating manual work).
3. Minimise manual entry to eliminate LCA mistakes.
4. Affordable and flexible.
5. Easy to use.
6. Use within BIM environment (same designer interface).
7. Support decision making (visualisation, different detailing of output, benchmarking).
8. Provide a possibility to reuse and expand in multiple projects.
9. Ability to add more LCA indicators in future with the same concept if required in the same system.

The next section will outline how the framework is formulated and the steps needed to structure and build all details and decisions required to build the model.

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6.3 Formulate proposed framework

In order to formulate the framework, decisions must be made related to scope, system boundary and sources of inventory database, enabling the researcher to set the scope of LCA calculation. These aspects were set in chapter 5 (in section 5.6.2) in order to plan the data and decisions required. All of these points will be addressed in this chapter in order to illustrate how objective 4 can be fulfilled. This section will begin by defining the scope of LCA calculation.

6.3.1 System boundary and LCA calculation scope

This part will identify the scope of LCA calculation, the boundary system and included construction elements of LCA. These choices determine the scope of calculation and are essential to select the appropriate coefficient factor.

RICS whole life carbon assessment for the built environment document (Royal Institution of Chartered Surveyors (RICS), 2017) sets the minimum requirement for whole life carbon assessment based on ISO 14044:2006 (Gervasio & Dimova, 2018). Although it is recommended to include all stages defined by RICS for whole life carbon assessment, only the product stage [A1–A3] is included in this research scope, for reasons relating to the inventory database. This framework will utilise a mix of database sources but will be highly dependent on a generic and non-manufacturer-specific database, which is ICE database. There is no other generic database available for the construction process stage [A4–A5] and replacement stage [B4] for façade. Data collection is required from manufacturers' Environmental Product Declarations (EPDs) in order cover the construction process stage [A4–A5], and from facility managers to cover replacement stage [B4] for façade. These stages are not considered in the scope of this research. In fact, 'One click LCA' reports on previous buildings revealed that the product stage contributes more than 85% to 95% of the material embodied carbon. Operational energy use [B6] is also excluded from the scope of the framework, as it is calculated using separate tools, and the limitations of using VPL to integrated operation stage, as mentioned before. Therefore, this framework's material life stages, which identify the boundary system, is cradle-to-gate product stage [A1–A3], as shown in figure 6.2. Other stages can be included where generic inventory data is available; this can be added in future studies during expansion of this framework using the same concept.

Regarding the construction elements included in the calculation, the framework will cover more than the minimum requirement of the RICS whole life carbon assessment for the built environment document (Royal Institution of Chartered Surveyors, 2017). The building parts that will be included in the framework are substructure, superstructure and finishes. This framework may be used from early design stage (stage 2: concept design) and during design development (stage 3: spatial coordination), and can be used in technical design as the model LOD and LOI are higher. The scope of the calculation is shown in figure 6.2.

Table 6.1: RICS minimum requirements for whole life carbon assessment (RICS, 2017)

Building parts	1. Substructure 2. Superstructure
Life stages to be included	• Product stage [A1–A3] • Construction process stage [A4–A5] • Replacement stage [B4] for facade • Operational energy use [B6]
Assessment timing	At design stage – prior to technical design

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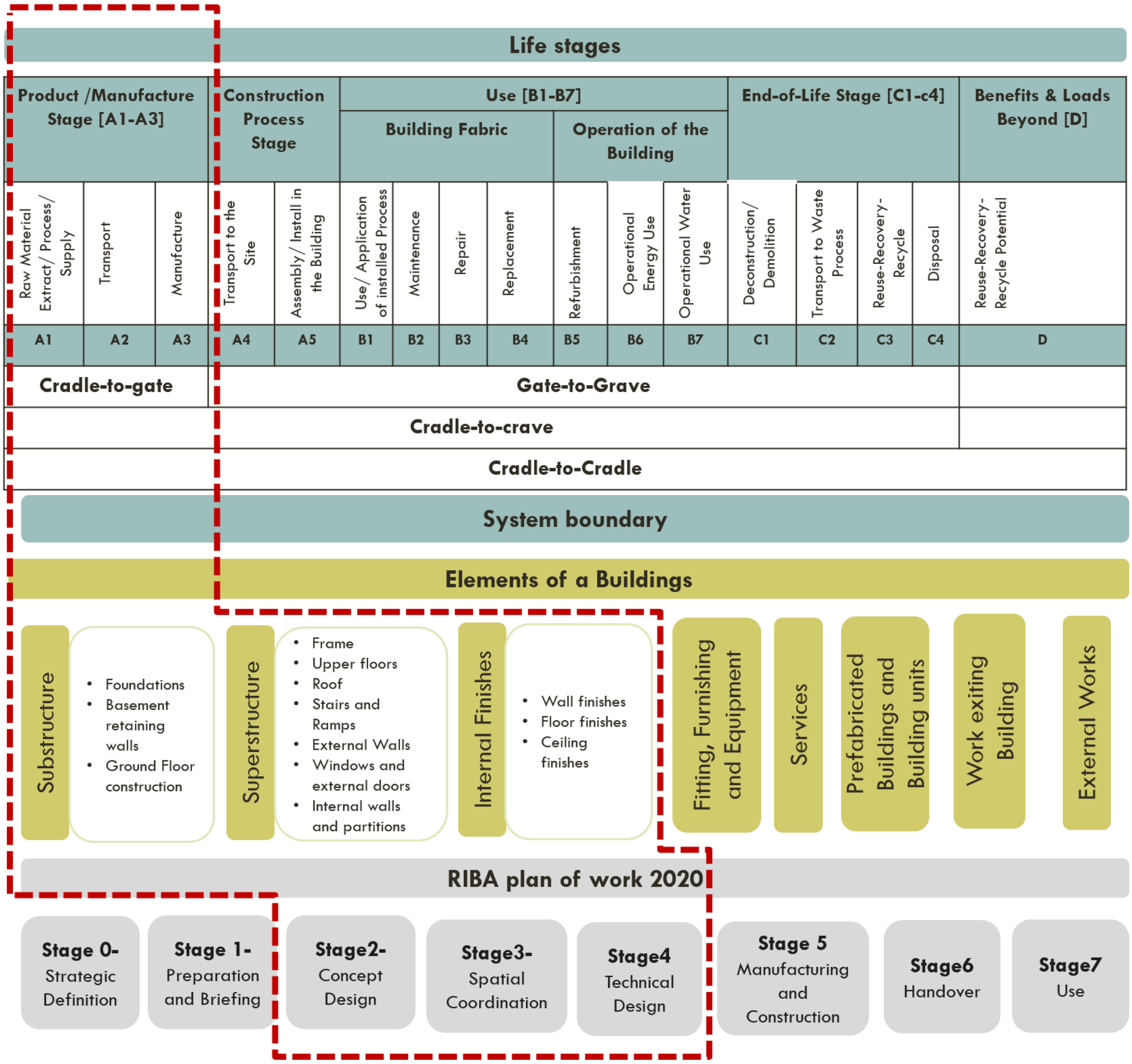

Figure 6.2 LCA system boundary, elements of buildings and RIBA plan of work 2020

6.3.2 LCA indicator

LCA is a standardised process for estimating the environmental impact of a product, for example. A large amount of emission data is collected during the LCA, including emissions from energy production, waste creation, and raw material production from stages categorised in the above section (CSN EN Standard, 2019). EN15804 + A2 standard defined the environmental impact categories which are labelled as indicators. These indicators represent emissions from harvesting raw materials, production of materials and other processes that are responsible for environmental impact. Examples of indicators along with their unit of measurement are presented in table 6.1. In the process of life cycle impact assessment (LCIA) required for LCA, specialists try to unite/quantify different emissions into actionable numbers (coefficient functional unit). These actionable numbers are collected and provided in an inventory database.

The most commonly used and significant indicator relates to climate change, and is also known as global warming potential or embodied carbon (EC). It is measured by Kg Co2 eq, as stated in the UK whole life carbon assessment standard produced by RICS (Royal Institution of Chartered Surveyors (RICS), 2017). **This study will include only EC as an indicator for environmental impact, due to database availability in the UK, which will be explained in section 6.4.**

Table 6.2: Sample of indicators describing environmental impacts (PN 514 Rev 3.0, 2020)

Impact category	**Parameter/ indicator`**	**Unit**
Climate change – total	Global warming potential total (GWP - total)	KKg Co2 eq.
Ozone depletion	Depletion potential of the stratospheric ozone layer, ODP	Kg CFC 11 eq.
Acidification	Acidification potential, accumulated exceedance (AP)	mol H+ eq.
Eutrophication aquatic freshwater	Eutrophication potential, fraction of nutrients reaching freshwater end compartment (EP freshwater)	Kg (PO4) 3- eq.

6.4 Dynamic LCA-BIM framework concept

Few scholars have attempted to develop a tool for dynamic LCA within the BIM environment using Revit and Dynamo software. Taking into consideration the parametrisation feature of BIM models, functional coefficient unit LCIA developed database, and ability to automate manual work using VPL scripts, several studies have used these features to develop dynamic LCA-BIM tools. Bueno et al. (2018) have established a tool that allows LCA assessment within Revit by linking the LCIA database into the elements library. The study used VPL to automate the import of database and LCA calculations. One manual step is required in this approach, to prepare a worksheet that contains all values of materials in the element and prepare a total functional value per element, before importing back to Revit. Another approach was introduced by Genova (2018), which attempts to automate all the steps required to build a dynamic LCA tool. The approach focused on importing an LCI database functional unit on a material level

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and applied the required equations in calculation scripts. The two approaches have been investigated, but Genova's (2018) methodology has been followed to build the framework in this research, as it is more fitting to UK database availability, as well as being more efficient as it eliminates manual work. Therefore, the framework concept proposed in this thesis is built on the approach developed by Genova's 2018 work, which was explained in detail in chapter 4. The main contribution of this model is that it is designed and built for a UK database and LCA calculation, which was previously found to be lacking, as mentioned in chapter 4.

The framework proposed in this research aims to allow architects and structural engineers in the UK to develop an adequate BIM material library and use Visual Programming Language (VPL) Dynamo to calculate and visualise the embodied carbon (EC) of their design decisions. This approach allows dynamic and iterative evaluation of EC and enables reuse of this information on other projects. The concept of the framework is to develop Dynamo scripts that allow the LCI database to be linked with the Revit material library using material ID, then run scripts on the designed BIM model to operate the required equation for calculations of LCA, and finally to produce results that can be visualised and compared to benchmarks. An illustration of the concept is shown in figure 3 and further details of the framework will be explained in the following sections.

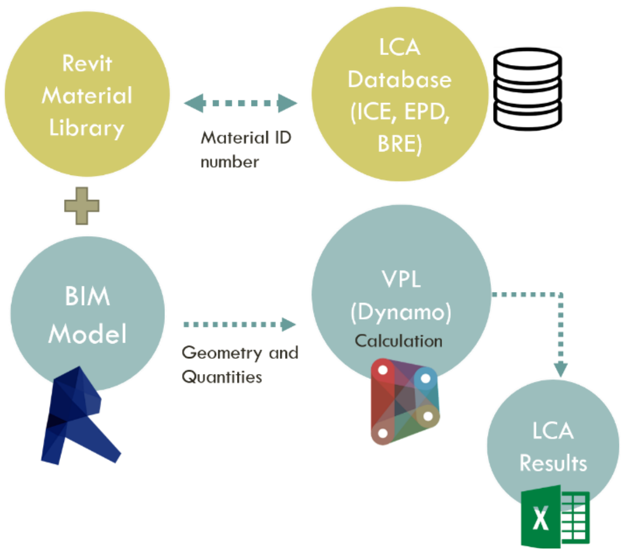

Figure 6.3: BIM-LCA integration concept

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6.5 Inventory database

6.5.1 Categories of LCI database

Internationally there are three categories of LCA database: floor area-based databases, component-based databases and material-based databases (Cavalliere et al., 2019; Genova, 2018). These three different database types allow users to calculate the indictors selected in different stages of the design at different LODs. Cavalliere et al. (2019) suggest that at an early stage of the design, a floor area-based database, such as the Swiss Buildings Database, is suitable as it gives an estimate for the user without specifying materials, which have not yet been specified. An example of the second typology of database is Bauteilkatalog, which provides a coefficient per building component, and this is suitable when not all materials are modelled. The third kind of database is material specific and provides a coefficient per material.

Sources of inventory database include: Environmental Product Declarations (EPD); industry data; government data; factors from commercial LCA database (ICE database); PAS 2050, compliant carbon footprint; and factors derived/aggregated from literature (Mohebbi et al., 2021). The level of depth, specificity, and accuracy of each data source varies. EPDs provide the most precise information. EPDs are assessments performed by manufacturers in accordance with BS EN 15804:2012 and A2:2019. The ISO 14044 standard must also be followed during the EPD production procedure. An EPD only needs to be performed at the A1–A3 boundary according to EN 15804:2012 standards, and all other life cycle stages can be completed voluntarily. Manufacturers are not required to publish EPDs; despite this, the number of published EPDs is continuously increasing, but the quantity of EPDs available is still limited. Standard procedures of the area or country where the EPD is published must be considered in circumstances when the other steps are included in the EPD. For example, a German cradle-to-grave EPD is more likely to anticipate energy recovery for a material's end-of-life treatment; meanwhile in the United Kingdom, materials are typically recycled or disposed of in landfills at the end of life. Industry data and national databases are two more sources of carbon data. BRE produced the Environmental Profiles Methodology in 1999, which highlighted the embodied carbon of over 200 of the most prevalent building materials, using data obtained from the UK construction sector. It was later modified in 2009. The Inventory of Carbon and Energy (ICE) databases, created by Hammond and Jones in 2008, is one of the most up-to-date and commonly utilised datasets in the UK. This database is updated on a regular basis, with the most recent version coming out in 2019. A cradle-to-gate carbon factor for over 500 of the most prevalent building materials can be found in this database (Mohebbi et al., 2021).

Therefore, ICE database and EPDs will be both used in this framework to overcome the lack of a one source database. Due to inventory database limitation, cradle-to-gate is set as the system boundary, as mentioned in section 6.3.1. The relationship between differences in level of information (LOI) and the mix of different database sources will be discussed in the next section.

6.5.2 Relationship between level of development and database

The level of development of the BIM model is described by level of detail (LOD) and level of information (LOI). LOD defines the maturity of the geometries or graphical definition, while level of information defines the assigned specification to the elements in the model. UK standards define them in four steps: LOD and LOI 2, 3, 4 and 5. Low information content and less graphical representation details are found in LOD 2 and LOI 2. The accuracy of the calculation increases as the LOD and LOI get higher, although LOD 5 and LOI 5 are rarely achieved. Therefore, the library built up contains different materials illustrating different levels of development of the model, starting with LOI and LOD 2 and going up to 4. An example of the naming convention for materials is illustrated for insulation materials in figure 4. The library should include generic materials with average values suitable at LOI 2, and this is available in the ICE database. Then at higher LOI will be reached when material specification is available. The third level is usually reached through having a manufacturer-specific material, with information being provided from the manufacturer’s EPD.

Material names and EC coefficient values	Suitable at LOI

ICE Database

Materials	Embodied Carbon - kgCO2e/kg
General Insulation	1.86 CO2 Only
Cork	0.19 CO2 Only
Fibreglass (Glasswool)	1.35 CO2 Only
Flax (Insulation)	1.7 CO2 Only
Mineral wool	1.28
Paper wool	0.63 CO2 Only
Polystyrene	See plastics
Polyurethane	See plastics
Rockwool	1.12
Woodwool (Board)	0.98 CO2 Only

LOI 2 (General Insulation)

LOI 2-3 (Cork to Woodwool (Board))

ICE & EPD

Material	Density	Embodied Carbon - kgCO2e/kg	Manufacturer
polyisoac			
PIR insulation boards, aluminum foil faced, <= 160 mm, L = 0.0215 W/mK, dens. = 32 kg/m3, Various products (Xtratherm)	32 kg / m3	169.38 kg CO2e / m3	Xtratherm UK
Insulated wall/roofing cladding panel, 100 mm, 12.6 kg/m2, U 0.18 W/m2K, KS1100 AB/CS Quadcore (Kingspan)	126 kg / m3	41.4 kg CO2e / m2	Kingspan
Insulated wall/roofing cladding panel, 100 mm, 14.4 kg/m2, U 0.18 W/m2K, BENCHMARK Quadcore Karrier (Kingspan)	144 kg/m3	45.2 kg CO2e / m2	Kingspan
xps insulation			
XPS insulation board, 0.033 W/mK, Polyfoam ECO Extra XPS (Knauf)	34 kg / m3	3.56 kg CO2e / kg	Knauf
XPS insulation board, 0.033 W/mK, Polyfoam ECO Standard (Knauf)	31 kg / m3	3.55 kg CO2e / kg	Knauf

LOI 3-4

Figure 6.4: Mix of sources of database relation with different LOI

6.6 BIM model structure

In order to achieve successful integration between BIM and LCA assessment, it is crucial to understand how information is structured in a BIM model. There are two main concepts that need to be emphasised in order to be able to link LCA database and structure Dynamo scripts. The first one is the Revit hierarchy in presenting and storing the model information, which is presented in table 6.3. The second is the calculation model of EC and the equations that need to be operated in order to automate the assessment process, which is presented in figure 5.

The first aspect is the hierarchy of the BIM model structure. Each BIM software constructs the model using a different logic of data structure. In this framework Revit software is used as a tool for model building. Table 6.3 shows the hierarchy of the geometric and information model in Revit (Genova, 2018). Dynamo scripts understand, read and write back the model information in this hierarchy as well.

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The Revit BIM model is divided into Revit categories which are grouped according to their function in a building, such as walls, roofs, columns, floors, etc. This is defined as level 1. Each category is then subdivided into different “families”; for example, the wall category can contain the curtain wall family and the basic wall family (Genova, 2018). Each family contains different typologies, defined as “types”, e.g. the basic wall family can contain “250mm brick wall”, “215mm blockwall_concrete blocks” and others. Family and type information levels are not utilised in the designed LCA calculations.

The element level is a constructed geometry of a specific type. At this level, the information that is needed to be captured and utilised in the Dynamo calculation model is element ID, quantity information, material composition and other functional information, such as whether it is structural or external. The third level of information is the material level, area and volume of material in a component, which will be captured from this level.

In this framework the database will be imported on parameters generated on Level 3 (material level). The scripts will capture the associated information on this level, as well as the area and volume of the modelled materials, in order to include them in calculations. Information on the element level is also required to construct the calculation model. The user can identify whether or not the element modelled is structural, and external, through check boxes, which will help in categorising the element. For example, the wall may be categorised as an external or internal wall, and as a structural wall or architectural envelope wall.

Table 6.3: BIM model information hierarchy (adopted from Genova, 2018)

<table>
<tr><th colspan="6">BIM model information hierarchy</th></tr>
<tr><th>BIM model</th><th>Category</th><th>Family</th><th>Type</th><th>Element</th><th>Material</th></tr>
<tr><td>Level 0</td><td>Level 1</td><td></td><td></td><td>Level 2</td><td>Level 3</td></tr>
<tr><td>Building model</td><td>Wall
Floor
Roof ..…</td><td>System family
e.g. roof</td><td>Structure
Roof type 1
Roof type 2</td><td>Information specific on drawn unit</td><td>E.g. concrete insulation clay tiles...</td></tr>
<tr><td colspan="4" rowspan="7"></td><td>Area</td><td rowspan="5"></td></tr>
<tr><td>Volume</td></tr>
<tr><td>Dimensions</td></tr>
<tr><td>Structural?</td></tr>
<tr><td>External?</td></tr>
<tr><td rowspan="2">Material</td><td>Material 1
Area 1
Volume 1</td></tr>
<tr><td>Material 2
Area 2
Volume 2</td></tr>
</table>

As shown in figure 5, the calculation of EC involves multiplication of the functional coefficient value Kg Co2* quantity of the material. Summation of all EC of the materials in an element gives the value of the EC of the element. In order to get the total value of EC of walls, all the EC elements will be added, and the summation of all the EC of the element's categories form the total EC of the building. This is illustrated in figure 5 and explained in the equations below.

EC wall element 1 (Kg Co2e) = Brick functional coefficient unit * quantity

EC of all walls = ∑ EC wall element 1 + EC wall element 2+ wall element 3…. etc.

EC of a building = ∑ EC of the walls + EC of floors + EC of columns…. etc.

There is one additional vital factor. The EC coefficient functional values are represented in the database with different functional units. For example, some materials' EC values are given as Kg Co2/m2 and others Kg Co2/m3, while most of them are given as KgCO2/Kg. In this case the calculation model needs to filter materials according to their functional unit in order to apply the suitable equation.

Equation for functional unit Kg Co2/Kg

Total material EC (Kg Co2e) = EC coefficient value (Kg Co2e/Kg) *material volume (m^3) *material density (Kg/m^3)

Equation for functional unit Kg Co2e/m2

Total Material EC (Kg Co2e) = EC coefficient value (Kg Co2e/m^2) *material area (m^2)

Equation for functional unit Kg Co2/m3

Total material EC (Kg Co2e) = EC coefficient value (Kg Co2e/m^3) *material volume (m^3)

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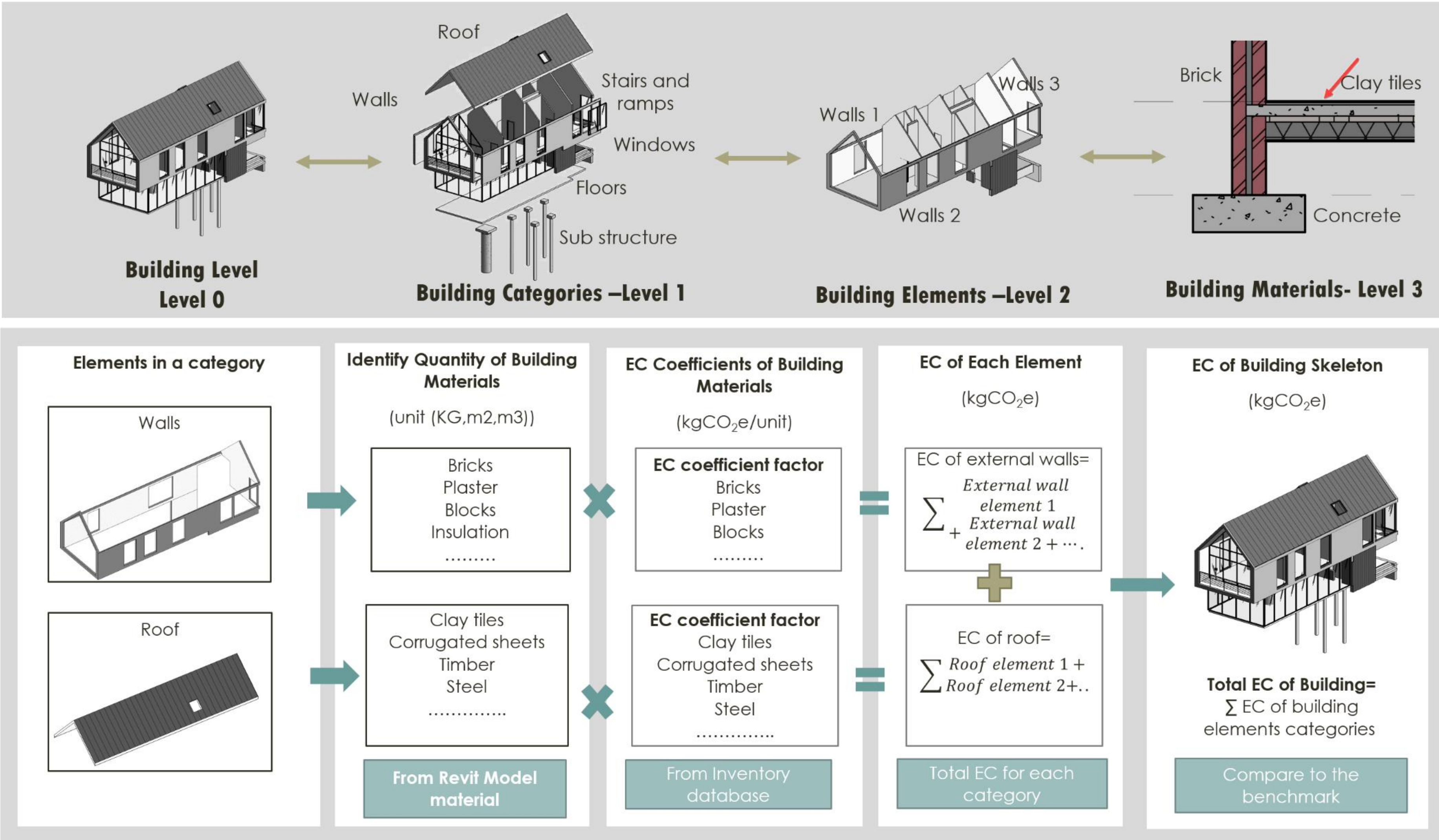

Figure 6.5: EC calculation and Revit model information

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6.7 Revit parameters for LCA

In the AEC industry, a potential opportunity has been created to integrate LCA into a BIM platform by using an LCI functional unit, parametrisation information-based objects in the BIM environment and automation capability provided by VPL tools. This approach is based on the parametric information-based modelling of BIM, in which modelled objects (geometries) are attached to the information. Therefore, after the review of the EC calculation logic, the structure and hierarchy of attached object information needs to be understood and corresponding information needs to be set in order to be able to generate suitable parameters. The parameters included in this framework contain the information and values required for assessment, and they are grouped into two types: material parameters and element parameters. Material parameters, identified in table 6.4, will be generated for the information prepared in the Excel standard file, which will contain all the information from the inventory database.

Table 6.4: Revit material parameters

Material parameters	
MA_LCA inventory source	Source of the value e.g. ICE database, EPD…
MA_coefficient unit	M^2, m^3, Kg
MA_embodied carbon Kg CO2/unit	Numerical value represents the functional coefficient of the material, which is the amount of EC in Kg CO2 per unit
MA density	Numerical value of the material density
Material ID	The material ID identified by the user (the link between database and Revit library)
MA_reference service life	This parameter is used if the system is expanded
MA_correction factor	This parameter is used to cover quantity inaccuracy in models with less LOD

Table 6.5: Revit elemental parameters

Elemental parameters	
Embodied carbon (Kg CO2 eq)	Calculated EC of the element quantity*EC functional unit
Element ID	Revit element ID (needed in calculation model)
% volume	Value of the percentage volume of the element to the total volume in order to display the contribution of the family with respect to the % volume
LCA_category	Text value written back by the calculation script which identifies the LCA_ category of the element, to be then read by the output script
EL_elemental ID	Used for future expansion of tool if database will be available per element (for calculation of EC in simplified calculation which needs less LOD)
EL_LCA inventory source	
EL_coefficient unit	
Total GWP value range	Future use: ranking of this family to similar family benchmarks
LCA_optimisation display	Future use: Colour name, which informs what colour should be displayed on the model depending on its sustainability ranking in comparison to identified benchmarks

6.8 Road map for the framework

The model is designed using a two-stage process, as illustrated in figure 6.6. The first stage is to set up an adequate BIM library using compliant databases and tools, and add parameters for storage of the database and calculated results. This stage attempts to create a Revit template file ready for the user to model the design. Then in stage two the template will be used to model several design alternatives which can be compared and visualised iteratively along with design changes. The framework allows the reuse of the data generated and provides a framework to build up, reuse and update the BIM library for LCA.

In this process all of the tasks required to build up the system and run calculations are automated by running Dynamo visual scripts. This eliminates time-consuming manual tasks. The only manual work will be in the preparation of the standard Excel material file (step 2 stage 1) as shown in figure 6, in which the user will prepare an Excel file containing information about all the materials. The next section will briefly explain the steps of the framework, and then detailed and illustrated steps will be described in section 6.11.

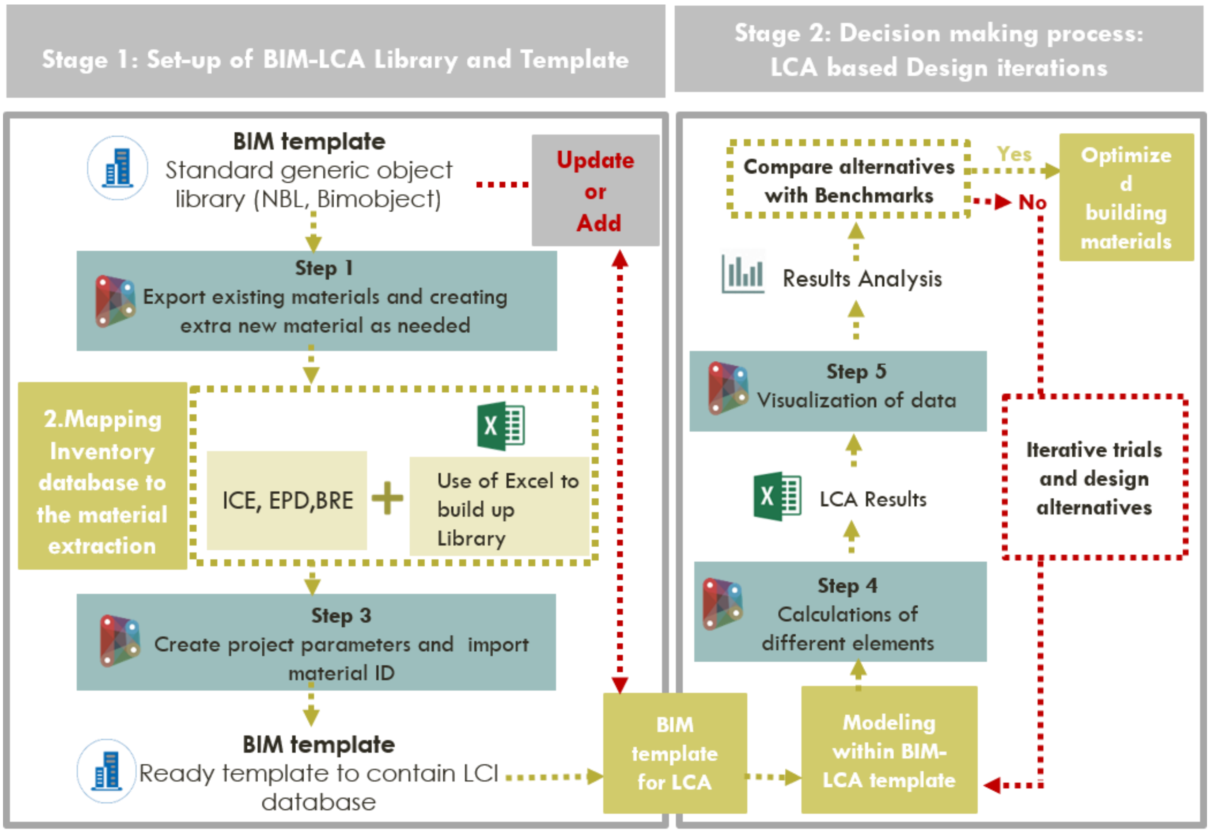

Figure 6.6: Framework road map and two stage process

6.9 Dynamo script functions

This section will briefly explain the sequential steps for building the system and running the assessment. All steps are summarised in figure 6.6 and the function of all scripts included in the framework is summarised in table 6.6, which acts as a user guide on the function, input and output of every script. The user needs first to understand the roadmap of building the system which is provided in the section above, then to know the function of each step and how to utilise the scripts, and finally to understand the different considerations and details that need to be undertaken in each step.

The VPL that is used in this framework is Dynamo, with Dynamo player as the user interface that constructs the connection to the BIM file and BIM model data and allows processing of EC calculated values. In order to automate the process, logical sequential steps need to be designed with the aid of Dynamo scripts to allow the user to link the model with the database, operate the assessment calculations and export the results; it was crucial to split these into subtasks to automate all import, generation, calculation and export steps. Because this type of approach may need a high processing capacity, the environmental impact assessment must be divided into logical subtasks, as shown in table 6.6. To carry out a valid LCA computation, these scripts must be executed one after the other, as shown in table 6.6; a detailed description of the steps illustrated in this table will be given in the next section.

As mentioned before, the stage one aim is to build a template with an adequate EC library; the steps to achieve this are only carried out once at the beginning, but may be repeated whenever the library needs to be expanded or updated. The first step in stage one is to access the current working template and download generic BIM objects as needed. The library of materials should contain generic materials and manufacturer-specific materials in order to suit different stages of design. If there is a requirement to add any extra material names to the library, Script 01_Create Revit materials can be used, then Script 02_Export all materials is used to export all material names and Revit ID into an Excel sheet. This Excel sheet can be used as a base for the user to manually prepare the standard Excel file that will contain all of the material information. This is considered to be the only manual step that the user needs to do. This step also is crucial for the reliability and accuracy of the library, which will directly affect the results. In the same stage, Script 03 will be used to automatically create the required parameters that will act as the containers of the data. The last step in stage 1 is to run Script 04_import material ID and EC database, which reads all the information in the Excel standard file and imports it into the Revit material library. Now the Revit LCA template library is ready to be used.

Stage two in the framework will be operated repetitively every time the design is changed and EC needs to be assessed to inform decision making on material selection to optimise EC. It contains two set of scripts. Stage 2.1, as shown in table 6.6, are responsible for applying calculation equations to all the materials included in the categories mentioned and the EC total value per element back to Revit parameters. The different element groups are split into different files to overcome any overloaded computational capacity errors. The second group of scripts, in Stage 2.2, are responsible for automatic exportation and representation of the results and visualisation of data.

Table 6.6: Detailed description of the Dynamo scripts function, input and output

	Script	Function	User Input	Output
Stage 1 –Create template with Library	**Script 1-Create Revit Material**	Automatic creation of Materials from Excel sheet to eliminate manual creation.	Excel sheet with Material name	Material creation in Revit library
Stage 1 –Create template with Library	**Script 2- Export All materials**	Export all Materials from Revit Library	Excel sheet output file path.	Excel sheet with all Materials name and Revit IDS
Stage 1 –Create template with Library	**Manual mapping of Material ID on Excel**			
Stage 1 –Create template with Library	**Script 3- Create project parameters**	Create the required global, elemental and material parameters which are containers to database and calculations.	No input	Project parameters created in template file
Stage 1 –Create template with Library	**Script 4- Import Material ID and Information in standard file family**	Read from standard inventory and write back in Revit material parameters.	Standard database excel file path	Standard file Inventory database and Material IDs imported to Material library
Stage 2.1 Calculation	**Script 5- Walls** **Script 6- Envelope** **Script 7- Floors** **Script 8- Interior** **Script 9- Doors** **Script 10- Structure**	Analysis and calculation of different element categories Through reading database from Excel standard file and filtering materials with coefficients m2,Kg,m3 and applying suitable equation accordingly.	Standard database excel file path	Writing back to elemental parameters the calculated values (% volume-embodied carbon-optimization LCA category)
Stage 2.2 Representation	**Script 11- Report total EC per category**	Collect all calculated EC for each element and apply summation to present the data EC per category	File path for total EC per category excel sheet	**Excel sheet with EC values per category and bar chart.**
Stage 2.2 Representation	**Script 12-Report Detailed EC per Material**	Present detailed calculated EC to examine and highlight the high EC contributors and act as check on the model calculations and missing elements.	File path for Detailed EC excel sheet	**Excel sheet with EC values per category and bar chart.**
Stage 2.2 Representation	**Script 13- LCA benchmarking**	Compare the total EC/ gross floor area to Benchmark	File path for LCA benchmark excel file	**Excel sheet with design total EC per gross floor area benchmark comparison.**

6.10 Different levels of user interference

The user of this model can interfere with the files on two different levels: front end interference, and back end interference. Most users are front end users and may interfere with the model through Dynamo player. In this case, the user needs to know the function of each script, what the input and output Excel files are, and how to run the script from the Dynamo player interface. The user has to be aware of the effect of changes in Excel files to avoid misuse and incorrect results. At this level the user is not required to have extra knowledge or skills in Dynamo scripting. The second level of interference is back end interference, in which the user is expected to have extra knowledge and understanding of the logic and structure in Dynamo script and be able to modify or expand the system using the same logic. This level of knowledge will also allow the user to be able to deal with any errors that may occur during the running of the scripts. A brief summary of the types of users and equivalent knowledge is presented in table 6.2. The next section will explain in detail the workflow for using the scripts, which is fundamental for both types of user to know. It will also describe the logic behind the structure of the scripts, which will be useful for back end users only.

Table 6.7: Types of users and model level of interference

Type of user	User interface	Knowledge and skills required
Front end user	Dynamo player in Revit	Does not need extra Dynamo scripting skills
Back end user	Both Dynamo in Revit and Dynamo player	Needs minimum knowledge of writing Dynamo script and extra skills required for modification or expansion of scripts

6.11 Script structure logic and showcase

This section will describe the logic of the Dynamo script structure and flow. It will also illustrate the steps of the model using a showcase. The model used to illustrate the steps in this section and in the workshops is a virtual model provided by BIM Academy and used for educational purposes. Permission was provided to use the model in this context. This tool is a folder-based one in which each Dynamo and Excel sheet required for a Dynamo file is placed in a folder named with the function of each script or group of scripts, as shown in figure 6.7.

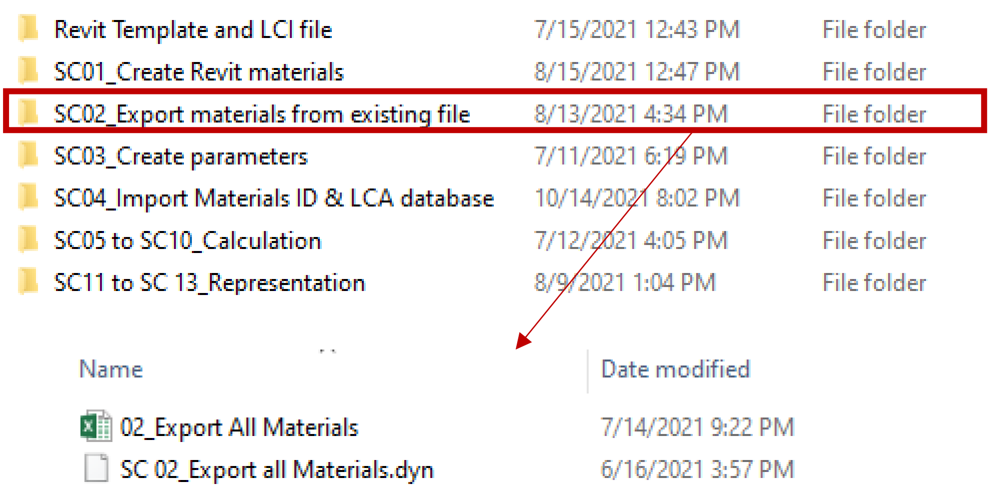

Figure 6.7: Folder system used to organise the scripts and Excel sheets

6.11.1 Create Revit materials

After accessing the Revit library and preparing material names to be added, as explained in section 6.5, the first script is used. "Script 01-Create Revit Materials" allows the user to automatically create multiple new material names to be added to the Revit material library. It is a very time-consuming process to manually add new materials one-by-one in Revit in order to build up a material library suitable for LCA. All new material names are inserted into the

6.8 Create list of materials in Excel file

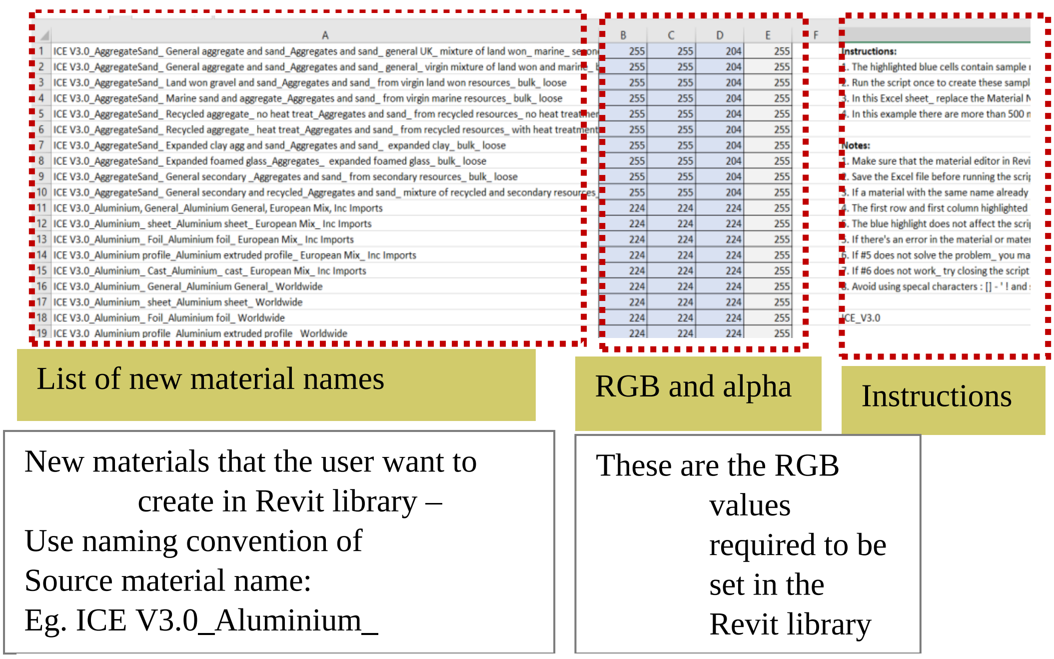

Figure 6.8: Create list of materials in Excel file

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provided Excel sheet “01_Create Revit Materials”. RGB and alpha are numbers of the assigned colour in Revit. Figure 6.8 shows a sample of the Excel sheet and how to use it.

The logic of the Dynamo script is to read from the Excel sheet the material name and assigned colour RGB values, then sort these data in the second step, and in the third step, to translate these values to set the material properties. Finally, the python custom node is created to convert the properties defined into the Revit library to create the new materials as defined (*Create Revit Materials with an Excel Sheet | Dynamo Now*, 2018). See figure 6.9.

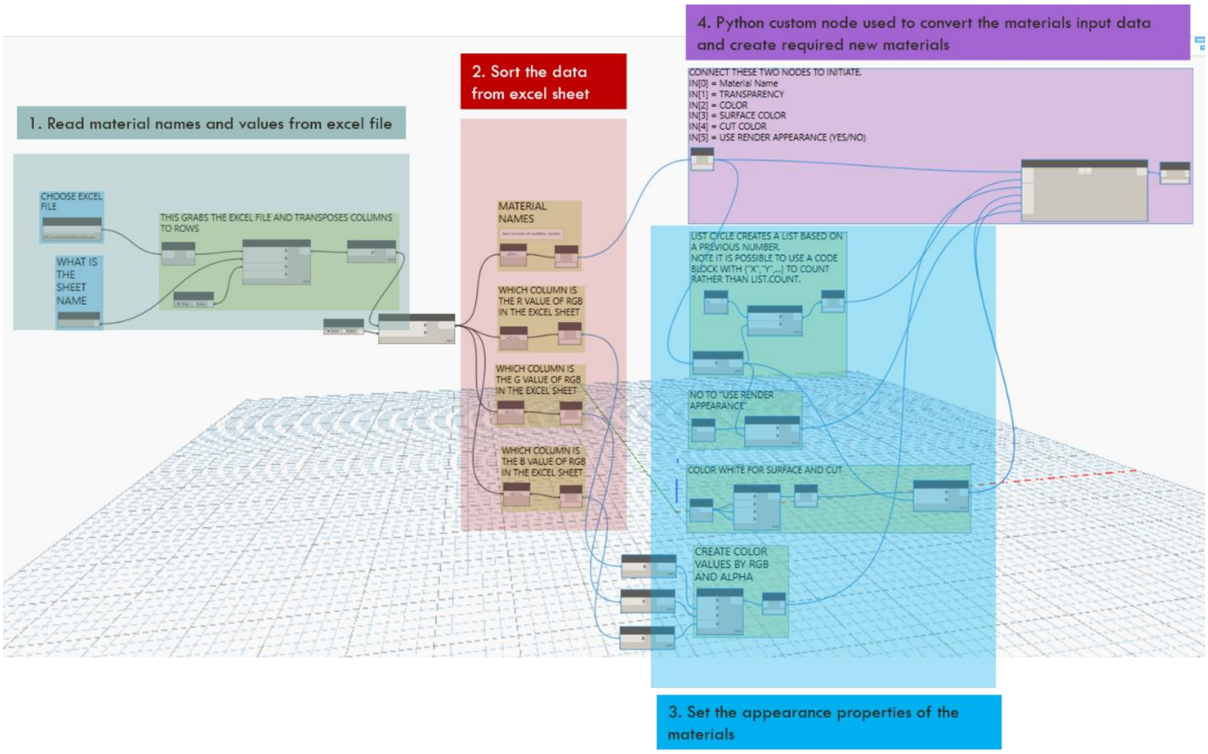

Figure 6.9: Script 01 create new project material structure

6.11.2 Export all materials

This script function is to export all of the material names and Revit ID, including existing and new materials, from the Revit library into an Excel sheet, as shown in figure 6.11. This Excel file will be used to build up the “standard manual mapped LCI database”. The order of the rows of material should not be changed because it will be imported using the same order. If the user has a material name that does not have an EC value, this should be retained with a value of zero, but not deleted. The logic of the script, as shown in figure 6.10, is based on three steps: first, to set the category that the script will work on, which is materials; then define what information is required (material names and IDs); and finally, to sort the data and export it into the defined Excel file. The material ID will act as a second check later on when importing data to avoid problems.

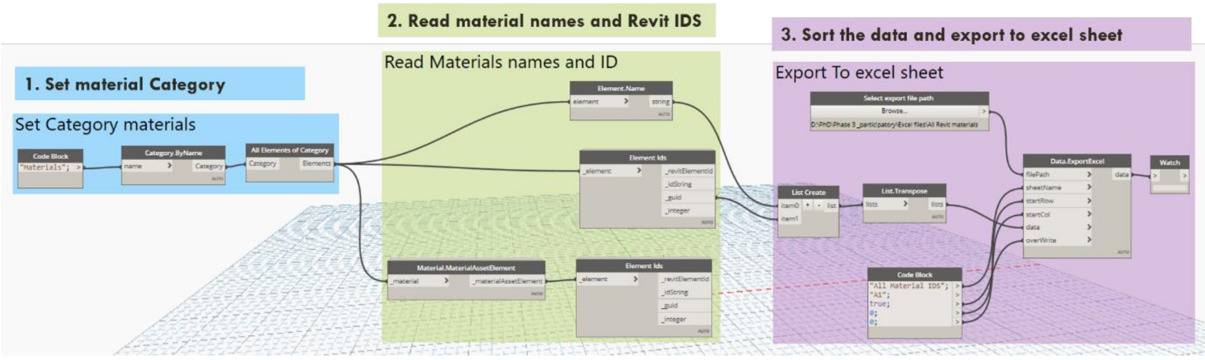

Figure 6.10 Script 02 export all materials structure

	A	B
1	Default	e3e052f9-0156-11d5-9301-0000863f27ad-00000017
2	Default Wall	e3e052f9-0156-11d5-9301-0000863f27ad-00000018
3	Default Roof	e3e052f9-0156-11d5-9301-0000863f27ad-00000019
4	Glass	e3e052f9-0156-11d5-9301-0000863f27ad-0000001a
5	Phase - Temporary	e3e052f9-0156-11d5-9301-0000863f27ad-0000001d
6	Brick, Common	e3e052f9-0156-11d5-9301-0000863f27ad-0000019e
7	Concrete Masonry Units	e3e052f9-0156-11d5-9301-0000863f27ad-0000019f
8	Metal Stud Layer	e3e052f9-0156-11d5-9301-0000863f27ad-000001a0
9	Plywood, Sheathing	e3e052f9-0156-11d5-9301-0000863f27ad-000001a1
10	Air	e3e052f9-0156-11d5-9301-0000863f27ad-000001a2
11	Air Infiltration Barrier	e3e052f9-0156-11d5-9301-0000863f27ad-000001a3
12	Vapour Retarder	e3e052f9-0156-11d5-9301-0000863f27ad-000001a5
13	Gypsum Wall Board	e3e052f9-0156-11d5-9301-0000863f27ad-000001a7
14	Earth	e3e05304-0156-11d5-9301-0000863f27ad-00000207
15	Concrete, Cast In Situ	e3e05304-0156-11d5-9301-0000863f27ad-0000020b
16	Default Floor	458c0f14-01bb-11d5-9302-0000863f27ad-000002f6
17	Roofing, EPDM Membrane	458c0f21-01bb-11d5-9302-0000863f27ad-00000318
18	Asphalt, Bitumen	458c1092-01bb-11d5-9302-0000863f27ad-00000361
19	Phase - New	00c6c04a-12df-4dad-941f-b193ceb216ca-0000225e
20	Door - Frame/Mullion	0eddca8c-7a33-4302-8e36-2334fb464e07-0000527c
21	Door - Handle	0eddca8c-7a33-4302-8e36-2334fb464e07-000052d8
22	Poche	d8c55e1e-6a1d-4cfd-b137-7536d455a562-0000c8ff
23	Default Mass Floor	c933d2f6-32e5-4d20-837a-f9359bdd8683-0000cbab
24	Plastic	654c5a4f-acf4-48d8-8b7e-4d3bee0acbbd-000191c8
25	Default Light Source	1d0aa0f6-39f7-481f-afaa-d7c0b72c18ad-000194df

Material names | Reference Revit ID

Figure 6.11: Output Excel file from Script 02

`

6.11.3 Prepare the "Standard file LCI Material database"

This is the only manual step required during material mapping in the framework. In this step, the user takes the Excel file extracted from the previous step (Script 02) and uses it to complete the standard database file. The user will only add the materials that are used in modelling; other materials, such as default, cavity etc., will be kept in the file but with zero value and NA value. Data sources used, as mentioned in the inventory database section, are ICE database, BRE Green Book Live, and manufacturers' EPDs. The following import script will read the data from this file, so no changes should occur in the arrangement of the columns and rows.

The user should add material ID that indicates the source of the LCI, coefficient unit, EC coefficient value and density. These are required for calculation, as shown in figure 6.12. LCI source also enables the sources used for calculation to be traced and evidenced. Reference service life of the material is included in the table in case the system is later expanded to include whole life cycle of the material.

Coefficient | EC Kg Co2 eq /unit | Correction factor

Material Name	Revit Material ID number	Material ID			LCI source	RSL	Density	
Wood - Dimensional Lumber	c3873aa1-fe32-4eb8-8950-1bf372d5ef1a-0005a725	ICE V3.0_Mat18	Kg	1.59	ICE database August 2019, V3.1	60	615	0.6
nbl_Plasterboard Gypsum	36b02730-badd-418f-a68a-da41d3709d95-00062505	EPD_BRE_Knauf_Mat 14	m2	1.95	EPD_Knauf Wallboard impregnated	60	688	1
nbl_PolyisocyanurateFoamBoards	36b02730-badd-418f-a68a-da41d3709d95-0006250a	EPD_BRE_Knauf_Mat 13	m3	121	EPD_BRE_Knauf	60	34	1
nbl_Cavity	36b02730-badd-418f-a68a-da41d3709d95-0006250b	GEN_27	Kg	0	NA	0	0	0
nbl_SteelFrame	36b02730-badd-418f-a68a-da41d3709d95-00062624	ICE V3.0_Mat15	Kg	1.55	ICE database August 2019, V3.0	60	7850	0.25
nbl_MineralWoolBatts	36b02730-badd-418f-a68a-da41d3709d95-00062625	ICE V3.0_Mat19	Kg	1.28	ICE database January 2011, V2.0	60	51	1
nbl_BricksClay	36b02730-badd-418f-a68a-da41d3709d95-00062626	ICE V3.0_Mat16	Kg	0.24	ICE database August 2019, V3.0	60	1485	1

Figure 6.12: Sample of how material data is structured in standard LCI file

a. Correction factor

When this framework is tested on the virtual BIM model, inaccuracy was found in the output calculation due to the lower level of detail. Therefore, a novel a approach is proposed to add a correction factor for material data sheet. This was inspired by the ready One click LCA profile element library, in which materials that exist in an element and does not fill 100 percent from the cross section area in an element profile is multiplied by factor that represents the real volume of the material. The next section will explain in detail how it works.

The correction factor function here is used to get more accurate results in models of lower LOD; the number represents the actual quantity percentage from the modelled element, as presented in the equation below. For example, the framed walls are not modelled with studs and boards until LOD 4. As shown in figure 6.13, LOD 4 will be reached at later stage of the design, so the quantity (area and volume) calculated by Revit is not the actual quantity, and therefore at this LOD the metal material used for studs is multiplied by a correction factor which in this case could be 0.3. This represents 30% only from quantity calculated from the model.

Actual quantity (area/volume) = correction factor (F) * modelled and calculated quantity (area/volume)

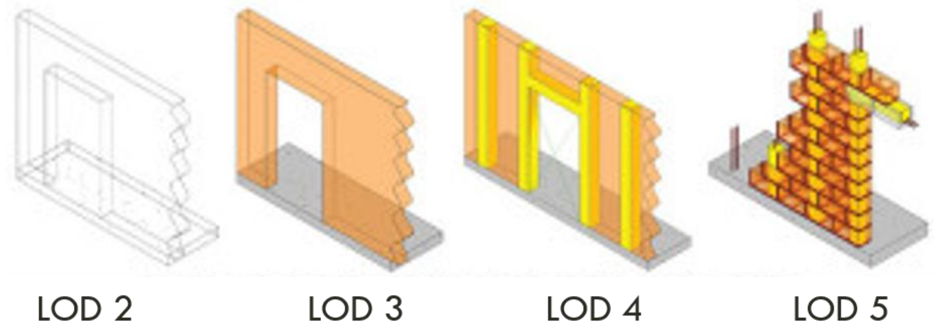

Figure 6.13: Model development - level of detail (BIMForum)

This correction factor is one way to overcome the limitation of use of EC database such as ICE database in low detailed BIM models. It is argued that this is considered a theoretical contribution from this research, which can be added in future development of elemental EC database.

6.11.4 Create project parameters

This script is responsible for automatically creating the required parameters defined in section in 6.6 for the Revit template file. The material parameters will act as containers for the data prepared in the “standard material LCI” Excel file, while elemental parameters will contain the data generated by the calculation scripts. The output after running the script is presented in figure 6.14.

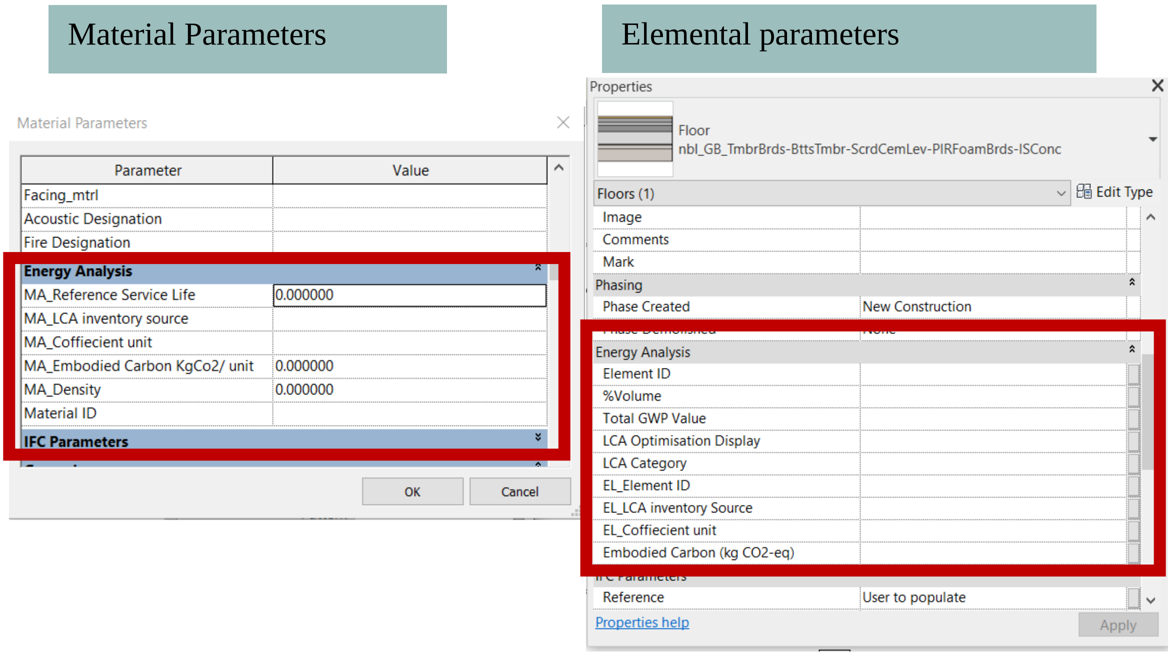

Figure 6.14: Output from Script 03

The logic of the Dynamo script is illustrated in figure 6.15. The first step is to create a list of the Revit categories that will be included in the calculation in order to add them for the parameter. The second step is to define the names of the parameters and check whether they are already present in the Revit file. This is done to avoid duplication of parameters, in the case that the working file already contained parameters from a previous project.

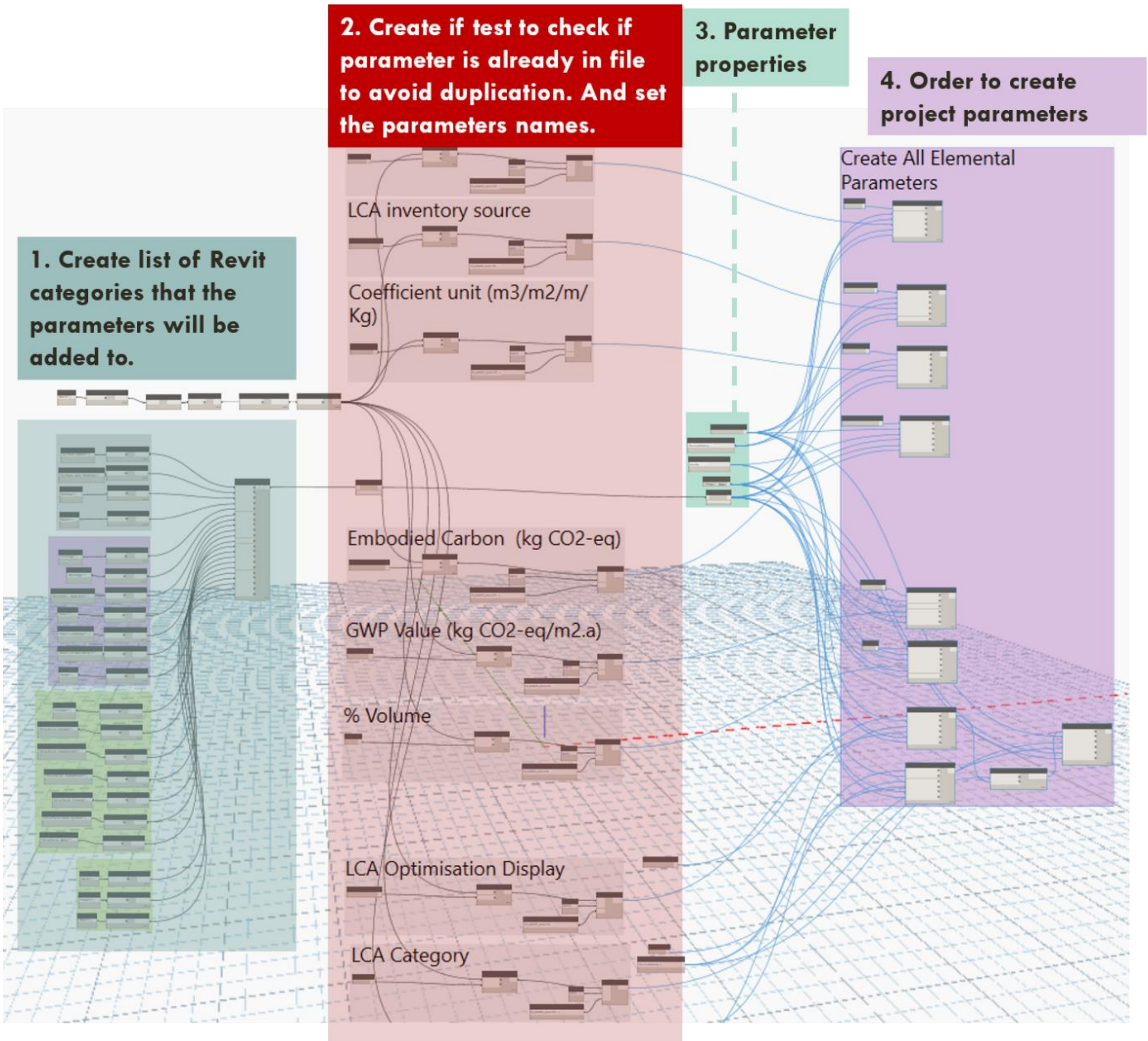

Figure 6.15: Script 03 logic (part that creates elemental parameters)

6.11.5 Import material ID and information in standard file family

This Dynamo script will import all the “all materials LCI database” prepared manually in the previous step into the material parameters. The output is to find the data imported in the material library, as shown in figure 6.17.

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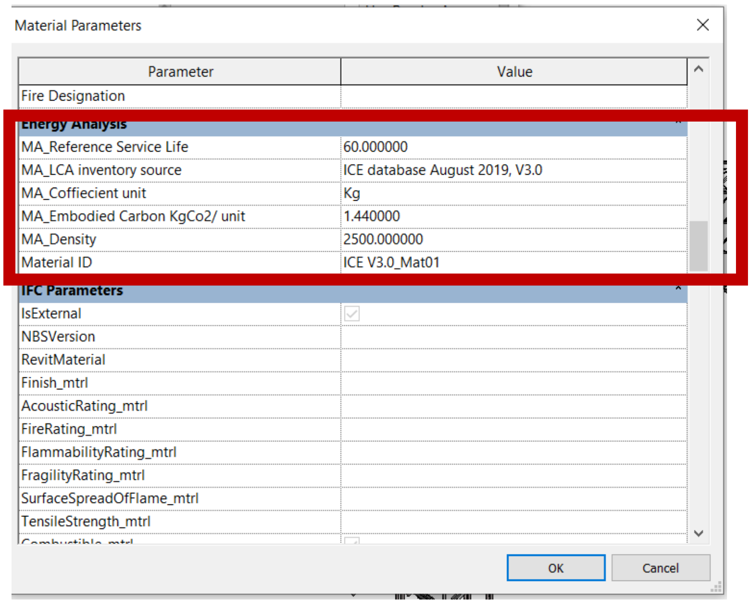

Figure 6.16 Material LCI data imported

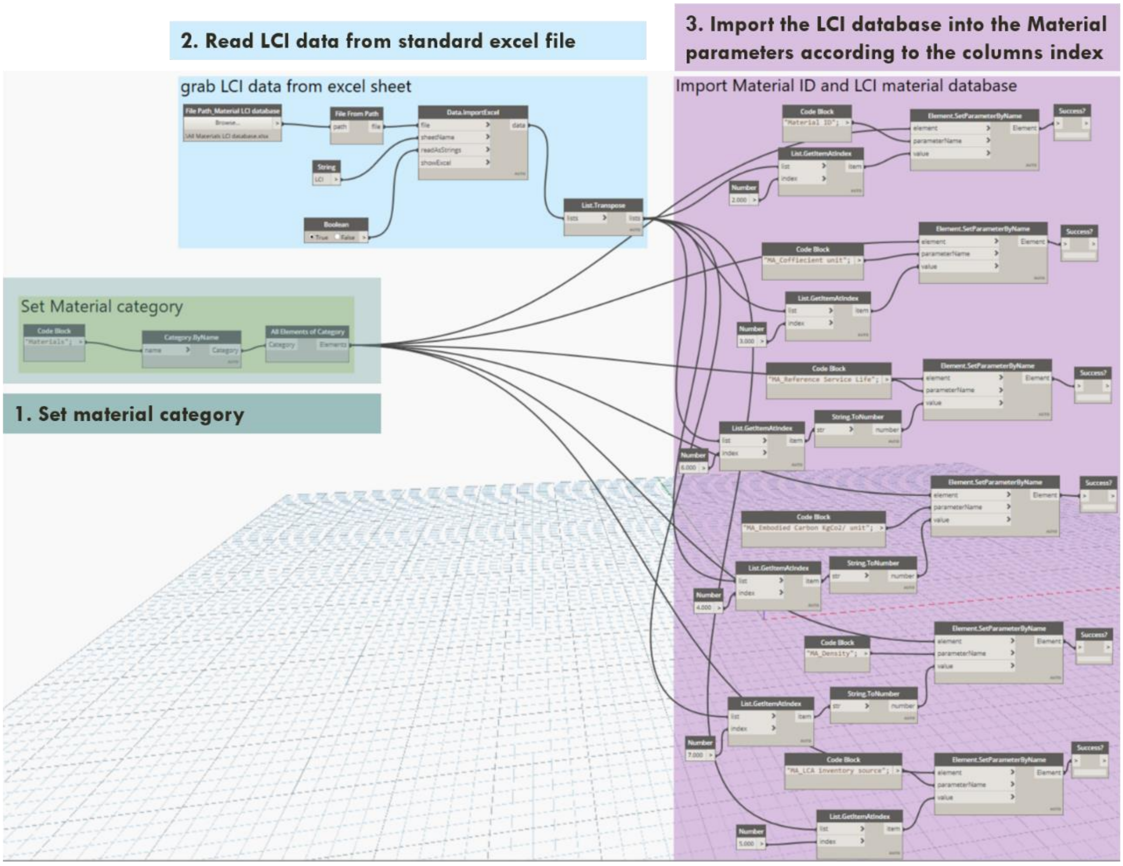

Figure 6.17 Script 04 import materials LCI database

The aim of this script is to read the LCI database from the LCI standard file prepared in the previous step and import it into the material library in Revit. The logic of the Dynamo script is shown in figure 6.17 and is structured as follows:

1. Set the material category to action.
2. Grab the data from the Excel file.

`

3. Sort the data and import in the parameters using the index order of the data.

This is the final step in stage 1 and following this, the template is ready to use for modelling. The next section will explain the calculation script, which is the core of the framework.

6.11.6 Calculation

The analysis elements are divided into six groups that are separated into six scripts, to avoid heavy files, long processing time and file error. All the scripts' structure has the same concept but they deal with different categories. The script is modified from a model previously developed by Genova (2018) and adapted to suit the UK context and the LCI. The scripts will apply the analysis and calculation of different element categories through reading database from Excel standard file and filtering materials with coefficients m^2, Kg, m^3 and applying suitable equations accordingly, as explained in section 6.7. The results will be written back to the output on the elemental parameters, as shown in figure 6.18. The user can navigate through the model, select any element and check the EC calculated value.

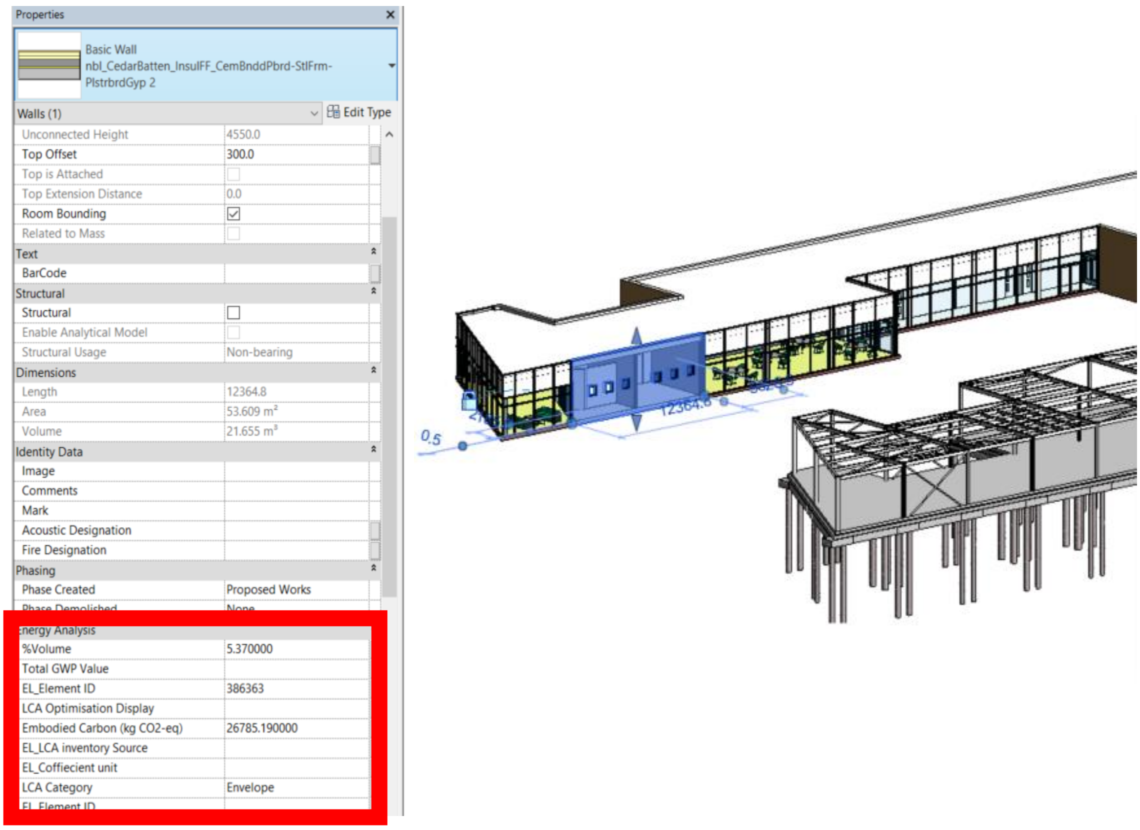

Figure 6.18 Output from the calculation scripts

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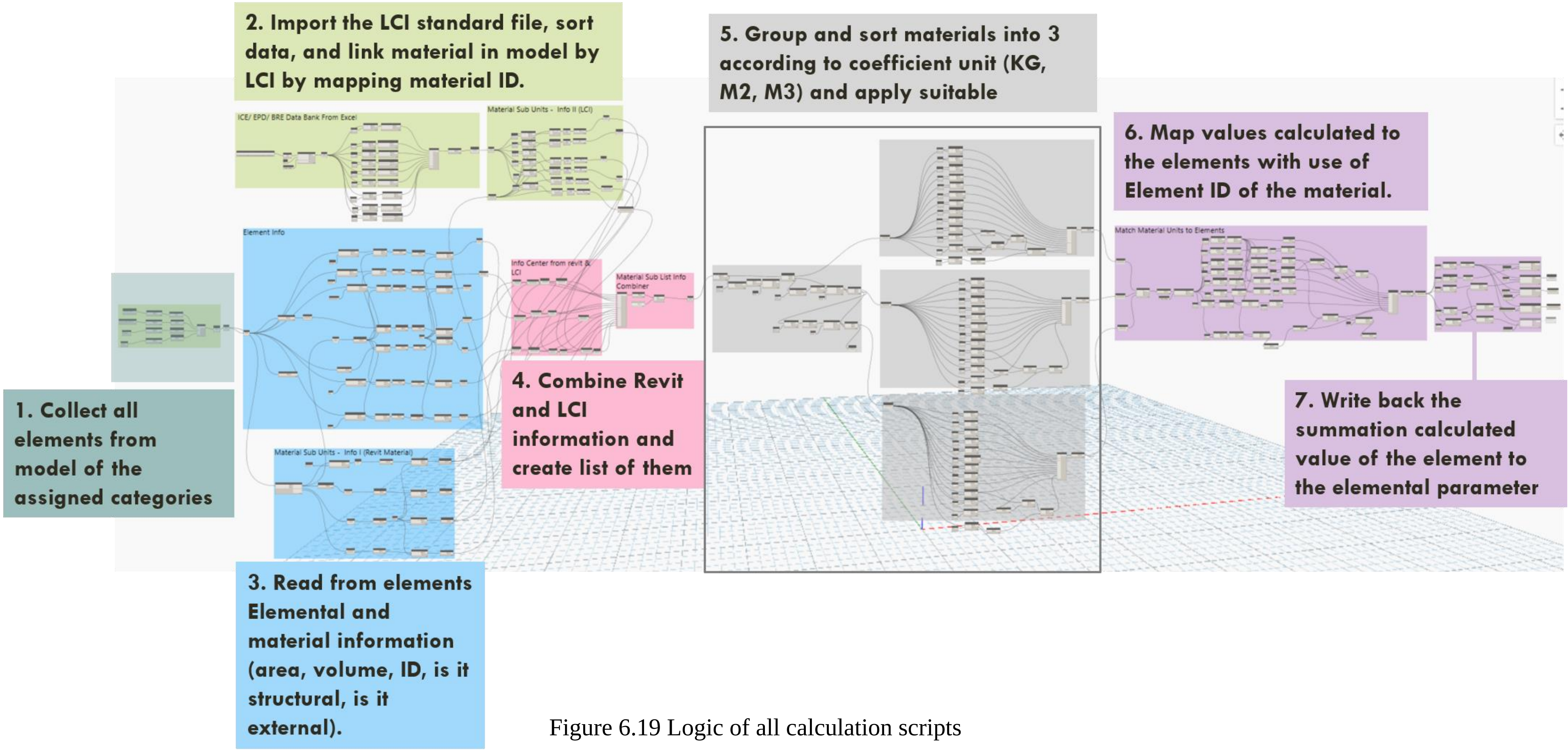

Figure 6.19 Logic of all calculation scripts

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The concept and structure of all the calculation scripts is the same. The only difference is in the categories of elements collected in the first step. Figure 6.19 shows the main stages of the calculation script and the relationship between them. The first group of nodes set the category or categories that the script will work on, giving the order to collect all elements modelled in Revit within this category. The second step imports the LCI databank from the standard LCI file and links it to the materials included in the model, using material ID to map them. The third group of nodes read the elemental and material information required for calculation and mapping groups. The fourth step is to combine all the required information from database and Revit parameters. The main calculation step, which is indicated in grey in figure 19, is responsible for filtering the materials into three groups according to their coefficient unit. This step is vital to make sure the right equation is applied to the material according to the coefficient unit, as explained before, after calculating the EC of the material in the element. These values are mapped to get the value of the EC for an element, by matching the element ID of the material. The last step is to write back the total value per element into the Revit parameter. Other information is also written back to Revit parameters, such as LCA category, which will be used later in the sorting of data in the representation and visualisation

stage, as shown in figure 6.19.

6.11.7 Representation and benchmarking

This stage contains three scripts which are designed to present the calculated EC and compare it to benchmarks. It is segregated into three levels in order to enable the architect to discover areas that need to be changed. The next three sections will explain the formulation and output of the three scripts responsible for visualising and benchmarking the calculated data.

a. Report total values per category

This script collects the calculated EC for each element and applies summation to present the data for EC per category. The results will be exported into an output Excel file and presented in a graph of total values per category and a table showing the amount of EC per category. Where zero value is shown in the table and graph, this means that no elements of this category is found in the model; for example, in the case shown in figure 6.20, the interior details are not modelled (indicated by the zero values shown for names beginning 'INT_'). The showcase applied on major elements shows which elements have the greatest EC contribution, which in this case are substructure and superstructure.

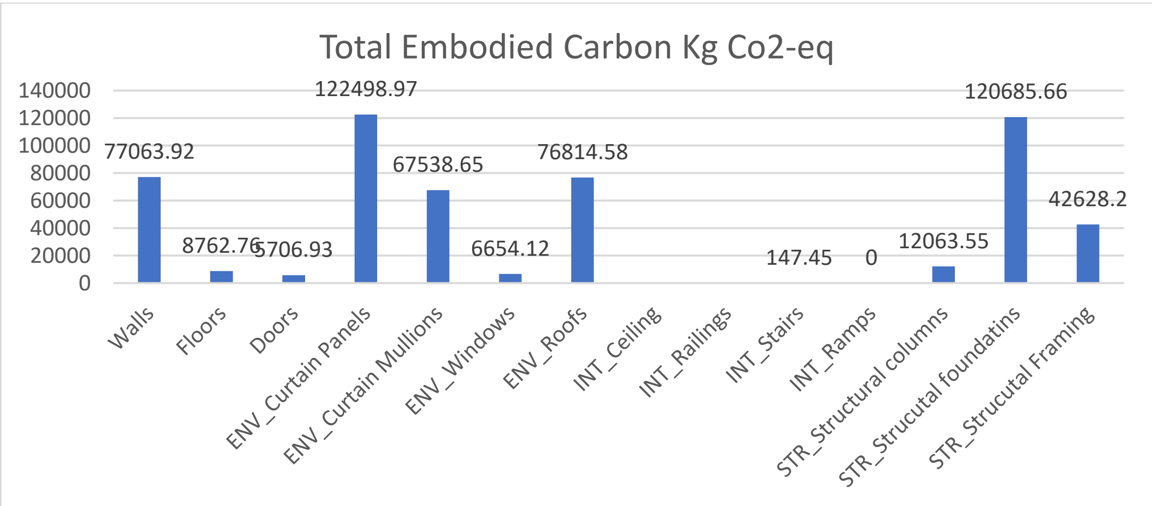

Figure 6.20 Exported Excel file with generated EC per category graph

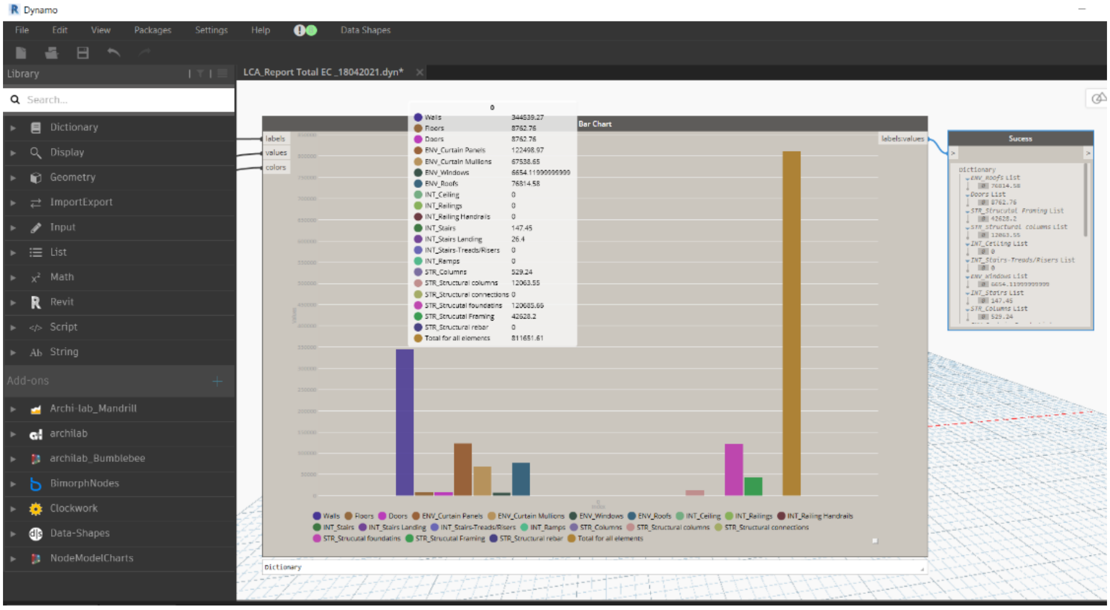

Figure 6.21 EC per category generated graph in dynamo

`

Table 6.9 Exported table of EC values per category

Category	Total embodied carbon Kg CO2
Walls	77063.92
Floors	8762.76
Doors	5706.93
ENV_curtain panels	122498.97
ENV_curtain mullions	67538.65
ENV_windows	6654.12
ENV_roofs	76814.58
INT_ceiling	0
INT_railings	0
INT_railing handrails	0
INT_stairs	147.45
INT_stairs landing	26.4
INT_stairs-treads/risers	0
INT_ramps	0
STR_columns	529.24
STR_structural columns	12063.55
STR_structural connections	0
STR_structural foundations	120685.66
STR_structural framing	42628.2
STR_structural rebar	0
Total for all elements	**541120.43**

The aim of this script is to export a report of the calculated EC values presented in graph and table form. As shown in figure 6.22, the script is structured as follows: the first group collects all values of elements within the same category and adds all values of elements to get the EC per category.

The second step is to create a list of them and apply summation of all values in order to get the total EC value per building. The third step is to export all values to an output Excel sheet, as presented in figure 6.20 and table 6.8. The final step attempts to visualise the calculated values per category inside Dynamo, as shown in figure 6.21.

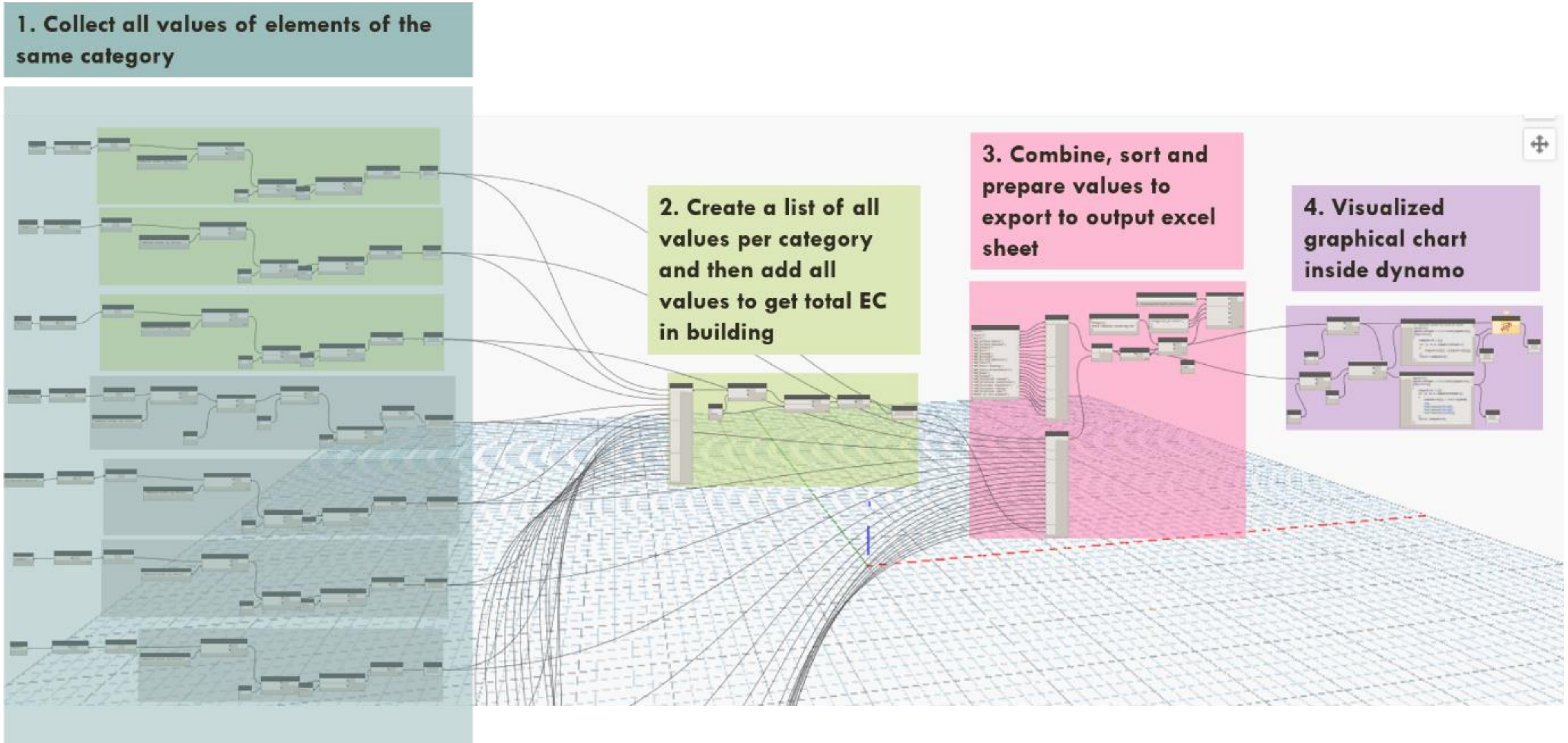

Figure 6.22 Logic of script 12 report total EC per category

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b. Report total EC per category

This script, “**SC 12_LCA_Detailed Report”,** presents the detailed calculated EC in order to examine and highlight the highest EC contributors and act as check on the model calculations and missing elements. The results are presented in an Excel sheet in order to analyse the EC per element type within the category, as shown in figure 6.23. This means the user can check the contribution of each material in a building category which highlights the greatest contributors of EC.

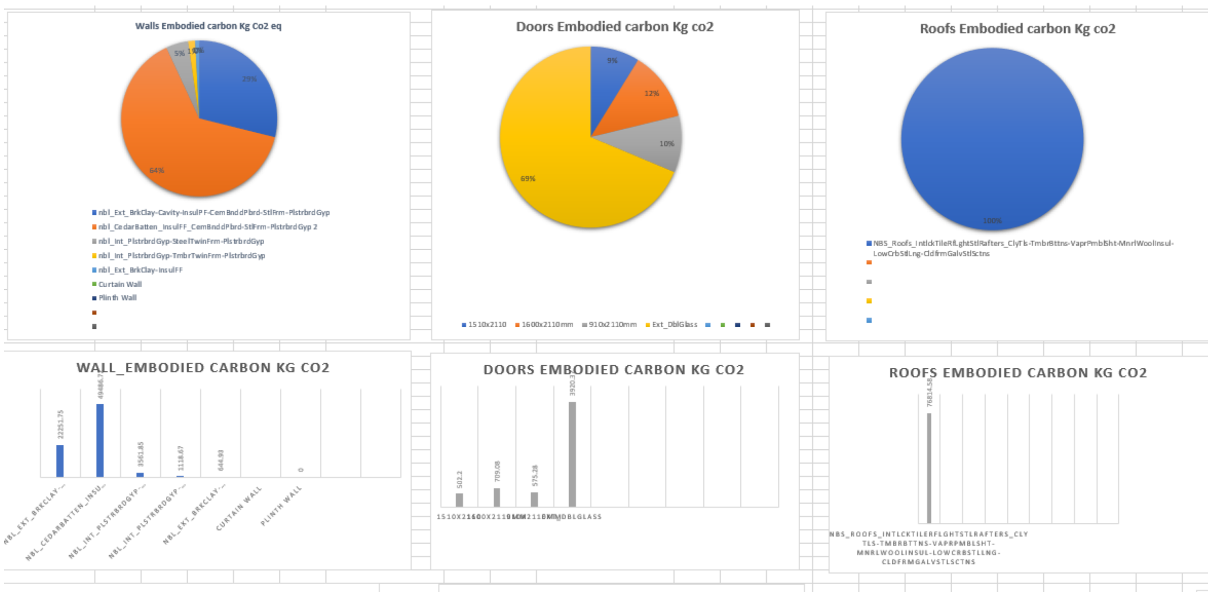

Figure 6.23 Output of script 12, detailed report

The logic of the script presented in figure 6.24 begins with collecting the element parameters of elements in a category. These parameters are element name, EC, area and percentage volume. The second group sorts and groups the elements according to their unique names, and adds values per element type. The group creates a list of required data and exports it to the Excel sheet to present the data, as shown in figure 6.24.

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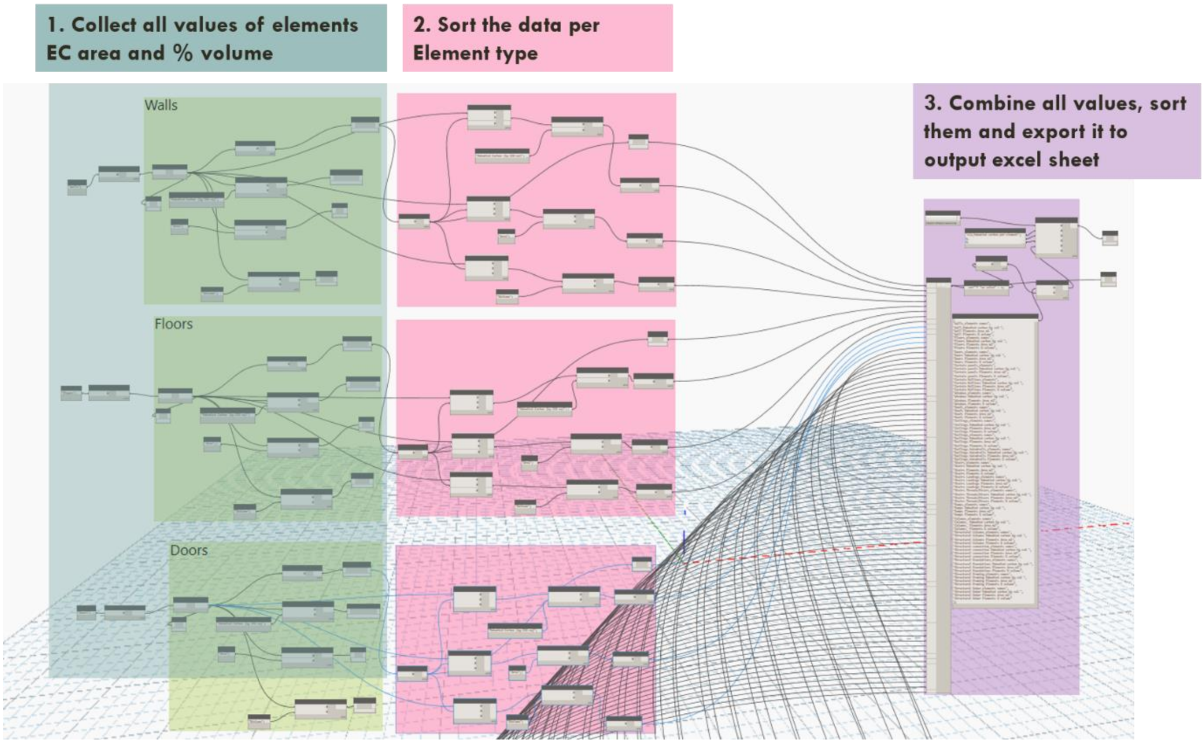

Figure 6.24 Logic of script 12 report detailed EC per element

*c. **Embodied carbon benchmarking***

The embodied carbon benchmarks currently available in the UK are RIBA Climate Challenge 2030 (RIBA, 2019), LETI 2030 design target (Bowles et al., 2021), and one click LCA report for EC benchmarks for European buildings according to EN 15978:11 and level(s) framework. All of these benchmarking methodologies include life cycle phases A1-A4, B4-B5 and C1-C4; meanwhile, this framework can only calculate phase A1-A3. Research has shown that this phase contributes 85% to 90% of total EC, as previously discussed. Therefore, a benchmark correction factor should be applied on the grading values to overcome this shortage in comparison included boundary system.

This script sums all the EC of the building and divides it by the total gross floor area **Kg CO_2 e/m^2** to generate the graph shown in figure 6.26. The logic of the script, as illustrated in figure 6.26, is simple relative to the previous ones. It reads the total values exported by script 11 and stored in Excel sheet 11 "**11_report total values"** and collects the gross floor area value from the Revit model. The grading of the benchmark values is set in the script, and this changes according to which benchmark is used. The last group of nodes export the values that are linked to the benchmark Excel sheet “**13_Benchmark Non domestic”** in order to generate the graph shown in figure 6.26.

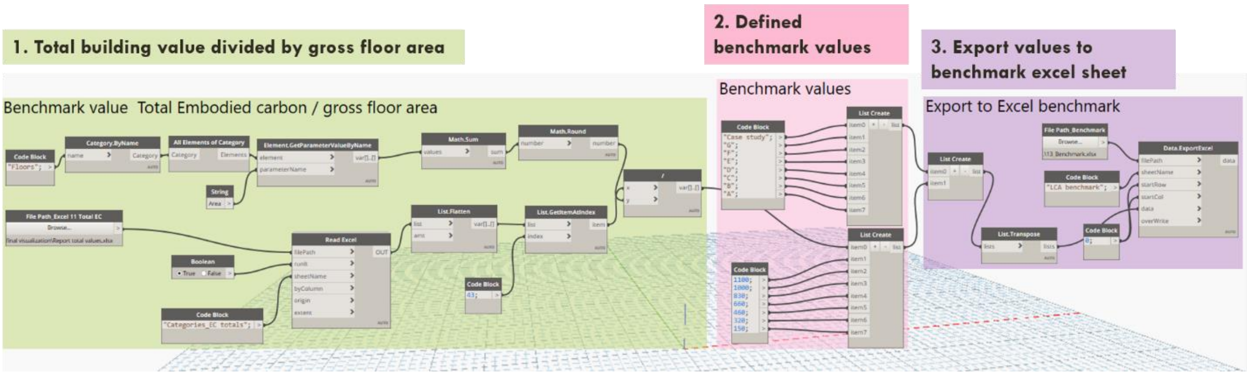

Figure 6.26 Logic of script 13 LCA benchmarking

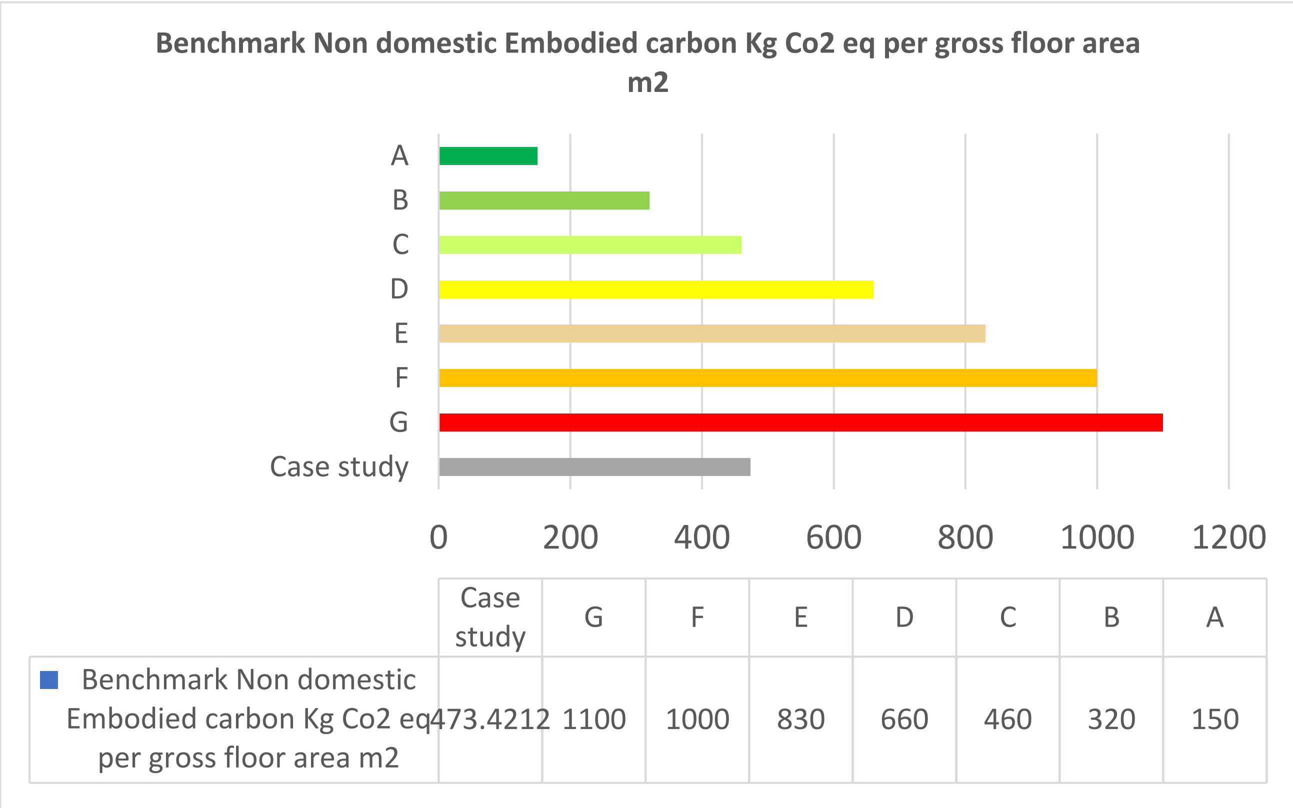

Figure 6.25 Output from script 13 LCA benchmarking

6.12 User interface: Dynamo player

The previous section extensively explained the logic and structure of each script of the framework, which is valuable for back end users if expansion or modifications are required. Most users are expected to be front end users and, as mentioned before, they will deal with all the steps mentioned by running Dynamo player and loading the script they want. The Dynamo player has a button to control the input file (Excel file) that needs to be attached to the Dynamo file, as illustrated in figure 6.27. The Dynamo script is designed to give an indication to the user as to whether or not the script has run successfully.

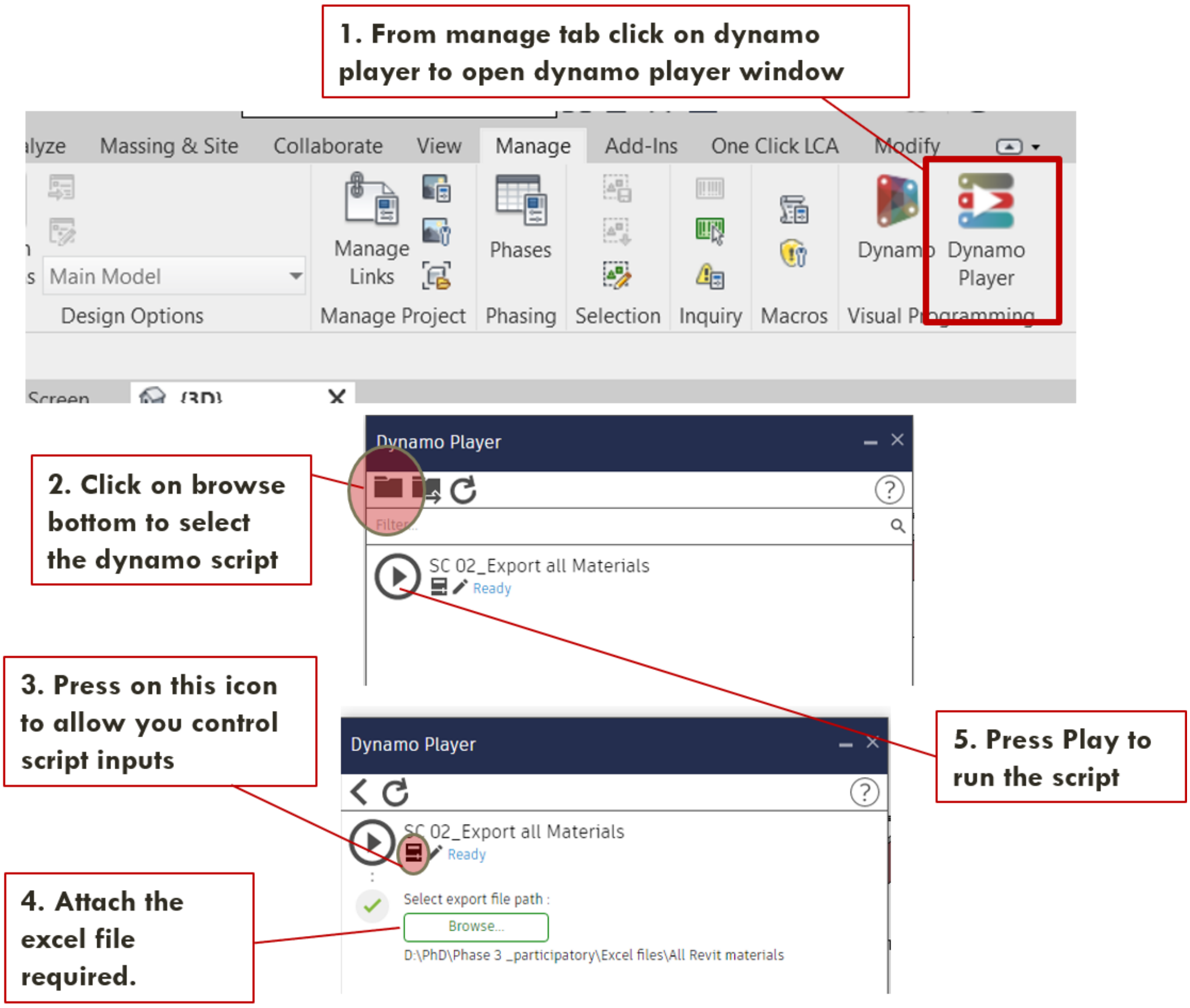

Figure 6.27 Dynamo as user interface

Lots of challenges were encountered while developing and testing the Dynamo scripts. The first challenge was dealing with the upgraded version of both Revit and Dynamo. With any updated version of Dynamo, some nodes need to be updated as well. Most of the nodes are replaced with the updated version, but in some cases the nodes need to be manually replaced by the new updated ones, especially ones from third party packages that are used within Dynamo. The second problem was that the script was modelled and tested by the researcher or Revit 2019, then when the testing user tested it on Revit 2021, this caused a problem in Dynamo. It was found that all drop down nodes, for example “elements categories”, were shuffled to other categories that were not selected. This problem was overcome by replacing those nodes with “code” text with the names of the categories, in order to avoid using drop down nodes.

In some cases, users may duplicate parameter names, which can cause errors when running the calculation script regarding inability to read the parameter’s values. In order to prevent this occurring, “if condition” is placed in the create parameter script; however, sometimes this is not read, meaning that duplication in parameters can occur. It is therefore recommended to always monitor and manage the parameters within the Revit file using an external parameter manager. In this case, the researcher recommends the use of ParaManager, which was developed by Diroots (Diroots, 2021.).

6.13 Summary of chapter 6

This chapter comprehensively presented the details and steps of the framework and how the user can interact with the proposed model. A virtual project model was provided in order to apply the framework, to validate the implementation of the scripts. The results were also used in a workshop, which will be explained in the next chapter. This chapter started by explaining the scope of the LCA assessment by justifying the choices made to build up the framework in terms of LCA system boundary, indicator, database and assumptions included. Following this, understanding of the LCA calculation and Revit hierarchy of information and structure was illustrated, to explain how integration will occur. The framework roadmap was then explained, followed by a detailed explanation of the input and output of each script. Finally, the logic of the structure of the Dynamo script developed to automate the process was outlined.

Chapter 7 : User experience design and analysis

7.1 Introduction

The proceeding chapter demonstrates the participatory phase which was used to validate the dynamo-LCA proposed model, with the framework and model being tested and analysed from the user perspective. As illustrated in figure 7.1, this chapter begins with a short summary of the usability testing. It then describes the methods and procedure used in order to design the evaluation in workshops, questionnaires, and interviews. This is followed by discussion and analysis of feedback from the participants. Finally, recommendations for model refinement and modifications are highlighted with insights for the architect's use in the design process, in terms of adaptability, flexibility, and comparison and feedback loops.

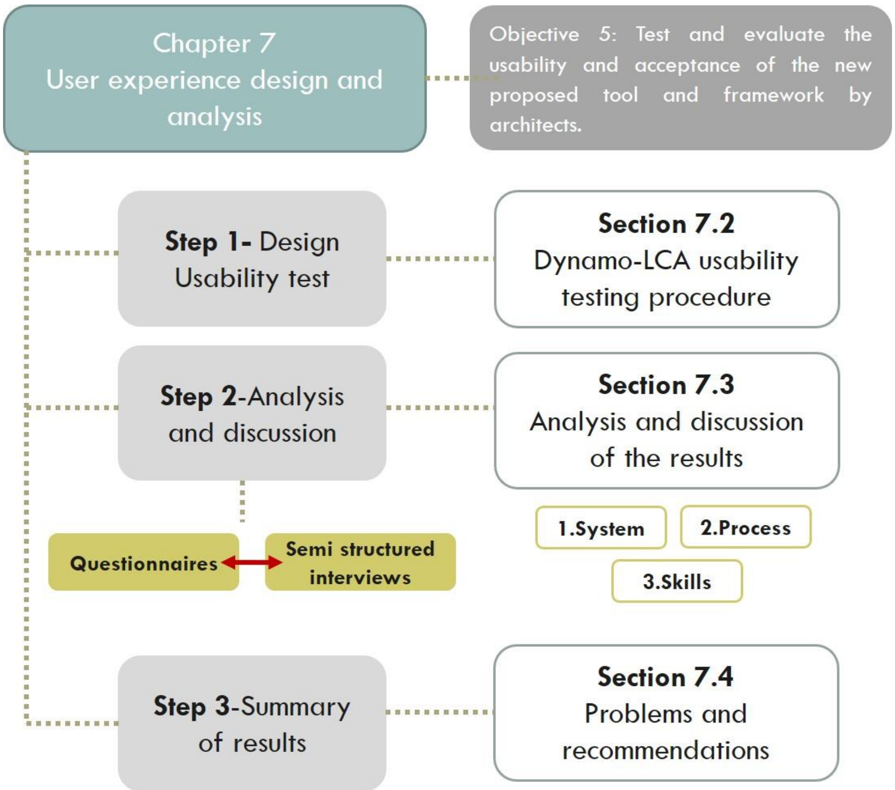

Figure 7.1 Chapter 7 structure

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7.2 Dynamo-LCA usability testing procedure

Usability testing is a well-known and established procedure used by all software developers and practitioners in order to determine the ease of use and acceptability of a system (Holzinger, 2005). A review of different usability testing procedures can be found in chapter 5, covering the design of usability workshops, the different techniques and methods that can be selected according to the purpose of the study, and the required and expected outcomes. The two main methods categorised by Holzinger (2005) are inspection methods and testing methods. The separation of these two categories of methods complies with ISO standard 9241-210:2010 (ISO 2010), which refers to the two main usability approaches as user-based testing and inspection-based testing.

In order to determine which method is suitable for the context of the system/software project, an understanding of the different techniques must be reached. Holzinger (2005) compares the most common usability evaluation techniques, as shown in figure 7.2, in terms of phase applicability, required time, users needed, required number of evaluators and required expertise. This acted as a guideline to select techniques and also to design the usability test.

Inspection methods are usually carried out before or in place of a user-based approach, and depend on experts (or evaluators) to evaluate the system. The main advantage of these methods is that they are simpler and consume less time than a user-based approach. They are usually used before a user-based approach to capture the expert's opinion to inform the design of the system, in order to make the procedure cost-effective. Heuristic evaluation, cognitive walkthrough and action analysis are the three main techniques within the inspection approach (Holzinger, 2005). Because these inspection methods did not serve the researcher's need to evaluate a novel tool, test methods were utilised in the design of the usability test for this research. The following section will describe the usability test design choices.

	Inspection Methods			Test Methods		
	Heuristic Evaluation	Cognitive Walkthrough	Action Analysis	Thinking Aloud	Field Observation	Questionnaires
Applicably in Phase	all	all	design	design	final testing	all
Required Time	low	medium	high	high	medium	low
Needed Users	none	none	none	3+	20+	30+
Required Evaluators	3+	3+	1-2	1	1+	1
Required Equipment	low	low	low	high	medium	low
Required Expertise	medium	high	high	medium	high	low
Intrusive	no	no	no	yes	yes	no
Comparison of Usability Evaluation Techniques						

Figure 7.2 Comparison of usability evaluation techniques (Holzinger, 2005)

In order to design usability testing, questions need to be answered to attain the output of structured, reliable and informative results through a rigorous process. The steps adopted in this study were guided by a similar study designed by Cemesova (2013) to evaluate a tool developed in the same field. Figure 7.3 illustrates the main steps of designing a usability test. The chapter sections mapped in the steps in figure 7.3 contain a description and justification of the choices made in each step.

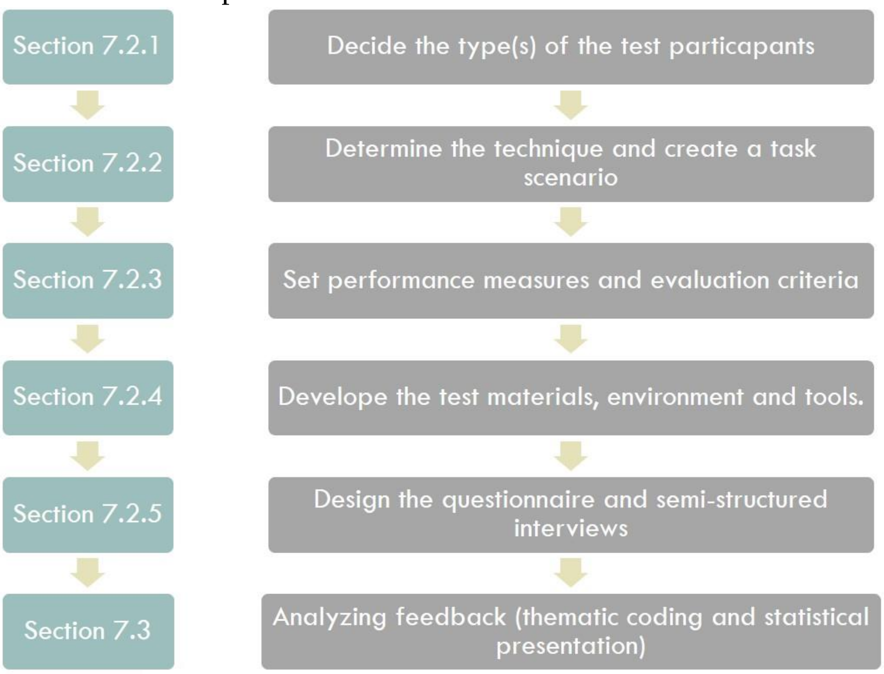

Figure 7.3 Steps to design and conduct a usability test

7.2.1 Participant selection and sample size

There is an ongoing debate on the number of participants that need to be included in usability testing in order to ensure data saturation. It is commonly agreed in usability studies that as a rule of thumb, five to eight participants are sufficient (Nielsen, 2012). Nielsen (2012) conducted a study of the 38-case study performed at Neilson Norman Group in order to provide evidence that five users are sufficient in some cases, and also included exception cases for the five participants rule. There are some exceptions to this; for instance, a) when the researcher is concerned with statistics rather than insights into aspects of a system, quotative tests need to include at least 20 participants; b) car sorting technique requires minimum of 15 participants; and c) eye-tracking technique requires at least 39 participants. Lewis (1994) found that a small sample size of 5 to 15 participants is adequate to reveal 80-85% of the findings for a particular study. For quantitative usability there are two types of study samples, with either 5-15 participants or more than 15 participants, in cases where statistical analysis is required (Barnum, 2010). In the case of this study, the researcher was interested in insights about the use of the system and its integration within the digital construction workflow, rather than statistical analysis. This meant that a sample size of 5-15 participants was sufficient in the current study. Therefore, it was decided that a series of workshops would be held, with two to five participants per session.

The second aspect of participant selection is the background and experience of the participants. Struck (2012, p.108) argues that 'competence, attitude, state, personality' are the main important factors for selecting participants, while Faulkner (2003, p.380) categorised them into 'expert' and 'novice'. For the current study there were two areas of expertise considered to be relevant to participant selection:

a) The extent to which participants have been involved with and used BIM software (Revit) before. Categories of BIM adoption level is shown in table 7.1.

b) The extent of participants' knowledge concerning embodied carbon LCA calculation in architecture projects. The targeted users are architects in small or medium enterprises (SMEs).

Both of these aspects were determined in the initial participant recruitment request and at the end of the workshop feedback questionnaire.

Table 7.1: Inclusion and exclusion criteria for participant selection (Cemesova, 2013)

Category BIM	BIM adoption	Inclusion/exclusion
Innovator	Develop BIM applications and tools	Included
Early adopter	Uses BIM regularly, and is aware of new BIM tools and standards	Included
Conservative	Uses BIM occasionally	Included
Non users	Does not use BIM	Excluded

Participants were recruited by sending an invitation flyer, attached in appendix 4, via email. The research supervisors provided several contacts for architecture firms that may be interested in participating in the study, and the researcher also used previous contacts and the Twitter social media platform to reach more potential participants. Individuals accepting the invitation were sent further details of the study and received a consent form along with a participant information sheet.

7.2.2 Procedure and task scenario

As discussed in section 7.1, a user-based testing 'questionnaire' was considered most fitting to the research aim. The approach used was to design an online workshop along with a feedback questionnaire and semi-structured interview, to be completed after the workshop. Firstly, a pilot workshop was conducted, then four series of workshops with two to three participants per workshop took place. This combination of methods, including workshop discussion/comments, quantitative questionnaire and semi structured interviews, was selected to achieve triangulation of the data and ensure the validity of the test. Evaluation feedback was therefore available from three sources: 1. rating scale questions; 2. open-ended questions; and 3. semi-structured interviews conducted at the end of the workshop.

The researcher presented a concise introduction to the framework and tool, that aimed to optimise design decisions relating to the evaluation of embodied carbon. A showcase presentation was used to explain and illustrate the use of the model. Participants were then given the model script and the database material with a template file to test the script; this was considered to be an additional task and was used as motivator to join the participatory phase. After the presentation, participants were asked to complete a feedback questionnaire, then at the end of workshop, semi-structured interviews were conducted to provide qualitative evaluation that would enrich the level of feedback insight for development.

The workshops were originally designed to be held face-to-face but the circumstances of the Covid-19 pandemic enforced a change to online workshops. Some scholars have stated that this is cheaper and more efficient than face-to-face evaluation, especially in techniques that do not need physical contact. The main limitations that may affect the reliability and validity of the results are that: a) it may be harder to illustrate new ideas and test it online; b) the objectivity of the participant's response is not assured; and c) "there is an assumption that the perception of scale is similar in the respondents (for example their perception of 'likely' or 'important')".

The questionnaire was available online on Google Forms and was completed anonymously. This was intended to enable participants to feel more at ease and objective with their feedback. The data was conducted, recorded and analysed through Google Forms. This was followed by semi-structured interviews, which were conducted, transcribed then thematically coded and reported anonymously.

7.2.3 Selection of performance measures and evaluation criteria

One key aspect in designing the usability test is the selection of performance measures. In observation and usability labs, the target performance measure may be the time required to finish the task, time spent overcoming errors, number of wrong activities or icon selections, frustration, confusion or satisfaction (Bastien, 2008). In the case of this study, these measures were not required and were not suitable for the aim of the study. Accordingly, the performance measures selected by the researcher were: overall efficiency, effectiveness, and satisfaction. They are defined as follows:

- **Effectiveness**: "accuracy and completeness with which users achieve specified goals" (ISO, 2010, p.2).
- **Efficiency:** "resources expended in relation to the accuracy and completeness with which users achieve goals" (ISO, 2010, p.2).
- **Satisfaction:** "freedom from discomfort and positive attitudes towards the use of the product" (ISO, 2010, p.3).

It was proposed that triangulation could be attained by testing these performance measures using different data gathering techniques. Table 7.2 shows the mapping of the performance criteria/measures with the method used.

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Table 7.2: Performance criteria mapped with collection and analysis methods

Performance criteria	Questionnaire	Semi-structured thematic coding	Analysis of discussion during workshop
Efficiency	Quantitative rating	Insights in system and process aspects feedback	
Effectiveness	Quantitative rating	Insights in system and process aspects feedback	
Satisfaction	Quantitative rating	User perspective ease of use	Post task evaluation

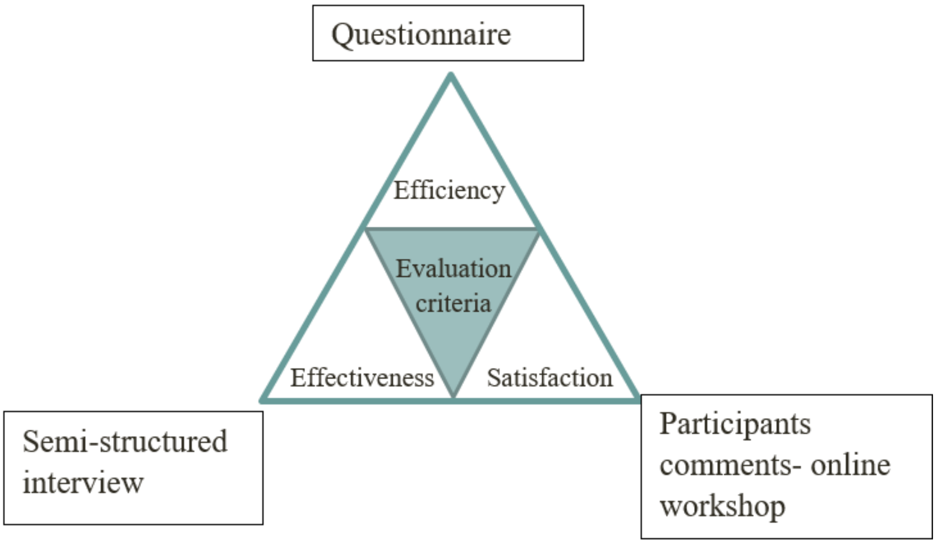

Figure 7.4 Triangulation of data and evaluation criteria

7.2.4 Development of test materials, environment and tools

The test materials included a Walkthrough presentation on a showcase using Microsoft PowerPoint (attached in appendix 2,3), tool and scripts with Dynamo player short videos (see appendix 2, 3). Comments and discussion with participants took place to illustrate the steps. A semi-structured interview was conducted at the end of the workshop. Participants were also asked to test the model and complete the questionnaire. The questionnaire (attached in appendix 5) was administered using Google Forms and the semi-structured interviews were recorded through ‘Zoom’ meetings.

Due to pandemic circumstances it was necessary to use a remote usability testing environment. Previous studies have agreed that remote study can provide rich, rigorous and reliable data to the same standard as that produced in a physical usability lab (Bastien, 2008; Dumas & Fox, 2012). Remote testing has been shown to have a number of benefits (Dumas & Fox, 2012): it is easier to find volunteers; participants from a wider range of geographic locations can take part; the test can be more realistic, as participants will be in their working environment and may feel more at ease; and both the cost and time required is lower, as a usability lab is not necessary. Remote access was therefore proven to be sufficient for this study.

There are two main types of remote testing: synchronous and asynchronous. Synchronous testing occurs when there is direct contact between moderator and participant while testing; while asynchronous testing occurs when participants work without assistance from a moderator. There are different pros and cons for each method, but one crucial aspect which led the researcher to select synchronous testing was that comments and discussion with participants are sources of rich data, which can replace observation to a certain degree.

Consequently, a mix between the two types of testing was attained. The introduction and showcase were given synchronously, which gave the opportunity to answer questions at each phase regarding the system's internal workings and to address any concerns. The asynchronous method was used for questionnaire completion after the workshop, and participants were also able to use the model afterwards, in order to enable them to give reliable feedback. The questionnaire was completed at the convenience of participants, and the semi-structured interviews were held after the workshops to capture detailed qualitative insights regarding the system, process and skills-related aspects; these will be described in section 7.2.5. The following section will describe how the materials were prepared and used to structure the workshop.

a. The workshop structure:

The workshop was divided into two parts and was designed to allow 45 minutes for the presentation and showcase, followed by a 45 minute semi-structured feedback interview. Participants' consent was sought to record the session and deliver the presentation via screen sharing, using the 'Zoom' application. The following section summarises the workshop structure and strategy, with further details on the presentation and the workshop available in appendix 2:

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1. **Introduction:** research objective, current approaches of the LCA, framework overview, and researcher justification of choices (database tool and Dynamo).
2. **Explain the overall framework and map of the Dynamo scripts:** main steps are introduced along with the difference between this approach and other LCA approaches.
3. **Explain, demonstrate, get feedback for each step:**

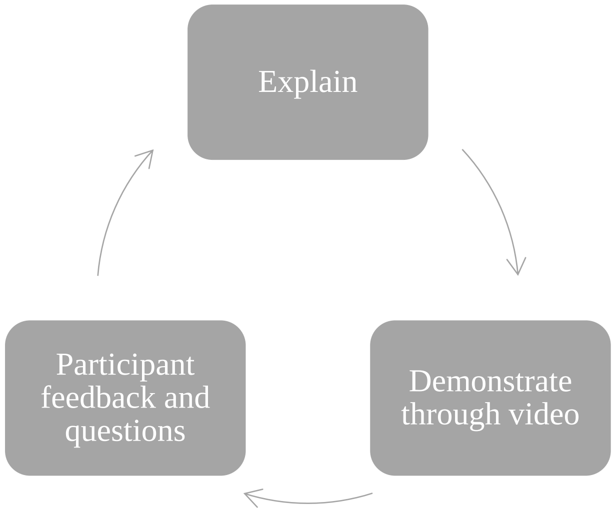

Figure 7.5: Cycle to follow for each step in the framework

Each step begins with an explanation about why we need to do it, followed by demonstrating how to do it through the video, and then asking for feedback and questions. This cycle was repeated for all steps, to encourage participants to engage with the workshop and share rich insights on their thoughts and understanding of the tool. The participants were welcome to comment on the workflow or to specifically ask for further explanation after each step. The steps are explained in full in chapter 6; only a summary is included here.

3.1 Phase 1: how to build up a reliable material library using the existing database.

- Analyse the material library and create materials extra in Revit template to enrich library.
- Export the materials from the template file.
- Create a material shared parameter.

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- Considerations to select the typical generic material for elements (walls, floors, roof, windows and doors) and different LODs.
- Prepare the Excel standard data file that has the mix of EC inventory database.
- Import the data to the template file.

3.2 Phase 2: calculate and visualise EC for a project

- Run the calculation scripts for each category.
- Run the report and visualisation scripts.
- Possible future visualisation to benchmarking on the model.

At the end of the presentation the participants were asked to provide their feedback through a semi-structured interview, and after the workshop, to complete the questionnaire. The next section discusses how they were designed.

7.2.5 Design of questionnaire and semi-structured interviews

Ozok (2012) states that there are three types of surveys: 'user evaluation', 'user opinion' and 'others'. In the case of user evaluation, the survey aims to provide data on the actual system, for example, is the product easy to use? Meanwhile, the user opinion survey gathers data on the general context of the system, for example, what modification are required in the system? The final category refers to the metadata gathered on specific information, such as population demographics. The questionnaire designed for use in the current study was a mix between 'user evaluation' and 'user opinion.' The main aim was to address the use of the model and how to improve it, in terms of the aspects mentioned above.

A mixture of open-ended questions and scaled questions were used in the questionnaire. The survey was divided into two sections: the first section included participant information, and section 2 contained five scaled questions, using a scale of 1-5. In this section, the user was asked to evaluate the efficiency and effectiveness of the framework, and their level of satisfaction with it, using standard questions. The responses to these were analysed quantitively, while data from the open-ended questions, user comments in the workshops and semi structured interviews was qualitatively coded to highlight insights regarding future use and modifications required.

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The aspects that the usability test needed to cover included the practice position from BIM adoption, evaluation of system-related aspects, evaluation of process-related aspects and, finally, ratings of user satisfaction. In order to design the aspects that needed to be covered by the questionnaire and interviews specifically for the framework, a guide that defines the user requirements for LCA tools for architects developed by Meex et al. (2018) was used. This study defines all user requirements that need to be included in the proposed LCA tool, and acted as a starting point to structure the themes of the evaluation criteria for this usability study.

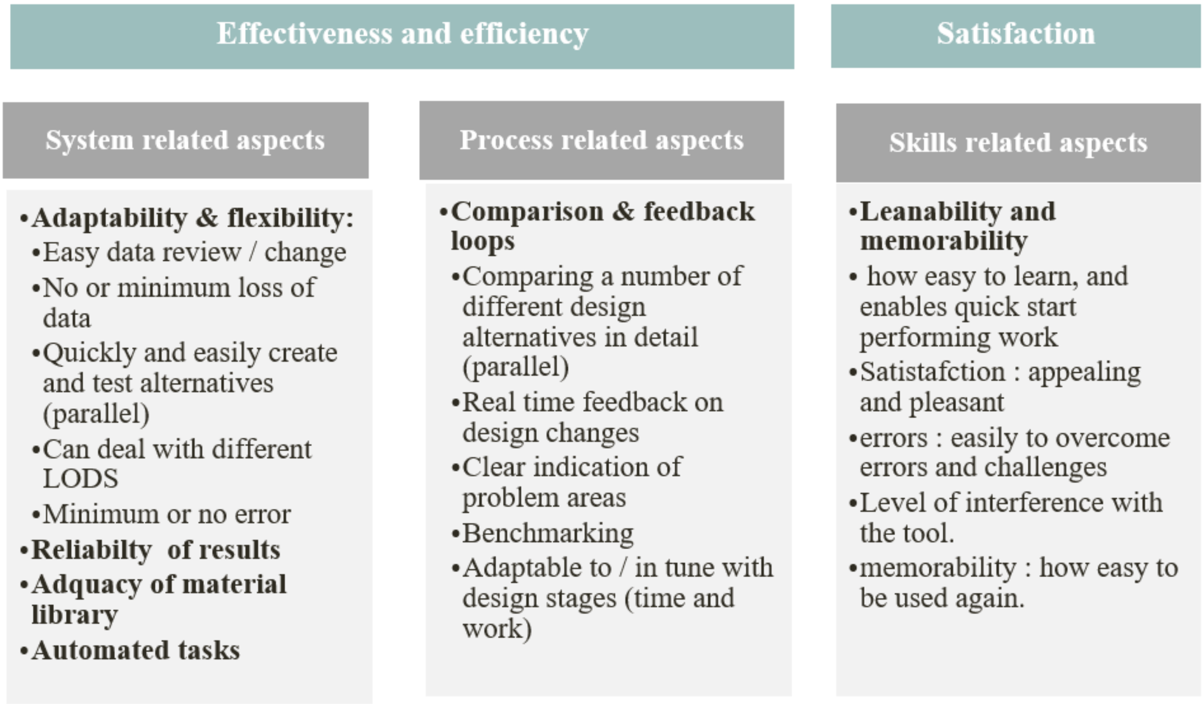

Figure 7.6: Performance evaluation criteria and aspect themes

7.3 Analysis and discussion of the results

Triangulation of data was possible due to using the mixed methods of quantitative feedback and semi-structured open-ended questions, which were analysed qualitatively, providing rich insight into the use of the framework. This highlighted the strength points and barriers to adopting the new technology VPL to change static building performance workflow into a dynamic process. The next sections discuss in parallel the results of the questionnaire and its meaning with the responses and discussion in semi-structured interviews, and are divided up as shown in figure 7.7.

Figure 7.7: Data gathering and analysis sections

7.3.1 Section 1: general information and participant profile

The first section in the questionnaire determined the demographic information of the participants, including their profile and experience. It also aimed to examine the problems and challenges of repeating the embodied carbon evaluation that were determined from literature.

In section one, responses to the first question showed participants had a range of different years of experience, assuring variety in the participant sample. The total number of participants was 13. Questions 2 and 3 were included in order to confirm the inclusion criteria set for the participants, which required experience in implementing BIM in previous projects, in addition to having a technical background of using a BIM authorising tool such as Revit, to provide assurance of participants' technical knowledge. The majority of participants had experience with implementing BIM and applying BIM software of between 5 and 10 years; this was considered satisfactory as it means the resulting data reflects a range of mid-high experience participants. The fact that the sample included highly experienced participants strengthened the study, as these individuals may be considered experts in the field and were therefore likely to provide more detailed insights on the use of the framework. They were sorted and grouped as shown in Table 7.3; this grouping will be used in the discussion, with group numbers referenced along with comments on different aspects.

Table 7.3: Participant grouping according to experience

Participant group	Experience	Years utilising BIM	Number of participants
Group 1	1-5 years	1 -5 years	4
Group 2	6-10 years	5-10 years	5
Group 3	11-15 years	5-10 years	2
Group 4	16-20 years	More than 10 years	1
Group 5	24	5-10 years	1

The fourth question: “Did you use Dynamo player before?”, also acted as a strength point in the sample of participants, as it confirmed that half of the participants had previous experience with Dynamo and the rest had no experience; this confirms that the results of the tool satisfaction rating included the opinions of participants with both of these levels of knowledge. This is used as a control measure.

In the fifth question, participants were asked whether or not they had previously been involved in a project that included embodied carbon, whether this involved them calculating EC or not. All participants had backgrounds of embodied carbon calculations, but not all of them had been involved in a project that included assessment of embodied carbon, as specified in the question. This was explained further later on, as participants mentioned in semi-structured interviews that third party experts (e.g. BREEAM assessor or sustainability assessor) are usually responsible for this process, and that it is segregated from the design process.

In order to confirm the outcome of the literature review regarding the most common tools used, how many times the assessment is repeated during design, and what are the main challenges or problems in repeating embodied carbon assessment through the design, questions 6-9 are included in the questionnaire. The participants’ responses showed that the most commonly used methods used to evaluate embodied carbon are ICE database, Etools, One Click LCA and H\B:ERT. With regard to how often LCA is performed, it usually occurs twice: once in the design phase and once in the post-construction phase. The survey showed only one participant who reported that the assessment was repeated five times during the project; this confirms that in most cases, if LCA occurs, it is not repeated adequately in order to inform the design decisions. The last question in this section provided confirmation that participants recognised the challenges and problems of performing EC assessment, with the most frequent concern regarding the time-consuming nature of the process, as shown in Figure 7.5.

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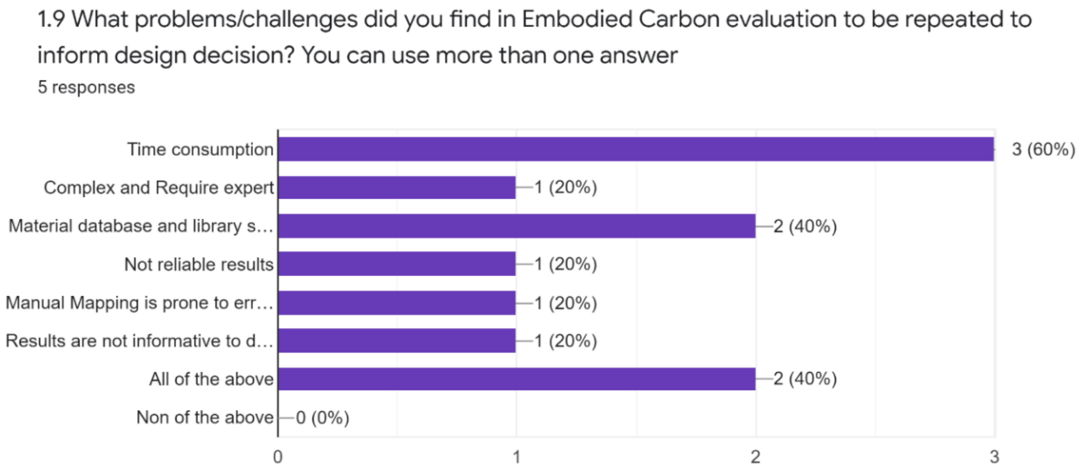

Figure.7.8: Questionnaire results for question 9 in section 1

7.3.2 Section 2: system-related aspects

This section discusses the system-related aspects. Findings from the analysis and reporting of the data collected from questionnaires, comments made in workshops and interviews will be presented together. Participants were asked to rate how much they agreed that the system successfully supported each aspect, then further elaboration on the importance of the aspect and their opinions on the model/system features was discussed in the interviews and through comments in the workshop.

a. System aspects - question 1:

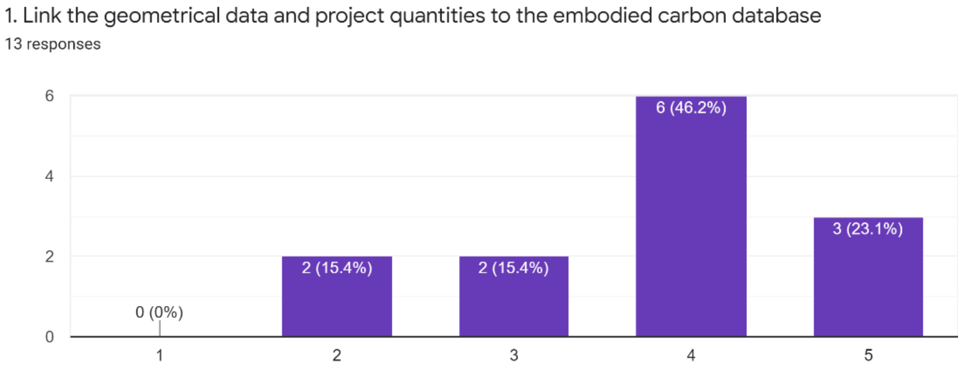

Figure 7.9: Questionnaire results on system aspects (question 1)

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The answers indicated a high success rate regarding the linking of geometrical data and model quantities to the embodied carbon database; 46% of participants agreed with the statement and 23% strongly agreed. The comments highlighted the importance of this framework in providing a flexible system that links performance calculation into BIM models in order to minimise labour intensive tasks, as shown in figure 7.8. Benefits that were mentioned by participants included that it was more flexible, less labour intensive, reduced manual error, and encouraged multiple and repetitive calculation. **The answers to this question showed that this feature provides high efficiency to the overall framework; this agrees with recommendations from the literature.**

*Comment 1: I think it makes it **more flexible**, in this new era you want **everything to be linked together** otherwise you are doing something that is **labour intensive**.*

*Comment 2: I totally agree that **dynamic link and automatic calculation is crucial** as you change the model to encourage **iterative performance-based design**, I found it difficult when I was doing updated and **repetitive calculations** through the design process before, this system tackled it.*

*Comment 3: It is brilliant to be able to have a framework that has this **level of intelligence** and be able to **link our library to an EC inventory database** such as Ice database is in valuable and it **takes out manual error** and perhaps it can be encountered with the hakin brown.*

*Comment 4: Once the system is being able to **pick up the volumes and areas** in the model to be able to sit down and work out all of that **manually every time** it will take forever, so I see the value and efficiency in adopting such a system to do calculations with the change in model.*

- Group 1
- Group 2
- Group 3
- Group 4
- Group5`

Figure 7.10: Comments on system aspects (question 1)

b. System aspects - question 2:

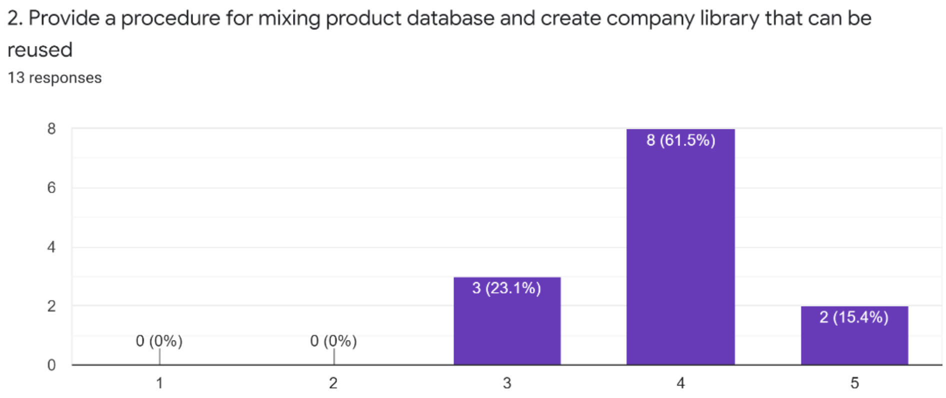

Figure 7.11: Questionnaire results on system aspects (question 2)

Although the questionnaire responses expressed participants' satisfaction regarding this aspect, their comments highlighted the challenges to be faced in building the reused library. This was first highlighted in participants' comments during the workshop while this step was being explained. Four participants reported that it is hard to begin it from scratch without the need for a technical expert or guideline. However, it was considered very valuable and important to learn how to build up a library that can be reused, even though there are details that need to be learned and considered. Another opinion mentioned as a potential resolution for this step was to provide a starting template file with an initial library that has the ICE database and some manufacturers' EPDs to begin with, and then the individuals in the company can build on it. These comments motivated the researcher to include a second round of trials, sending participants the template library as required – along with other modifications that will be mentioned later – in order to get feedback after their trial.

An additional concern revealed by a highly experienced participant (see comment 2, figure 7.10) relates to the management and maintenance of this process to ensure the system is consistent. Participants reported that monitoring by a BIM manager is required to ensure the reliability of the built-up library, and this is hard to attain for small scale practices. A second insight highlighted was the need for a platform which provides knowledge and resources with an easy and accessible step guide to educate users on this crucial step (see comment 5, figure 7.10).

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Responses to this question indicated that this feature is effective in providing an ontology in constructing a material library, but participants find the upfront effort required to build up the system challenging.

Comment 1: *Reuse of the created library is amazing but it is a bit of from* ***load of effort*** *but after that it is just a case of tracking it as you go through the designing elements stage. The positive point here that the use of scripts helps* ***in automating the tasks*** *needed.*

Comment 2: *you have to be careful with this with* ***monitored process****, while creating template library user can duplicate materials and remapping parameters because you can end up with* ***potentially error somewhere in calculation****.*

Creating new material is ***challenging*** *as the user have to make sure that all parameters are filled in correctly.*

Comment 3: *On small scale firm without BIM manager I find this* ***difficult to be sustain the consistency of the system****, in our company sometimes people are using different files with different materials on different models and in my experience, it is the all about* ***the fairness in modelling in Revit*** *that varies from project to project. Also, it depends on the users to fill in all these data at building it* ***highly depends on their time and also resources*** *they have to build up this file.*

Comment 4: *I think having a* ***template file ready*** *for the company to* ***start*** *with and build on may be important for the adoption of this tool.*

Comment 5: Being able to ***build and reuse*** *our own library is great, I think it went further from just a tool for calculation to a system to generate, record and link information required for Embodied carbon calculation. But first users need to be* ***guided and trained*** *to understand how to use it.*

Group 1
Group 2
Group 3
Group 4
Group 5

Figure 7.12: Comments on system aspects (question 2)

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c. System aspects - question 3:

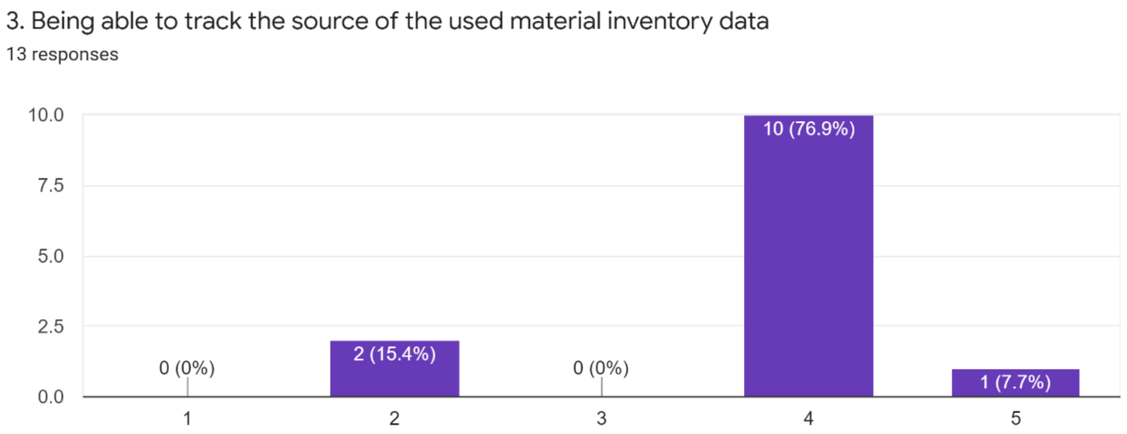

Figure 7.13: Questionnaire results on system aspects (question 3)

This feature is achieved through the parametric option in the BIM model, which adds information to any category in the model, in this case the materials, as shown in detail in chapter 6. Participants reported the high significance of tracking the source of the material inventory by adding a parameter for it and importing it with embodied carbon values and a functional unit. The value of adding the inventory source as a parameter with the material is that it is easily tracked at any time in the project and proves the results are reliable, as expressed in figure 7.14. Also, one respondent acknowledged the value of documenting and tracking the material inventory data source to ease the reporting and evidencing process of the calculations that need to be submitted to any green rating system. In addition, a recommendation was provided to add a parameter that contains a link for the resource or EDP from the manufacturer's website, which was described as a useful easy quick link to any additional information or documentation required (see comment 3, figure 7.14). **The answers revealed that this feature is effective and very efficient in keeping records of the inventory source, especially when a document is required to be submitted to evidence the reliability of the results.**

Comment 1: I imagine that this point is covered in your proposal through adding ***sufficient supporting parameters****.*

Comment 2: Structing data is very important for the ***reuse*** *and is a key for* ***consistency and proofing reliable results.***

Comment 3: I think if you can also ***add a parameter*** *where you can put the* ***link of the EPD*** *of the manufacturer website it will* ***be more efficient****. Also, if the library is provided* ***online the website link*** *will be very useful.*

Comment 4: The value of working with structured data and library is obtained when a need to provide ***evidence document*** *to green building rating system as for BREAAM for example.*

Group 1
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Figure 7.14: Comments on system aspects (question 3)

d. System aspects - question 4:

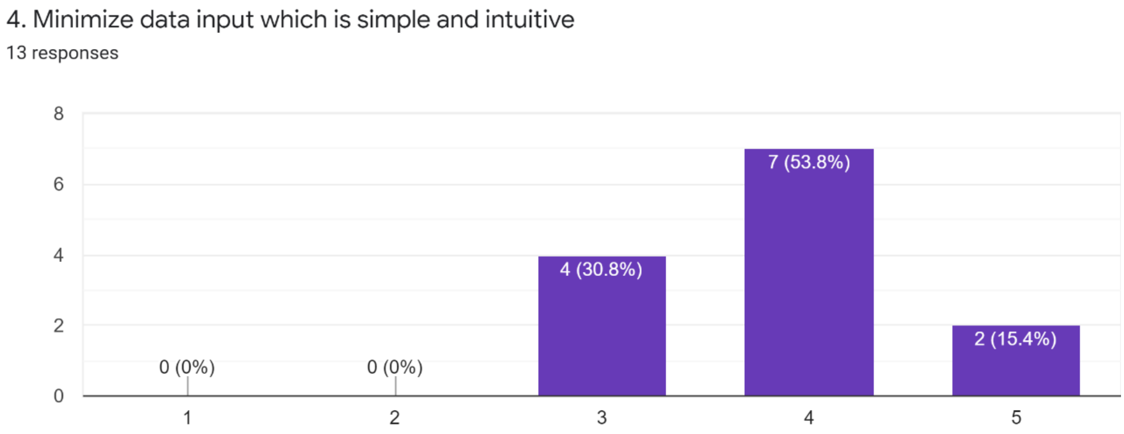

Figure 7.15: Questionnaire results on system aspects (question 4)

Both the results from the questionnaire and the answers from interviews showed that this point is valid, with only one suggestion being added. Approximately 70% agreed with the statement. On the other hand, one participant was not convinced that this aspect applied to all stages of the design, as shown in comment 3 in figure 7.16. The participant's opinion was that the system input on a material level and having to model it was suitable from stage 3 and 4 but not suitable from the early design stage. Discussion continued with the architect highlighting that there is no available database on component level provided in UK, unlike other countries, which provide databases on different levels, such as the Swiss building database that works on an average value for buildings, and Bauteilkatalog, which provides an average value at building element level and on component level (Cavalliere et al., 2019). These different levels database allow the construction of system that is based on a building element and component level not material level. The lack of availability of such a database for the UK is admitted as a limitation for the proposed model. This agrees with the findings from Meex et al. (2018) that more research is required to produce a back end calculation model that contains values on element and component levels that are suitable at screening and simplified LCA to suit early stages of design.

Answers to the fourth question showed that the proposed framework is efficient in saving time and effort due to its success in minimising input data. On the other hand, the tool lacks the need revealed by the architects to have a component generic database that can support early stages of the design.

*Comment 1: I think the **workflow** for this system is **very simple** and it **saves time**, when I tried before on previous project to apply suitable equation for the material functional unit it took ages.*

*Comment 2: As an architect I find this **very useful** as I don't have much time to invest for EC calculations.*

*Comment 3: I know that this model is designed for detailed and reliable EC calculations but for me I find this model **usable at only stage 3 and 4** as the input needed on a material level, I think if the library is constructed on a component level even if the deviation of the results reached is 20% it will be useable more at early stage of design at stage 2.*

Group 1
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Figure 7.16: Comments on system aspects (question 4)

e. System aspects - question 5:

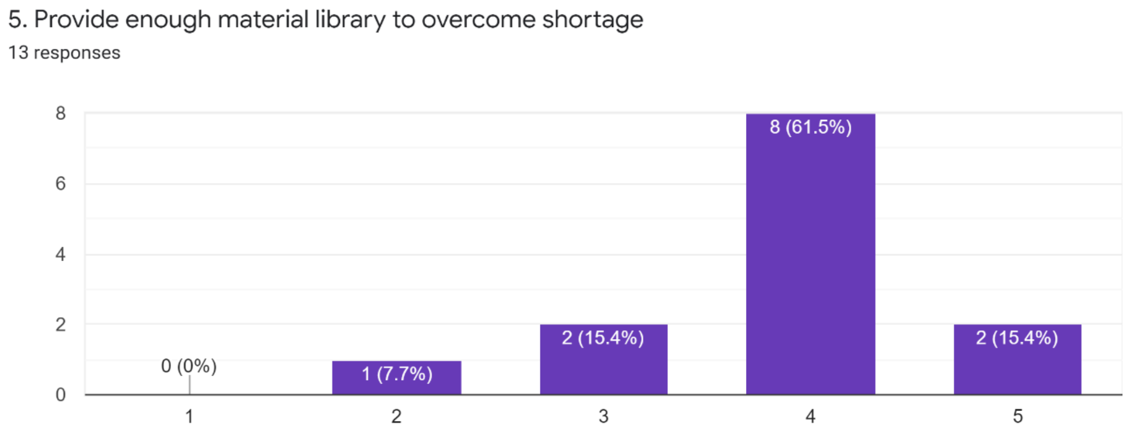

Figure 7.17: Questionnaire results on system aspects (question 5)

The fifth question attempted to discuss further the framework proposal for building a material library and its effectiveness in the mix of LCIA database, together with keeping consistency and to overcome shortage in one source of inventory database with the current provided resources.

The results from the questionnaire showed that more than 75% of participants agreed that the framework provided a procedure and enough suggested resources to overcome shortage of one source inventory database.

Participants who had experience with other tools expressed the value and importance of having control over adding more materials into the system. They suggested that existing tools have an advantage in that they have a ready embedded library to use, but they specified that this sometimes acts as limitation as they are constrained by the library in the tool and cannot add more external materials (comments 1 and 2 in figure 7.18). Highly experienced participants highlighted the importance of having a system to expand the library, while less experienced participants from group 2 were more concerned with the technical knowledge, education and guideline material to use external and multiple resources, as expressed I comment 3, figure 7.18.

An important suggestion made by a participant from group 3 was to provide a starting Excel with mixed database and template Revit file to ease adoption and use for SMEs. This would also act as a learning resource for them to follow and build upon it. One aspect highlighted by the same participant was that the tool has to be provided along with a clear, detailed guide for the user, to avoid confusion in using the library at different LODS. Although the method of mixing different sources of database has great potential for overcoming the shortage of the one resource in covering different stages of the project, the user needs to be aware of the assumptions used, such as correction factors, to avoid misuse of the library.

Answers to the fifth question showed that the framework is effective for allowing users to have control over mixing different sources of LCI, but this may be dependent on the knowledge and education of the user. This highlights the importance of clear guidance and a starting point template for both Excel and Revit files, to increase the adoption of the tool.

*Comment 1: We used other plugins the advantage that they provide ready to use library but always **with limitation** of we can't **add more materials**.*

*Comment 2: I think the logic proposed in the framework provided the ability to **expand materials** that we can't find in database as we use EPD for manufactures, or materials that are **not commonly used** like rammed earth that are not listed in external tool or plugin.*

*Comment 3: I think it still not enough to inform **users (building practitioners) with resources** to build up their libraries, it will be more useful for small scale firms to provide them with ready template to start with.*

*As resolution my suggestion maybe to help the smaller and medium size practices, you could issue a **table or spread sheet and a revit template file** with those materials already there like a library of materials that they can just update if they need and have these different levels of details in the library with understood and labelled naming convention.*

*Comment 4: In the guide for the users you must make it **clear what assumptions** are made so that they know the use of **coefficients stated in lower LOD** can't be used in higher ones because of the correction factor. Make it clear that they use it in just this stage and they are not using it later on when assumption is not appropriate anymore.*

Group 1

Group 2

Group 3

Group 4

Group 5

Figure 7.18: Comments on system aspects (question 5)

f. System aspects - question 6:

Questions 6 to 9 all related to the users' evaluation of the effectiveness and efficiency of the output from the tool. This question was included in the system aspects in accordance with the literature about the importance of the representation of the data to support design decisions.

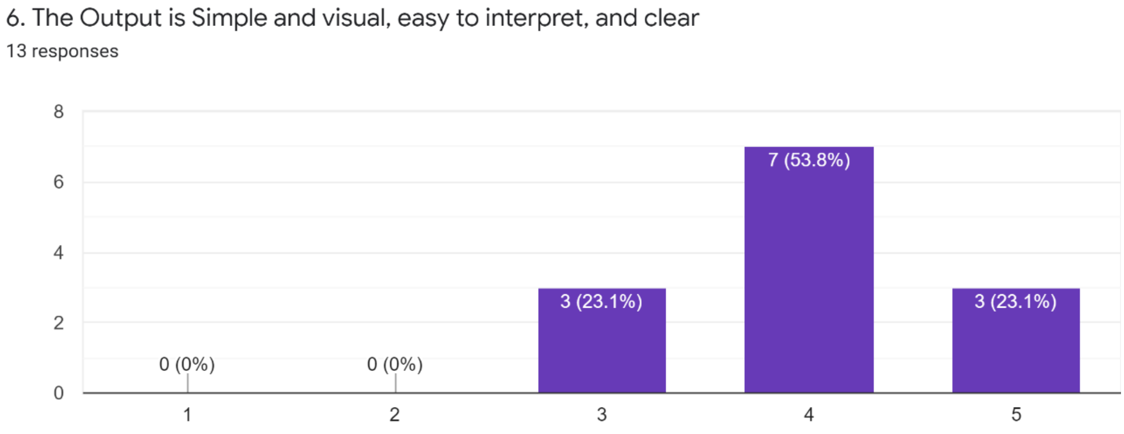

Figure 7.19: Questionnaire results on system aspects (question 6)

The results from the questionnaire, as shown in figure 7.19, showed that the majority of participants agreed that the output provided by the tool was simple, clear and easy to interpret, and this was supported by the feedback given in the interviews, shown in figure 7.20. As this was a very important issue, extensive, in-depth discussion occurred to reach a deeper perspective of interpretation of the output from the architects' point of view. The first advantage reported in interviews was that it was clear and provided supportive information for design decisions, and was not overcrowded with too many details. This may help to facilitate communication with clients and other team members. Moreover, the link of the output with the model elements and its storage within the BIM environment was mentioned by one participant as an advantage in the tool, as shown in figure 7.20 . It was recommended that future development of the tool so that it is possible to visualise the results on the model would be beneficial. Most of the participants mentioned the value of making the tool more visual in response to different feedback questions; this may be explained by architects' preference for linking performance assessments to geometry rather than reading graphs. As mentioned in chapter 6, it is possible to expand the functionality of the tool by adding this desired function when the values of the benchmarks of EC per category or material are developed further; however, this information is currently unavailable in the UK. One the other hand, one participant highlighted the limitation of the calculation system boundary (product stage A1-A3) on the output, which neglects the effect of other stages, such as the example mentioned in stage D of using biodegradable materials or offsite fabrication to minimise waste (see comment 5, figure 7.20). **With the currently available database and benchmarks, participants agreed the output was effective and efficient for informing design decisions. The comments supported this view on the effectiveness of the tool, and enriched the vision**

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towards future development. Participants recommended both the need to develop a supporting database that includes all stages of the system boundary, as well as incorporating tools that embed these stages within the BIM environment, which is technically possible with VPL and may be an expansion for the proposed tool.

*Comment 1: I think the output **is very clear and simple to interpret**, but it would be better to **add also colour code on the model** to indicate the values in the graph.*

*Comment 2: I found that **navigating through the model** and being able to check the **value for each element by selecting it is great**.*

*Comment 3: The graphs of the output are **simple and easy to communicate** with other team members and clients but last point when you showed potential for **future visualization options** on BIM model is **worth development**. Architects usually prefer more model visuals than just graphs.*

*Comment 4: The output provides **supportive information for design decisions** suitable for early stage of design and design development.*

*Comment 5: I think still the **lack of indicators** that includes the effect of **stage D** in **the boundary system** won't inform the design team with the **effect of using natural and bio materials** as the end of use (disposal stage D) is not included. This is not a problem in the model it is problem in the **shortage of database** and information about those materials.*

*Also, things like **offsite fabrication** when you start to think about the **efficiency of offsite fabrication** vs in situ construction there is always wastage in that process. These are all counting when a material is all assembled in the building and so all of these factors need to be added on as well to include all waste of materials and they are **"easy go" or easily avoided**, so it needs to be factored in construction industry calculations. So I find it a useful thing as an **expansion for the tool that your are providing**.*

Group 1
Group 2
Group 3
Group 4
Group 5

Figure 7.20: Comments on system aspects (question 6)

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a. System aspects - question 7:

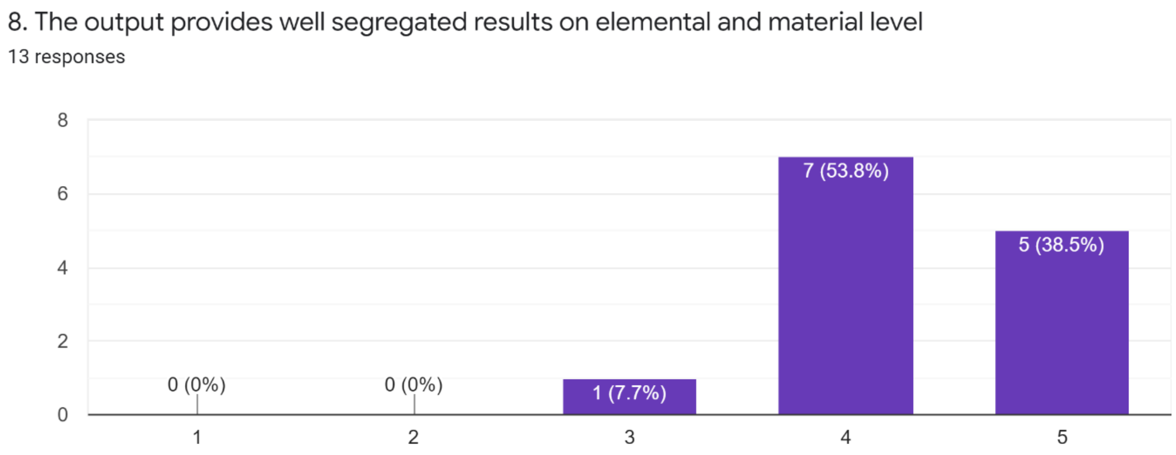

Figure 7.21: Questionnaire results on system aspects (question 7)

The answers confirmed that participants saw the benefit of presenting the results on two levels of detail: per category of building element, and other detailed per material sorted by building element as well. Two different participants highlighted that this option allows investigation of the contribution of the weight of the materials to EC, so the biggest contributors can be identified in order to inform actions required to be taken in the design (see comments 2 and 3 in figure 7.21). Also, this representation has been shown to be efficient, with the output dynamically changing automatically with decision modifications.

*Comment 1: I found the output very important and **well segregated** which **ease communication and discussion with clients**.*

*Comment 2: I think the output provided an understanding where the **biggest amount** of embodied carbon is, It looks like the tool you have shown us works quit effectively in **split down of the element and then split down materials** to show which is the **biggest contributor** to EC because you can really pull them apart.*

*Comment 3: For Decision making we need both **total figures and detailed values** and I found the detailed chart very will presented to show the **hotpots that need action**.*

Group 1
Group 2
Group 3
Group 4
Group 5

Figure 7.22: Comments on system aspects (question 7)

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g. System aspects - question 8:

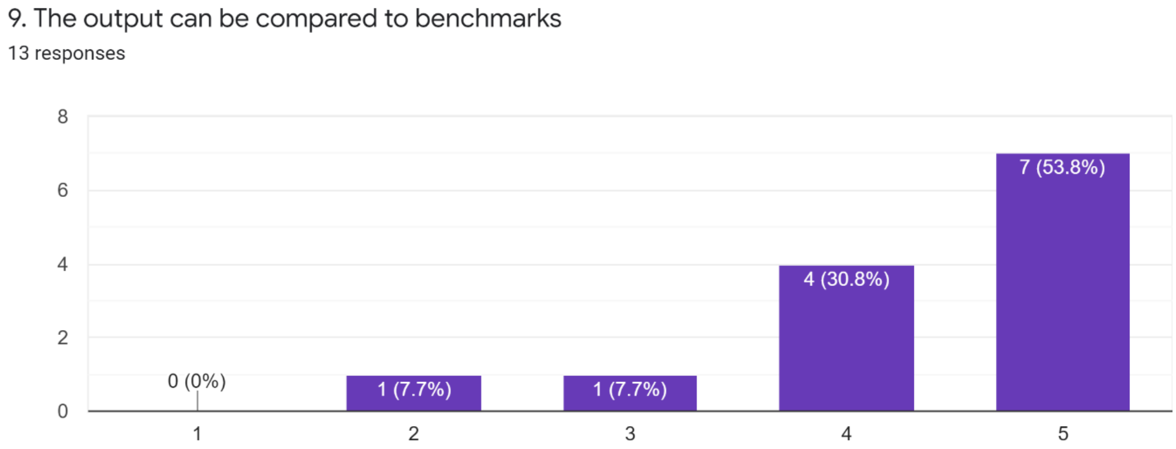

Figure 7.23: Questionnaire results on system aspects (question 8)

The last question for the output and for the evaluation of system aspects related to comparison of the total EC value of the design to the available specified benchmarks.

It asked participants about the effectiveness and efficiency of comparing the total EC of the designed model with current published benchmarks in the UK. The results showed that 75% of participants agreed or strongly agreed that the tool provided this feature; participants also expressed their views on the importance of this feature in semi-structured interviews, as shown in figure 7.23. Only one participant was not satisfied with the benchmarking methodology used. This participant argued that the assumption of the 90% correction factor to overcome differences in the included boundary system between published benchmarks and the value calculated in the tool was not sufficient and may decrease reliability. On the other hand, most participants reported that this feature in the tool was efficient, as it would save the team time spent searching for the correct values, and effective, as it was informative and supported design decisions. It was specified as a good indicator as it enabled teams to keep tracking design performance without the need of an external expert or sustainability assessor. Finally, it was recommended that other published targets also be included in the benchmark selection, not only UK ones. **The answers to this question revealed the high effectiveness and efficiency provided by the feature of automatic benchmarking. The architects highly recommended such a feature to provide them with easy quick checks for their designs. Also, the answers**

indicated the importance of applying the same concepts in other tools that quantify other sustainability aspects, as this method supports architects' decision making processes.

Comment 1: *It is great to automatically have* ***embedded comparison*** *with current benchmarks UK benchmarks, it* ***saves the team time*** *to* ***search for the right values*** *by searching in regulations, it is not an information that we use on daily basis.*

Comment 2: *Still I can see* ***deficiency*** *in this point as the calculation includes only the product stage (A1-A3), while regulations and benchmarks require a comparison for whole life cycle including waste, transportation and end of life, and 90% percent benchmark correction factor is not always constant and can vary.*

Comment 3: *It is great to see our model and design on a scale benchmark as the final value as value by itself* ***doesn't inform me with anything unless compared*** *to the desired targets.*

Comment 4: *This feature is an* ***indicator*** *for us to inform whether we are on track or not in terms of EC without the need of expert or external assessor to evaluate or design, I wish we had this ability on all sustainability assessments.*

Comment 5: It is recommended to include different benchmarks for domestic and non-domestic in the output excel sheets not only covering UK benchmarks

Group 1
Group 2
Group 3
Group 4
Group 5

h. Summary of system-related aspects evaluation

Evaluation of the system aspects revealed both the great potential of the system's integrated features, and deficiencies and problematic areas. Interestingly, a difference in interests has been highlighted between the different groups of participants. The younger participants with less experience were more concerned with details in the system and process that affected their day-to-day tasks, such as how the system affects their work efficiency and might ease their tasks. They also showed willingness to learn new skills if needed to maintain and expand the system. More highly experienced participants looked at how well the tool features might fit and adapt into their process, and were more concerned with management, consistency and value added as a result of using the tool. Overall, analysis confirmed the effectiveness and the efficiency of the tool in comparison with current available tools, despite the limitations in database and system boundary. All of the aspects discussed in this section are thematically categorised and presented in figure 7.25.

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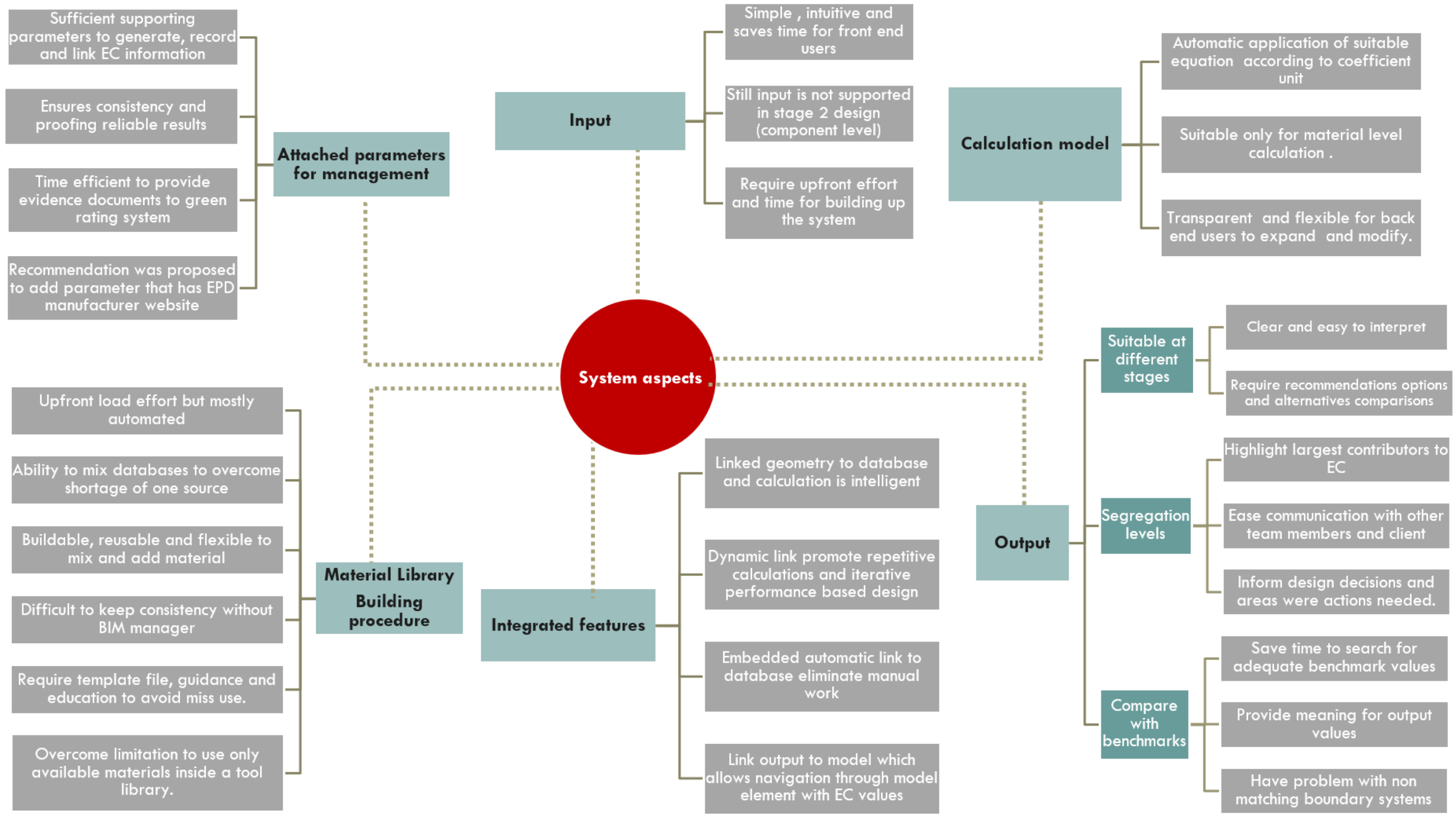

Figure 7.25: Summary of system aspects

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7.3.3 Section 3: process-related aspects

Following the same procedures in discussion as the above section, which provided insights related to the evaluation and user perspectives on the system features, this section focuses on process-related aspects. The themes used in analysis were initially informed by the literature review, with additional themes being generated through the process of qualitative data analysis.

a. Process aspects - question 1:

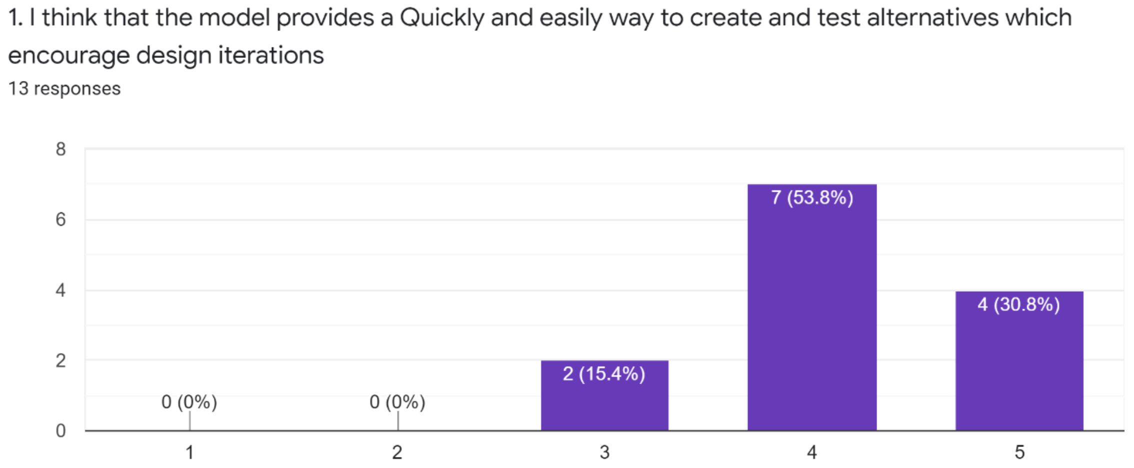

Figure 7.26: Questionnaire results on process aspects (question 1)

The results from the questionnaire, shown in figure 7.25, supported participants' agreement that the tool provides ease of use and time saving processes. As shown in figure 7.26, most participants agreed that the elimination of manual work and ease of use of the tool advocated repetition of the assessment, meaning that EC is more likely to be dynamically assessed with changes in design iterations. A concern expressed by more experienced participants related to dealing with difficulties with Dynamo. One participant mentioned that the process was straight forward and easy, unless there is a need to modify or write a script in Dynamo (see figure 7.27, comment 1). Another fear expressed in the comments, linked to previous experience with Dynamo, when errors having occurred in running scripts, reflected on participants' opinion of the stability of the tool (see figure 7.26, comment 5). **Overall, the results suggested that the participants agreed that the process was quick and easy, and converted EC assessment from ad hoc static work into a dynamic integrated assessment that motivates iterative performance-based design. The responses also revealed a fear of dealing with technical issues associated with either errors or having to modify scripts in Dynamo.**

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Comment 1: I think it doesn't have to be necessary applied on every project but having a template file that we can import our BIM model at ***any time*** *of the project and building able to calculate the design EC is definitely better and* ***straight forward*** *but this is in case that we don't have to write something in dynamo.*

Comment 2: Yes, I agree It allows to run ***periodic millstones*** *along the project timeline easily.*

Comment 3: I would recommend if it can also ***compare alternatives together automatically****.*

Comment 4: I worked on couple of projects where we assessed EC multiple of times. In best cases we evaluated EC five times through the project but most cases we couldn't do it more than twice, I think by using this tool will be ***limitless as a lot of repetitive time-consuming tasks are now eliminated****.*

Comment 5: We tried dynamo several times in our firm, we ***experienced errors*** *when running some scripts, so I am not sure about the* ***stability of the tool****. We have to try it on several projects to decide.*

Group 1
Group 2
Group 3
Group 4
Group 5

Figure 7.27: Comments on process aspects (question 1)

b. Process aspects - question 2:

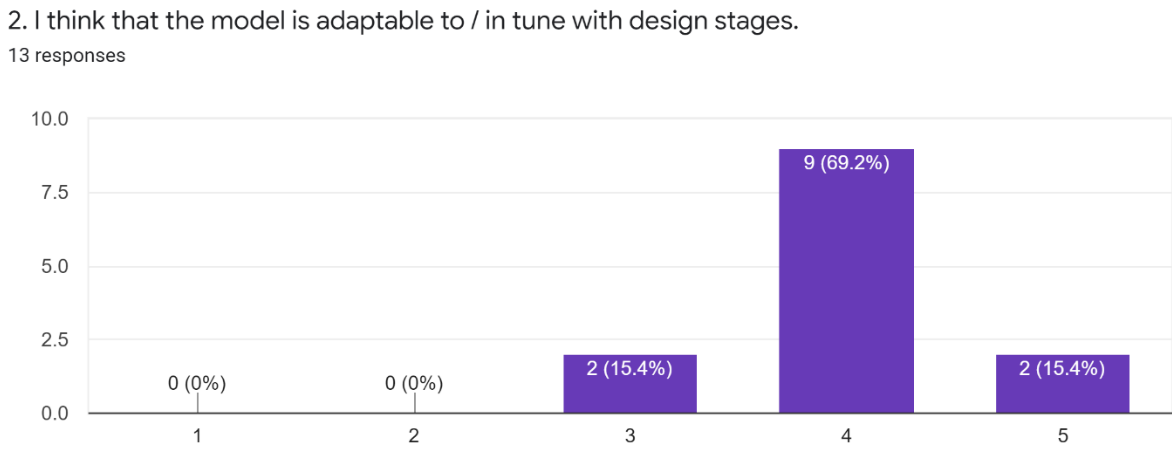

Figure 7.28: Questionnaire results on process aspects (question 2)

This question is related to two aspects. One was the adequacy of the input and the modelling technique, which has already been covered in the system-related aspects discussed in section 2. The other aspect relates to its adaptability to design decisions. Most of the participants agreed that the model was adaptable to design stages and to the decisions required in each stage; this was shown through their appreciation of the flexibility of the model for dealing with different LODs and for informing different decisions by comparing suitable alternatives at each stage. One highlighted piece of feedback was that the model needs to be tested on a real case project in order to learn more about its adaptability to design stages, as expressed in comment 1, figure 7.28. Several drawbacks were mentioned in terms of aspects that were missing in the model. The first one was mentioned in the workshop presentation, when one participant asked whether it only captured new construction, or does it recognise the phase existing and new construction? This revealed a weakness in the script, that the calculation script captures all elements in the model and not according to the specified phase. Interestingly, this participant had previous experience with Dynamo and noted that this filter is easily added to the script, as shown in figure 7.29, comment 5. The second drawback was the difficulty of including or excluding elements in the calculation model, unless the user has sufficient knowledge to modify Dynamo scripts as a back end user. **Overall, architects recognised the value of the flexibility of the**

tool to adapt to different design stages. In addition, it was suggested that phase filter and element inclusion/execution options are crucial to support the usage of the tool.

*Comment 1: I can't say now, but I am interested to use the model and see how it works with **different design phases** and when you add other element such as structural elements into wall and check factors that would be left out.*

*Comment 2: With this model we will be able to have feedback at each stage of the project, unlike all the tools that we are all plugins that we **can't control the level of detail** we are working with, so I think this is really useful and I can say it will **inform the design and specification at each stage unlike other methods**.*

*Comment 3: I think this tool may **empower architects** to consider EC **through all project stages**, in early design phases decision like structure typology, substructure and generic elements are experimented, then while as we go along project more detailed decisions like specification of insulation used for walls and roofs are decided, so I think this model will allow us at **all of these stages to consider EC** as one of **main design variables**.*

*Comment 4: Yes, but It depends on the **constructed library** that we mentioned before.*

*Comment 5: In dynamo there is a possibility to **filter element** according to **phase parameter**. It is not added in the calculation scripts.*

*Comment 6: Currently while using dynamo player we won't be able to exclude elements from the dynamo unless you will deal as a **back-end user** for the scripts and **understand how to remove the analysed elements from calculation and representation scripts**. There could be another solution to take this a step forward .and develop a user interface.*

Group 1
Group 2
Group 3
Group 4
Group 5

Figure 7.29: Comments on process aspects (question 2)

c. Process aspects - question 3:

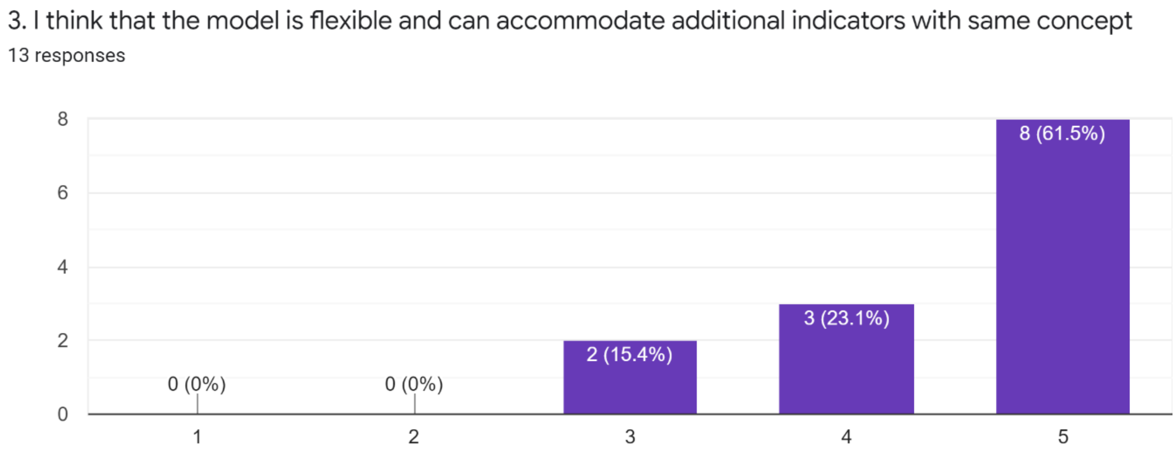

Figure 7.30: Questionnaire results on process aspects (question 3)

Questionnaire responses showed that more than 90% of the participants were convinced that the model provided a flexible way to accommodate other indicators with the same concept. Surprisingly, however, the results from the interviews suggested that this option is unlikely to be beneficial due to significant resistance to learning additional Dynamo skills among companies in order to expand such systems in house (see comments in figure 7.30). The first comment, from a highly experienced participant, suggested that the level of skills and knowledge of Dynamo acts as barrier and limits the possibility of expanding this framework in future in architecture firms. Comments 2 and 3 agreed that although there is flexibility in the tool, SMEs will be unlikely to benefit much from this option because of the lack of technically experienced architects to expand the system. Only one participant from group 1 had a different opinion from the majority: that Dynamo or VPL will be a required skill in future, that needs to be mastered by architects. This indicates a willingness to experiment with expanding the scripts if necessary in future. This may be explained by previous studies which evidenced that younger individuals are more open to learn and adopt new technologies, making them more likely to be early adopters (Gledson, 2016). **This important insight supports the finding from Gledson (2016) that the diffusion of digital new innovative tools should be led by a bottom-up approach hybrid with top-down control. This may provide an area of freedom for younger employees to explore and develop in new ways, once the value of new technology is recognised at management level. Therefore, it is possible that significant change in construction innovation processes can be attained through a hybrid two-dimensional**

approach of top-down adoption decisions and bottom-up innovation in solving/learning techniques.

Comment 1: Front end users (which in my opinion until now it's 80 -85% of the industry) ***are less likely to benefit from this option*** *as still knowledge and skills with dynamo need to be developed to be able to edit in the existing scripts.*

Comment 2: With my knowledge with dynamo and with my understanding of the scripts flow and concept other LCA indicators can be added, but I am still not sure that our skills can expand and modify the scripts.

Comment 3: One a small-scale firms it is hard to find an individual who can write a dynamo script to expand the tool, I don't think we can have it by our own.

Comment 4: I think it acts as a ***great base for dynamo scripters****, and dynamo by any means is the future essential skill that needed to be mastered by architects so future extension for the tool is possible.*

Group 1
Group 2
Group 3
Group 4
Group 5

Figure 7.31: Comments on process aspects (question 3)

d. Process aspects - question 4:

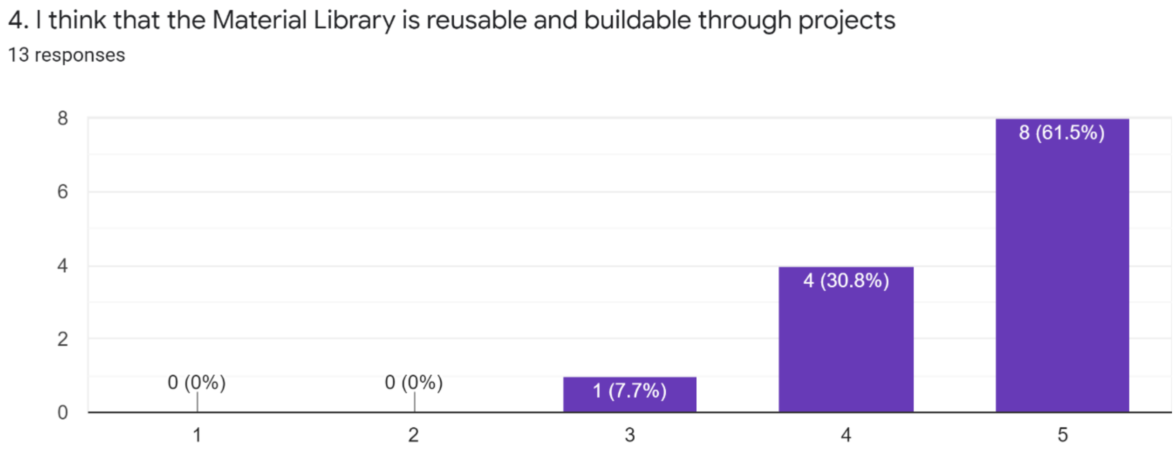

Figure 7.32: Questionnaire results on process aspects (question 4)

This question is related to question 2 on system aspects (see section 7.31), but this time the context being discussed is the change in process. Again, over 90% of participants agreed - with 61% strongly agreeing - on the advantage of the reusability and buildability of the material library through projects to the design process. The two main positive points stated were the ability to add material to the library at any stage of the design, and the depreciation of time and effort required over time and more projects, which may have a significant effect on the process of implementation. This means designers may have more time to devote to innovation in design solutions, as the process of assessment accelerates and becomes easier over time. In addition, another participant brought up a point made before in system aspects, which is that the process of maintaining the consistency and reliability of the library needs to be monitored by the BIM manager (see comment 2, figure 7.33).

Comment 1: Great option I see is If you want to ***add new materials*** *you can add it to the existing data base "standard bank file" at* ***any stage of the design****.*

Comment 2: It depends on having ***BIM manage****r* ***to monitor the process*** *and making sure that all files are consistent and the information for new materials are filled in template files.*

Comment 3: I think this is very important part of forward planning.

Comment 4: ***Effort and time*** *required to do the assessment* ***decreases overtime*** *and more use over projects as the library will mostly cover all materials that we need.*

Group 1
Group 2
Group 3
Group 4
Group 5

Figure 7.33: Comments on process aspects (question 4)

e. Process Aspects: question 5

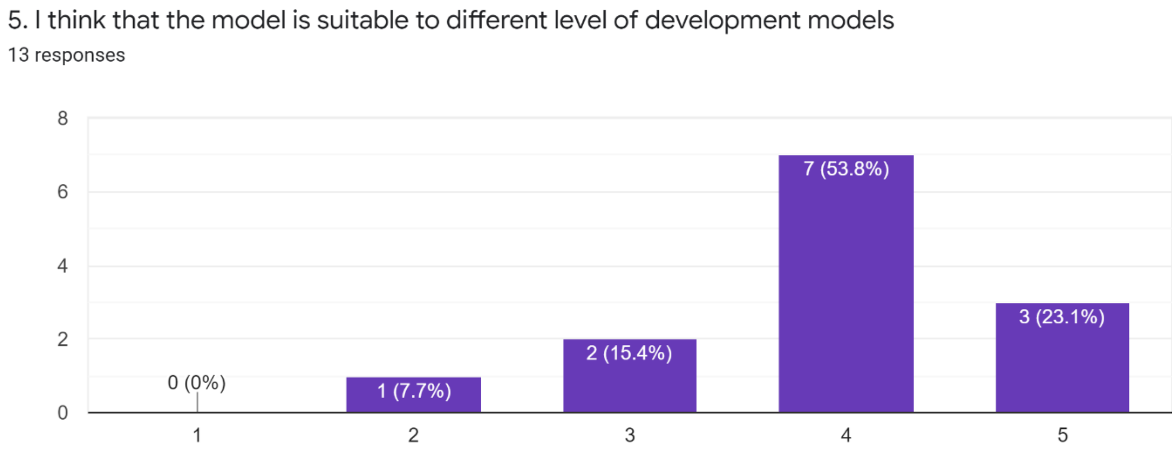

Figure 7.34: Questionnaire results on process aspects (question 5)

In terms of process in digital construction different level of development models and its interference with calculation is an important aspect to discuss. The level of development of the model is defined by the level of details (LOD) that controls the accuracy of material quantities and Level of information (LOI) which define material specification. LOD difference is controlled by correction factor while different levels of LOI is controlled by the structure of the material library, as explained in chapter 6. The high percentage of agreement in the results of questionnaire is supported by the expressed positive feedback provided by participant, see comments 1,2,3. As stated the framework and added details such as correction factor and ontology of material library provided new contribution of the feedback process. Also, it was highlighted that the success of the ability to use the tool adequately with different level of development has high correlation with building a rich well-structured library.

On the other hand, although it is stated the added correction factor parameter is a great approach to overcome in accuracy of quantities in low LOD models, being alert of all affect of use is crucial for the accuracy of results. This was demonstrated by an example provided by participant, see Comment 4 figure 7.35, as same material can be used in walls that need deduction correction factor to the area because of frames and roof that doesn’t need this application of the deduction factor. Also, It was recommended to experiment the integration of other generic excel based tools like the one developed by FCBStudios to overcome the limitation of the framework in setting estimate targets at the start of the project. **These results matched those observed earlier in this section, question 2 that confirms the new VPL**

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approach effectiveness in integrating assessments in different digital design stages with additional factors to be considered.

Comment 1: Considering the LOD is very good as you don't have to wait till you reach a ***technical stage to get any feedback****, I think that allows you to get feedback* ***right at the start of deciding materials*** *and knowing that it* ***doesn't have to be fully accurate at stage 2*** *but at least you get an idea that can help inform the design stage.*

Comment 2: The idea of including generic to intermediate and then manufacturer specific library allows the use of the tool at different levels. But then we get back on creating a ***rich and well-structured template****.*

Comment 3: Correction factor can be a solution for more ***accurate results*** *because it can be added to material in order to overcome inaccuracy in the modelled geometry at low LOD models.*

Comment 4: This correction factor is added on material level and in some cases, like insulation correction factor won't be applicable as insulation can be used in walls that need correction factor and roofs which won't need it. That's why I mentioned that the user has to be ***aware of those details*** *to extract* ***reliable and accurate results****.*

Comment 5: I think it would be quite useful to see how other tools (excel based ones) could be integrated with your workflow. eg. One developed by FCBStudios which is useful to use before you start the project, as working out with your target should be upfront, we used that as ***sort for benchmarking and how do we expect this building could perform*** *and that uses a lot more assumption with much detailed model and information about the project. Which lacks still* ***in low level of detail mode****l in Revit won't allow to do rough calculation.*

(grey)	Group 1
(purple)	Group 2
(green)	Group 3
(blue)	Group 4
(red)	Group 5

Figure 7.35: Comments on process aspects (question 5)

f. Process aspects - question 6:

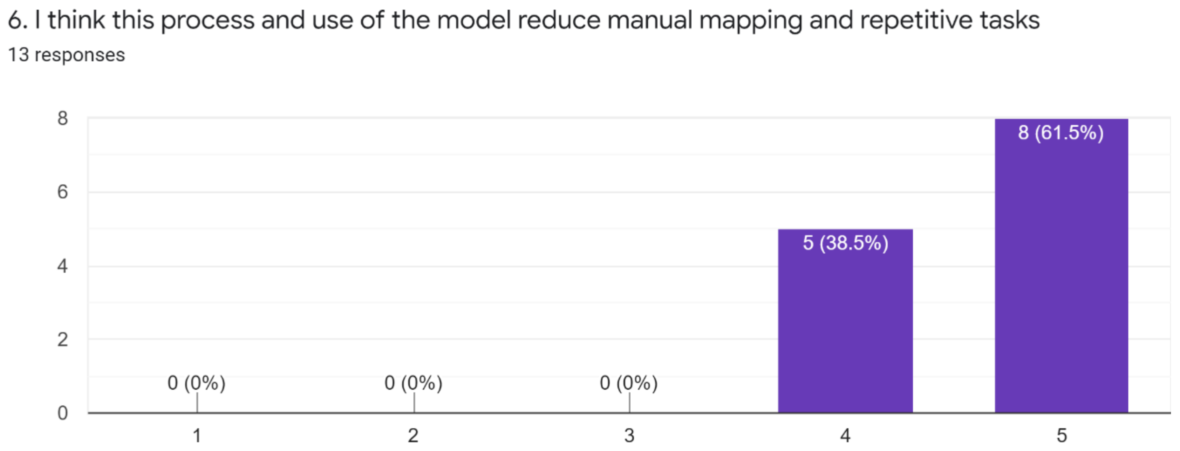

Figure 7.36: Questionnaire results on process aspects (question 6)

The last question on process aspects evaluated the overall efficiency of the process provided in the framework by reducing manual mapping. Responses were closely connected to the comments and results discussed in section 7.3.2 on question 1. All participants agreed that the framework was successful in reducing manual mapping and repetitive tasks; this was illustrated in both the questionnaire results and the examples from interviews (figure 7.37). This aspect potentially makes a great contribution in reducing errors during the process. **This indicates that the objective of creating a framework that overcomes challenges of repetitive EC assessment has been validated as successful from the users' perspective.**

*Comment 1: It is valuable on all project scales but when it comes to **large scale project the value is significant** as it reduces the headache of possibility of errors in manual mapping and manual calculations.*

*Comment 2: I think you **automated a lot of tasks** which is really **useful** and it reduces the time you need to sit down and work through the model if it also calculated automatically, and reduce possibility of errors.*

Comment 3: Definitely agree once the upfront effort done at the beginning and library is revised, we will be able to reuse the library and run calculation to test alternatives with respect to the design.

Group 1

Group 2

Group 3

Group 4

Group 5

Figure 7.37: Comments on process aspects (question 6)

g. Summary of process aspects

The analysis of process-related aspects confirmed the potential benefit that the framework and tool provide to change the process of interaction between design development and EC performance assessment. The content analysis enabled a thematic map to be drawn that contains all points covered, between potential existing points, limitations of the process and recommendations from users, as illustrated in figure 7.38. In addition to the main themes discussed in section 7.33, users' perspectives suggested other factors relating to the potential changes to the process that the tool can make.

These other factors include enhancing communication of sustainability aspects (material selection) with clients, as the tool provides an interactive and visual method to discuss embodied carbon as one of the variables in the design. This might change the degree of contribution from clients in the process of building performance decision making and convince them to consider EC in their projects, as one participant commented:

> *"I think this tool provided* ***a free and more flexible way*** *of calculating EC than other licensed paid tools which increases the possibility of* ***convincing clients*** *to consider evaluation of EC in their buildings/products*"

A second factor is the potential role of the tool to educate architects about the impact of material selection on embodied carbon, as the assessment process is automated and allows an iterative method with comparisons between multiple alternatives, as described in the opinion expressed by participant:

> *"Tool like this is going to help us to be educated about important aspects that is up cross our profession…. I guess teaching people the process of integrating that into the model and use it as a tool because it is not something that you have normally think about, you think about sustainability broadly but you don't think about it on material level"*

However, it was also noted by more experienced participants that external factors relating to changing policies and more strict requirements for EC would also be likely to encourage architecture firms to adopt more tools like the proposed one, in order to be able to change their assessment process and make it more efficient.

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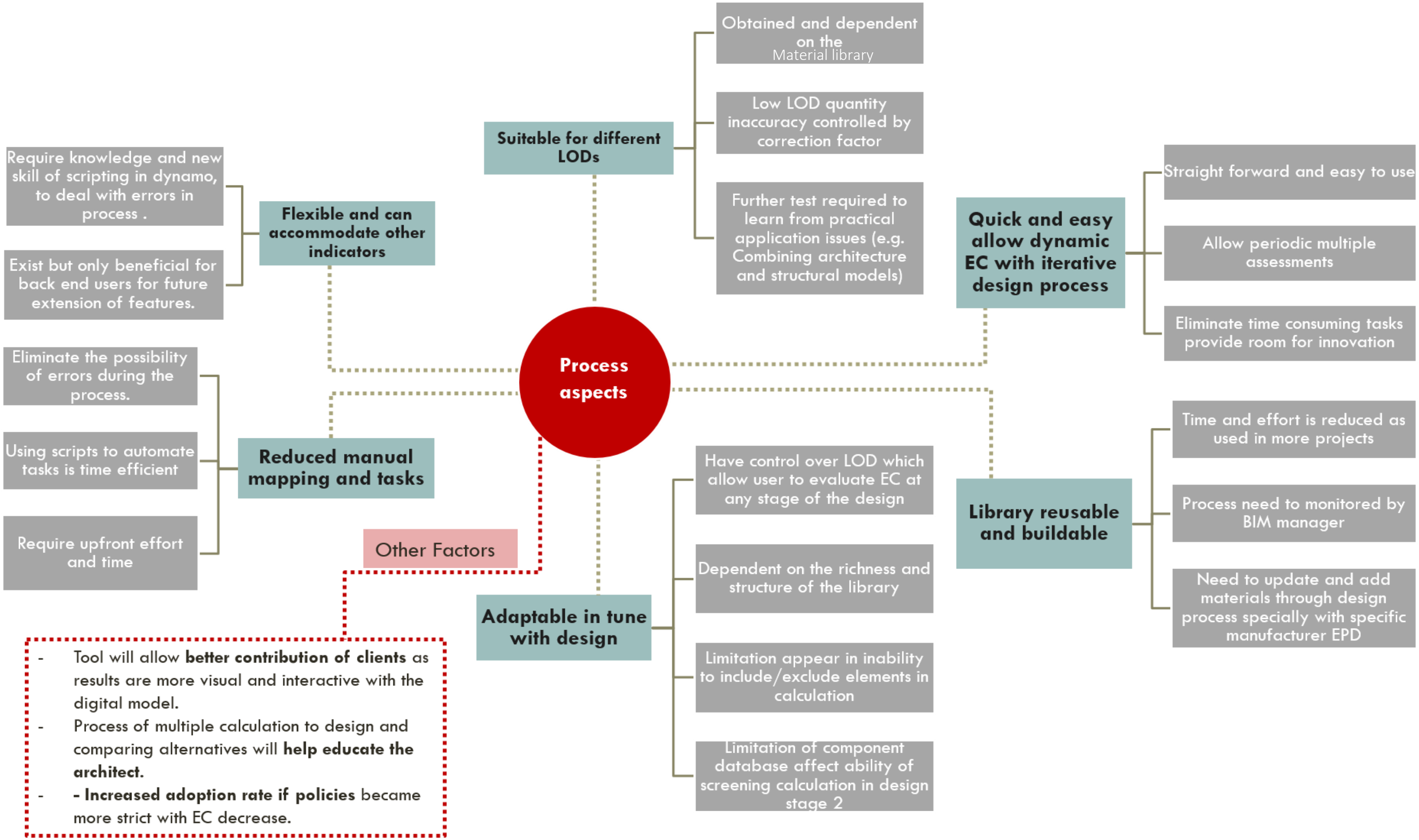

Figure 7.38: Summary of process aspects

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7.3.4 Section 4: skills and satisfaction aspects

The last aspects to be considered were the skills and overall satisfaction of users. This part was only analysed using questionnaires, with indicator comments being extracted during workshops and from within answers to other questions in interviews, as it is hard to discuss participant perspectives directly on skills issues, and also regarding overall satisfaction, the questionnaire provided more freedom to do so than interviews.

The nine questions above provided an insight into participants' satisfaction with the framework and proposed tool; the criteria are attached to the responses to the questions shown in table 7.4. It was noted that all questions in this section should be responded to from a front end user perspective.

Overall, the responses indicated user satisfaction towards using the system, and this was also confirmed by the positive feedback expressed in their comments.

> *"I think in comparison with other plugins this one seems to be much* ***more intuitive."***

> *"I think there is a lot of mileage in that* ***the visual representation*** *of the Ec is brilliant, it* ***gives anyone working on a project in BIM environment****. And gives insights of* ***what to resolve****."*

> *"I think this is very interesting work and I think there are couple of architects I know would be interested to try such a tool."*

> *"SMEs will find more valuable to have free tool without having to pay expensive license".*

Looking closely at the results, a couple of relationships and insights were derived. Firstly, a positive correlation was found between participants' agreement that the system was uncomplex and easy to use, and agreement that there was low demand on technically skilled staff to use the system. Secondly, high reliability and satisfaction with the integration in the system function were confirmed by the responses to questions 5 and 6.

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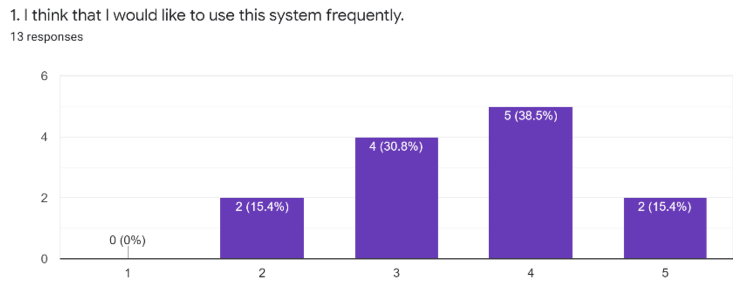
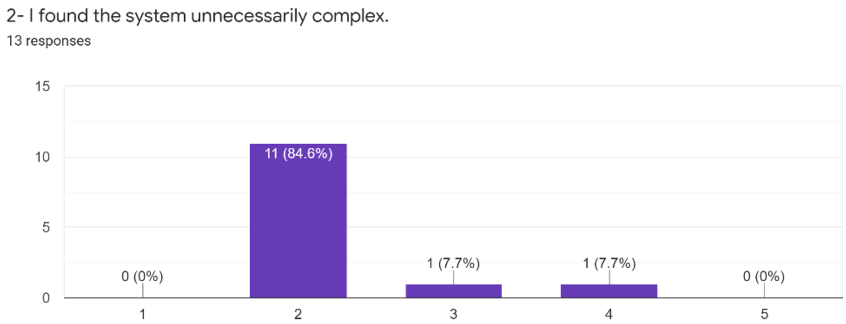
Surprisingly, although the majority of feedback was positive on the ease of use and lack of complexity of the system, with a high reliability indicator, question 1 responses suggested that only 55% of participants agreed that they would use the system frequently. This may be explained by the idea that adoption and use is not just linked with satisfaction, but is also determined by the need to use the system, as expressed in the participant comment below.

> *"If new policies will be applied like the one discussed to have compulsory calculation to EC for any new construction in London, this would increase the uptake of such models. So, it is either having incentives, client is willing to pay for it or it become necessary."*

Exceptionally, questions 7, 8, 9 had normal distribution or mostly average equal responses between 'agree' and 'disagree', with the highest percentage of participants opting for the "3" response, which indicated that they had no opinion regarding this aspect. These questions mainly inspected the level of ease of learnability and memorability of the system, which demonstrates that further testing is required to answer these questions.

As mentioned before, due to the emergent COVID-19 situation, the workshops were conducted online. Limitations were found in this evaluation method (online workshop). Besides, time constraint of the research project did not allow the application of the tool throughout all phases of a real project, acted as another limitation. Accordingly, the researcher found that the evaluation partially failed to investigate the relation between the skills aspects and learnability of the system. Therefore, further future testing is recommended in order to inspect those aspects and a summary of skills related aspects that need more investigation is summarised in figure 7.39.

Table 7.4: Section 4, overall satisfaction and skills aspects

<table>
<tr><th>Criteria</th><th>Question</th></tr>
<tr><td>Satisfaction
Need to use the system</td><td>
</td></tr>
<tr><td>Satisfaction
Learnability</td><td>
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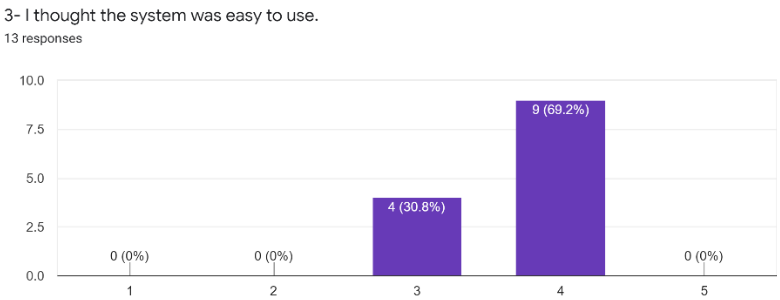
<tr><td>Satisfaction
Learnability</td><td>
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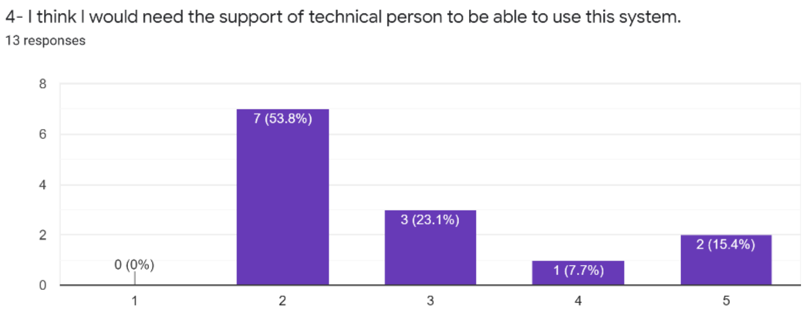
<tr><td>Learnability</td><td>
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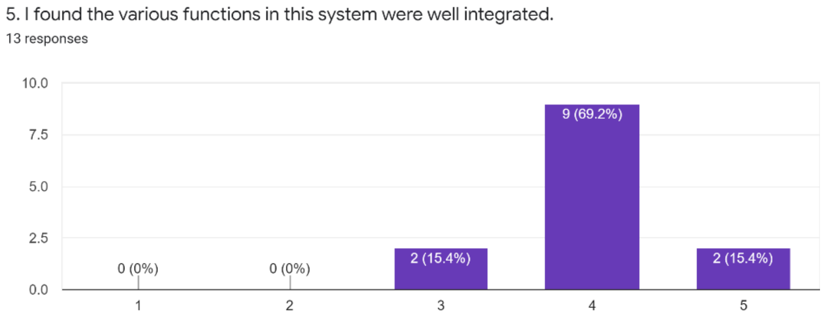
<table>
<tr><td>System Reliability</td><td>
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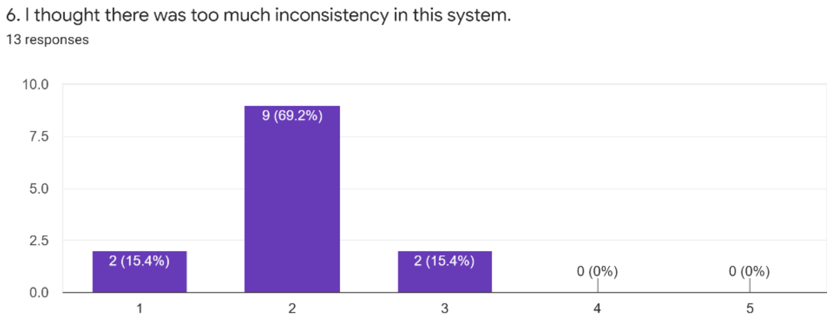
<tr><td>System Reliability</td><td>
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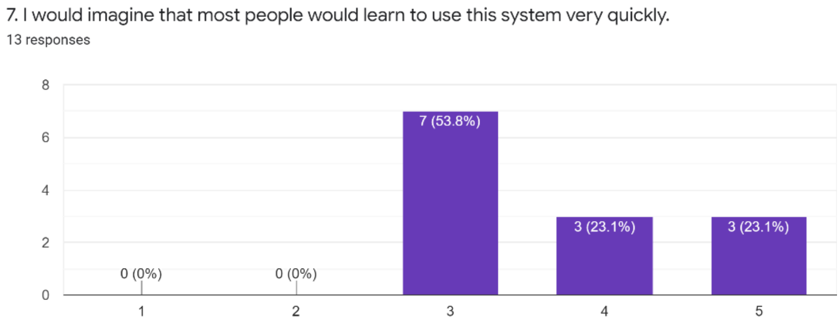
<tr><td>Learnability</td><td>
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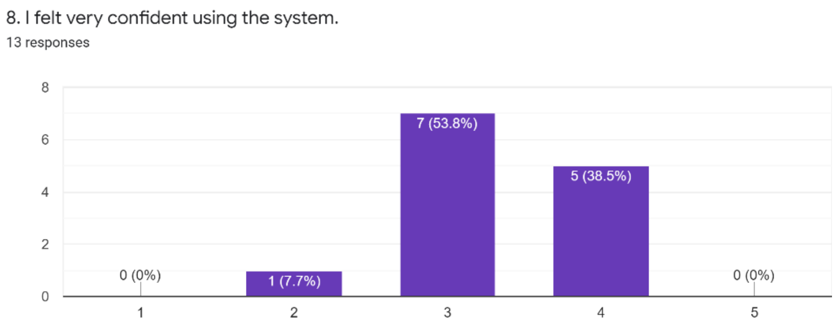
<tr><td>Memorability</td><td>
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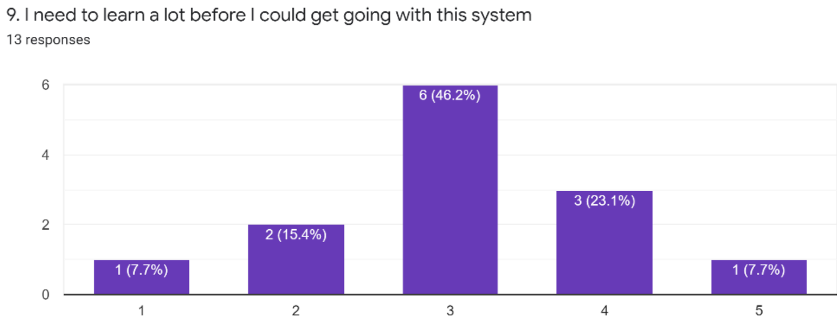
Learnability **Memorability**	

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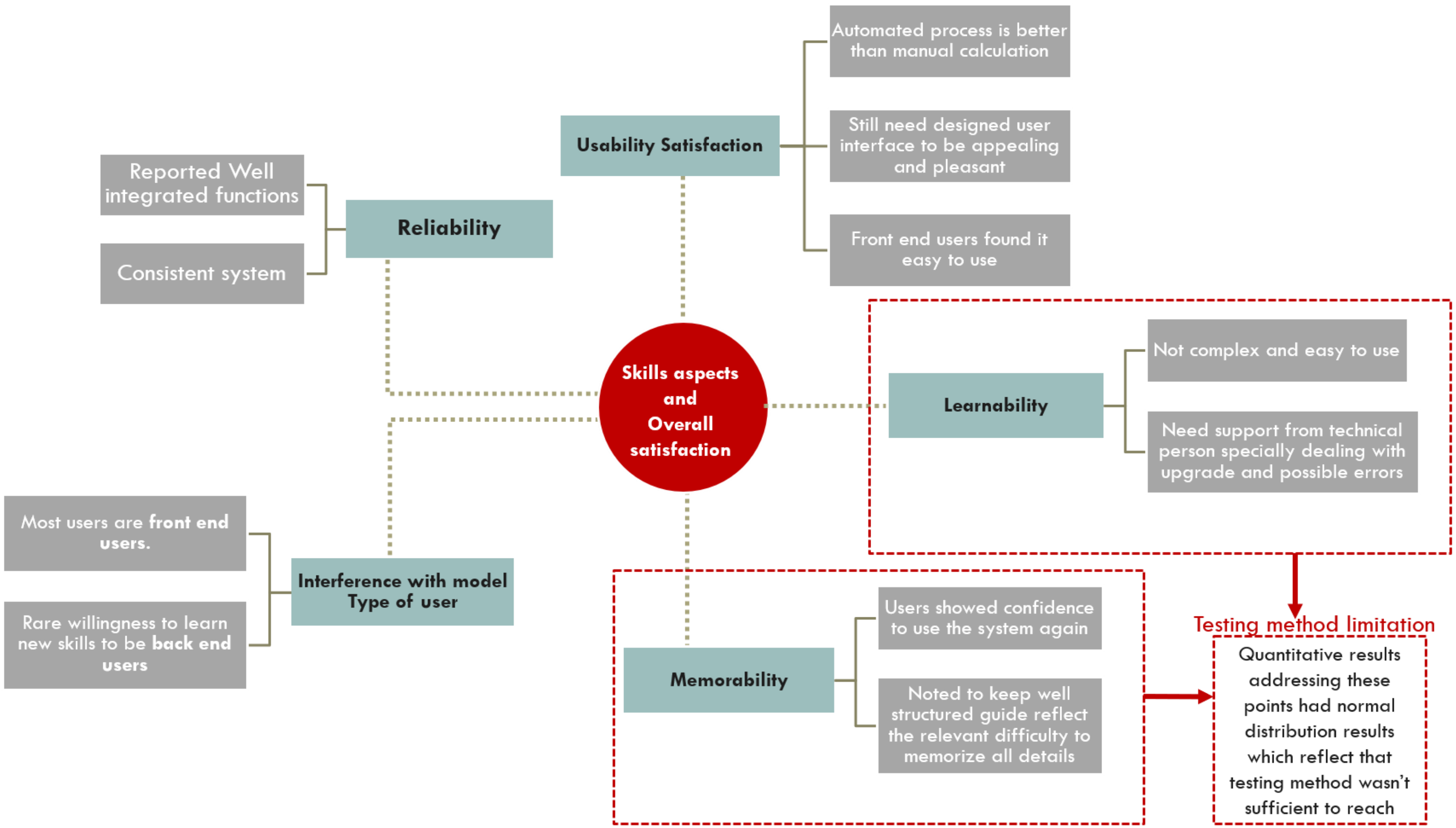

Figure 7.39 : Summary of skills aspects that need more investigation

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7.3.5 Summary of reported problems and recommendations for future improvements

The last two questions in the interviews explored the participants' perspective regarding general problems and recommendations to enhance the framework and tool. The purpose of these final two questions was to allow participants to add any additional opinions or ideas that had not already been covered. The final part of the analysis section will analyse and present these findings, which act as recommendations for future work.

a. Problems and limitations

Participants were asked whether they had any other problems with the framework and the use of the tool; the answers given were related to technical issues, educational challenges, and management challenges.

The technical issues mentioned were:

1. Dealing with the upgraded versions of Revit and Dynamo.
2. Not having interface for guiding the steps within the tool.
3. Possibility of errors and not having an expert to solve it.

On the second category, educational challenges, one participant commented:

> *"Main challenge I see now is educating the architects in our studio about EC as calculation itself, I think it is fairly new to most people, I don't think that most architects came across it. It became more familiar this year"*

Another participant commented:

> *"Keeping the team informed with this process, so it is an education aspect with need to monitor the process"*

This revealed both education and management challenges to using the tool. In order to complete the map of problems, another layer of analysis was conducted, in which answers in sections two and three and any other problems mentioned were extracted. Together these results contributed to provide important insights, enabling a whole picture to be drawn of problems and limitations in the use of the tool. The emerging broad themes were technical, management, skills and culture, limitations in existing database, and education and resources. The details are presented in figure 7.40.

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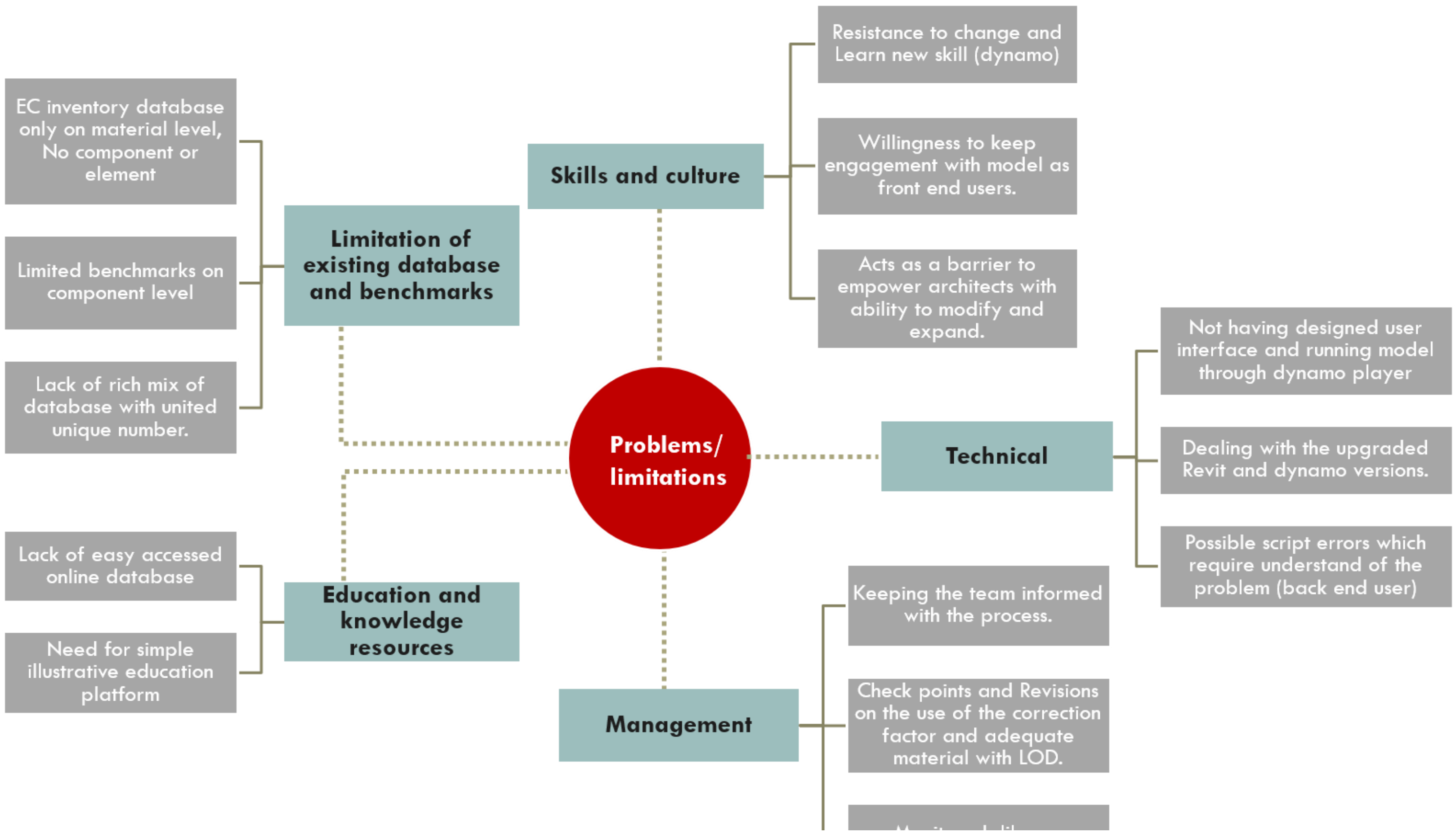

Figure 7.40: Summary of problems

b. Recommendations and potential improvements

The last question in the interview was “Do you have any suggestions for improvements?”, which provided an opportunity for users of the tool to express their needs and opinions on this issue. All of the suggested ideas related to enhancing usability to increase potential adoption rates.

The first group of suggestions concerned functional features to be added to the calculation model:

1. Calculation to capture element phases and have a phase filter to existing and new construction.

2. Having more indicators within EC, such as embodied energy.

One participant highlighted the importance of this by giving example of insulation selection:

“for example Rockwool insulation have very low EC but very high EE”

3. Include whole carbon life cycle assessment with the construction stage.

The importance of this was expressed in the following comment:

“Include transport and end of life and include the RSL as a factor in your calculation as actually this is what is useful to the industry to think about the whole life cycle of the building, we need to think about how we are demolishing things and how things are used after replaced and removed (stage D is the hardest one (that where timber comes to life, that’s where you get the most use for natural materials because they don’t have to go for land fill and they can be used for something else.”

The second category of suggestions were all under the theme of designing a user interface with the ability to:

1. Guide users through the steps of the assessment: illustrate and mention in text and diagram the steps required.

2. Include and exclude elements from calculation.

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3. Filter and sort families in BIM environment according to EC values and colour code them.
4. Add material search window and replace feature.
5. Provide recommendations for alternative products. This was illustrated by an example given by a participant, as follows:

> *"It could be nice if you can interrogate the material that is causing the biggest contribution to carbon with alternative suggestion or alternative material spec. that you could use instead to make it more environmentally friendly. Because for us as an architects it is not about finding out how much EC is there in a building, it is more to addressing that and find alternative options as you specify materials may be so it could be done as filter for example if you are looking for an insulation a drop down menu can be filtered from low to high attached with other important key specification as U value and Embodied Energy to select an alternative."*

The third category related to adding visual features, including:

1. Colour coded feedback indicator according to the EC benchmark value in comparison to other similar materials.
2. Being able to present results more visually on the model.
3. Output to be presented according to the RICS categories to ease using the exported documents for BREEAM evidence documents.
4. Visual indicators check on the model completeness: coloured check test on the model to inspect that any added material or element contain parameter values and is not empty.

The value of this option was described as follows:

> *"The visual reference with colour codding you proposed as a recommended addition, I think there is so much value in that. It would be very useful if we can check by any elements if any parameter is not completed represents as red object, so that people could look at the model again and see what was content and also check if any elements doesn't have any value in them yet. That would be an immediate visual indicator, as someone can on to a project that doesn't work on it previously and didn't probably*

know the principle that are going along, so it gives the project lead the ability to use this visual 3D model as a reference that all of the parameters are in and populated with some value"

The last group of suggestions related to providing an easily accessed online platform for guidance and resources, including educational materials such as an illustrative video and guide, resources enabling users to start using Revit, Excel template and a combined material database that is searchable and can be linked directly to the BIM model. In summary, a map was developed in order to compile all these findings, which is presented in figure 7.41.

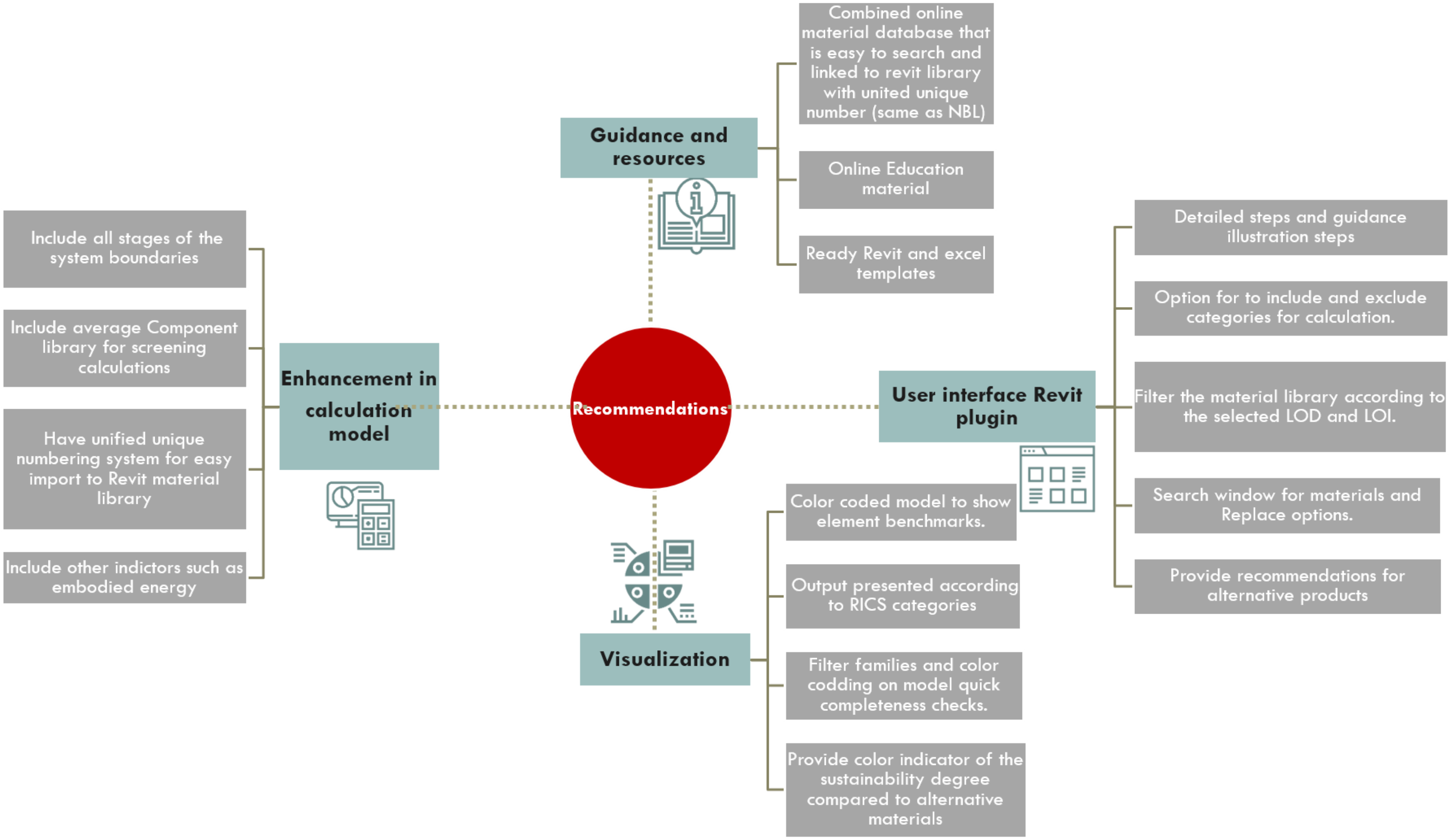

Figure.7.41: Summary of recommendations

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7.4 Summary of chapter 7

This chapter examined the possible application of Dynamic LCA assessment framework. Dynamo scripts were evaluated by potential users with different levels of experiences to assess aspects such as how it could affect current workflows and provide insights regarding future modifications and recommendations.

The first task was to design a usability test, relying on previously determined definitions for the types of usability tests discussed in section 7.2. A user questionnaire and interviews were chosen to be used as testing methods, as these were considered to be the most suitable methods for meeting the research objective. All of the details and steps required in order to ensure a rigorous procedure, such as sample size for data saturation, types of participants, and evaluation criteria, have been considered and discussed, and the design process for the workshop, questionnaire, and interviews is illustrated in sections 7.2.4 and 7.25.

Section 7.3 included and discussed in-depth analysis of participants' feedback, by analysing both the questionnaire responses and the interviews' content and thematic analysis simultaneously. Subsections were included to address system-related aspects, process-related aspects, and skills and overall satisfaction aspects.

The discussion including content analysis is considered both validation for the proposed framework and practical contribution to knowledge. Based on the analysis discussed in section 7.3, the following conclusions can be made using the performance criteria set for this approach:

- **Effectiveness:** The framework and tool proposed have eliminated a lot of problems and challenges in static and conventional methods of EC assessment. The concept has shown high potential in supporting iterative performance-based design, which may be reflected in changes in decision making processes.

- **Efficiency:** The framework and tool proposed proficiency to save time and effort, and this was confirmed, albeit with concern regarding the upfront effort required to build the system. The ability of Dynamo to automate tasks was validated to reduce time and manual work, as well as addressing the problematic issue of the high possibility of human errors in manual work.

- **Satisfaction:** There was overall positive feedback and appreciation of the value added by the proposed tool. Participants indicated that the features of the tool are well

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integrated and useful for informing design. Concerns were revealed concerning the skill related aspects. Additionally, further testing is required to draw conclusions regarding the learnability and memorability of the system, as the results failed to show a trend. Participants reported multiple times that further testing should take place on a practical project in order to assess satisfaction. Recommendations for enhancements required are summarised in section 7.3.5, which revealed that some of the first areas that should be addressed are designing user interface/Revit plugin, and visualisation recommendations to make it more appealing for users.

Chapter 8 : Conclusion and future research

8.1 Introduction

This chapter summarises the research conclusions based on the objectives, as well as how they were achieved during the period of the research. It also lists the intermediate dissemination achieved in the research project and highlights the research findings, contributions, and recommendations for future work.

The first part of the aim of this thesis was to investigate incorporating sustainability aspects through performance-based design using BIM-based sustainability tools and identify challenges and problems in workflow. This was fulfilled in chapters 2, 3 and 4 by achieving the objectives mentioned in chapter 1. The second part of the aim was to develop and evaluate a framework for a dynamic integrated process, which was addressed in chapter 6 and validated in chapter 7. In this part the decision was made to focus only on integrating LCA due to the limitations mentioned in chapter 4. The three phases of the research and the research methods utilised are described in chapter 5.

This chapter is the last in this thesis, in which consolidation of the study takes place including reflection on the research objectives and summarising of the lessons learnt during the research. It starts with a summary of the steps taken in the research phases to satisfy the research objectives (section 8.2). It goes on to present concluding remarks (section 8.3), followed by a discussion of the contribution it is considered to make to knowledge (section 8.4). Finally, limitations will be outlined in section 8.5, which will partially inspire the recommendations for future work presented in section 8.6.

8.2 Summary

This thesis started with an introduction to sustainability in AEC and digital construction (BIM), which identified the significance and the problems connected with both (chapter 1). In this chapter the outline of the research along with the structure, aim and objectives were presented. Chapter 2 provided a definition for the sustainability in AEC industry and reviewed the existing schemes with a special focus on LCA. It also highlighted the current reported conflicts between architectural decision making and sustainability assessments. It emphasised the problems and challenges in current approaches in sustainability assessment. The thesis continued with literature review of the topic in chapter 3, giving details on current integration between BIM and sustainability. The outcome of chapter 3 emphasised the gaps in the literature regarding the synergies between BIM and SBD, by reviewing problems in the current approaches and focusing on the potentials and shortcomings of BIM capabilities in attaining sustainability goals. This chapter contributed to theoretical understanding of possible development areas in the synergy between BIM and sustainability.

Chapter 4 focused on applications of visual programming languages in providing dynamic sustainability assessment that is integrated within BIM workflow. Approaches for assessing daylighting, operational energy and LCA through VPL platforms (Dynamo and Grasshopper) were all reviewed in this chapter. The scope of the thesis framework was then narrowed down to addressing material selection through LCA automation, as both the investigation and the literature showed problems using smooth workflow in the BIM environment (through BIM authorising tool Revit). Although the outcome of this chapter revealed a high potential in previously developed approaches for automating LCA, a lack of studies providing a VPL model that is suitable for UK LCI databases was found. In addition, it highlighted the gap in knowledge regarding the dynamic of architects' perspectives regarding adopting the new VPL approaches in automating sustainability assessments.

Chapter 5 described the research methods and design of the research stages according to the exploration phase presented in chapters 2, 3 and 4. A logical foundation for the research philosophy was set in this chapter, which adopted relativism as an ontological perspective and pragmatic epistemology. An abduction approach within a pragmatic epistemology was followed, which allowed a flexible iterative theory building and testing process. These principles served the action-based research approach which has been adopted in this thesis. The corresponding data collection and analysis methods were described: an exploratory case study, interviews, testing workshops and questionnaires were designed along with research phases to meet the set objectives.

In order to satisfy objective 4, to build up a model and framework for providing a BIM integrated sustainability assessment, which was selected to be EC within LCA, a VPL model and framework was presented in Chapter 6. This chapter presented the details and steps taken to develop the framework and how the user can utilise the proposed model. Comprehensive description was provided of the Dynamo scripts built to automate the LCA process and build the model.

Finally, chapter 7 contributed significantly to developing an understanding of the architect's perspective in adopting the proposed dynamic approach for automating EC calculation. The method chosen to test usability of the proposed model was also used as a validation method.

8.3 Contribution to knowledge

The novelty of this work can be found in its contribution to theoretical knowledge for enhancing sustainability integrated in BIM workflow. This research argued that one of the most significant challenges in delivering a successful sustainable building is the lack of technological incorporation between sustainable design decisions and BIM workflow. In order to pursue the aim of this research, a comprehensive literature review combined with empirical evidence of an exploratory case study together revealed that sustainable design processes still suffer from the lack of dynamic workflow. A gap in the literature was found in utilising digital technology to serve iterative and automated processes of sustainability assessment, considering its usability and adoption. Accordingly, the first contribution of the thesis was achieved by interrogating existing literature and presenting a novel analysis map which highlighted the limitations and successes between BIM and sustainability practices.

Consequently, a Dynamo-based model was developed to automate the LCA process, which was found to be lacking for UK context. This is considered to be a practical contribution for the industry, with great potential impact for transforming the integration of LCA in the design workflow. The model and framework developed will be of interest to practitioners (architects and structure engineers) and will assist in automating the assessment of embodied carbon in their designs. In practice, it is believed that adoption of such models is especially important in the light of compulsory new legislation and motivational climate challenges and benchmarks that need to be achieved.

Although previous VPL Dynamo models have been developed to automate LCA, a unique approach has been taken to automate all of the preparation and calculation processes. A methodological contribution is presented in the framework in providing the ability for practitioners to create a flexible, expendable LCI library that can mix different sources of LCI databases and keep calculations consistent. The major contribution of the research is the theoretical novel role of the correction factor proposed in the model to increase the accuracy of LCA calculation using low detailed BIM model which usually exist in early design stage. This contribution may influence the developers of future database by providing a methodology to add correction factor calculated figures that is suitable for BIM model LOD along with the material EC coefficient value.

The final contribution is the detailed understanding of usability from the perspective of the architects who provided a comprehensive insight into the aspects affecting the adoption of VPL-based frameworks in the industry. The outcome from the usability study had a significant practical implications that directs the future work for both practise and theory .This part of the research acted as validation and evaluation of the tool, and the findings of the validation also have significant implications regarding the perceptions and expectations of practitioners towards the features required in technological solutions in the industry.

8.4 Limitations

Various limitations were identified during the course of study that should be acknowledged. The major limitation of this study was the scope of the study, which developed only a VPL-enabled model for LCA. It was determined from the exploratory case study and findings from the literature review that in practice, operational energy, daylighting and LCA are optimised together. Hence it was recommended to develop a model that allowed multi-optimisation dynamic ability for practitioners. However, unfortunately, due to the technical limitations explored in chapter 4, the scope was set only for LCA.

The second limitation appeared due to the constraint of conducting the validation workshops online. Despite the wide range of experience included in the workshop validation phase, it is unfortunate that the study did not conduct the workshops physically with the participants. The limitations of the pandemic situation along with the time restrictions made face-to-face testing impossible, therefore the findings from the usability testing were not completed. In addition, the time constraints of the research did not allow an opportunity to test the model and framework on a real life project. Since the study was limited to validating usability through online workshops, it was not possible to provide detailed insights regarding skills aspects and learnability of the system, as mentioned in the summary of chapter 7.

Another constrain appeared in utilizing and selecting suitable database that can be used in the model, as current available database (ICE database and EPDs) do not cover all building materials, as well as benchmarks. Currently, different parties (BRE, RICS,RIBA,carbon trust, ICE, and others) are collaborating to develop the Built Environment Carbon Database (BECD) for the UK. The database is expected fill this gap and become the major source of carbon estimation and benchmarking for the UK construction industry, as well as a useful tool to aid in the decarbonization of the built environment.

8.5 Recommendations for future work

The findings of this study have a number of important implications for future sustainable architecture practice. The theoretical and practical contribution presented in this thesis should be the basis for further research in various areas. These different areas can be applied in different perspectives that serve the adoption of such systems in industry. The next section will discuss these areas of potential future work.

8.5.1 Additional testing

Firstly, analysis of the testing in chapter 7 has revealed a limitation in terms of drawing conclusions regarding the learnability and memorability of the tool. Further testing is required, with other methods suggested for assessing usability, such as usability lab studies or an ethnographic field study. These methods will allow reporting of the behavioural attitudes of users to enable evaluation of their learnability and ease of memorability of the system. These different methods of testing will provide different insights into system use, such as ability to deal with errors, modification and expansion of the system. Also, the proposed model needs to be investigated on different real case studies to test the capability of the tool to deal with large scale projects with more complex geometry.

Also, the output of future testing can provide a specific set of criteria required in any VPL tool to increase its' adoption in AEC industry. This could be a theoretical direction for future investigation that could directly lead to practical implications.

8.5.2 Optimisation capabilities

The proposed design of the model providing the required functions were encountered with the agreement of the industry practitioners (architects) during usability testing, but other recommendations were also suggested for additional capabilities. One potential capability that requires further investigation and development is increased functionality of the optimisation option. This includes adding more visual (colour coded) elements to results shown in the model to enable easier comparison between the design and the benchmarks. Colour visualisation is possible using Dynamo and can be developed as a script, but the data on comparable benchmarks on an element level is still lacking and needs more development. Included in the latest version of One Click LCA is a rating for each material – a sustainability meter - which indicates its EC level in comparison to other materials in the same category. This capability was reported by users as important; however, it would require a publicly available database that contains this information in order to be able to utilise it in future modifications of the model.

8.5.3 Develop easier interface for users

On technological side, in the usability testing presented in chapter 7, the majority of users suggested there was a need to develop an easier graphical user interface than Dynamo player. Suggestions included the ability to control other functionalities in the model. Examples of these functionalities are inclusion and exclusion of categories in the calculation, and a guide to assist users through the steps of the assessment, in addition to filter, search and provision of alternative suggestions. Other than the design of the interface, future research may include the data required to provide the user with sufficient suggestions and recommendation for better alternative for the material selected.

8.5.4 Expanded LCA indicators and system boundary

Regarding the expansion of the model, there is potential to achieve whole LCA integration including whole life cycle of the materials (expanded system boundary) by developing a database that is publicly accessible. Also, the findings from usability testing highlighted the importance of including other indications along with embodied carbon, such as embodied energy, for use in the UK. On a technical basis, these coefficient database developments will allow expansion of the model. In addition, a multi-levelled database, such as the approach implemented in the Swiss database discussed in chapter 6, needs to be developed for the UK in order to enhance dealing with the LCA in different BIM levels of development (LOI & LOD).

Unified code and naming conversion for materials are required for integrating the developed database with standard naming and labelling convention such as Uniclass developed by NBS.

8.5.5 Development of different database suitable for various LOD

As mentioned before there is a shortage in EC database and benchmarks in UK. So, development of material database on building element level with different benchmarks, is a major area of development for future work. Also, correction factor as conceptual idea proposed in this study can be extended by future researchers to provide architects with default values that can be used to increase the accuracy of LCA calculation.

8.5.6 Education and skills for architects and AEC practitioners

A theoretical direction for future work is the investigation of the influence of the change required in the education and skills of the architects. Several previous studies have discussed the role of changes in the education and skills provided to architects with regard to both digitisation and the delivery of sustainable buildings. In this study an unexpected finding reinforced the same argument. In the validation phase, responses revealed the importance of this aspect to the participants. Participants reported that this tool can potentially act as an education tool for the industry. This raises interesting questions regarding the effect of use of the automating tools developed with regard to educating architects in issues relating to low carbon buildings. To assist in answering these questions, future research is needed to investigate:

- How can changes in education of building practitioners (architects) enhance the design process for sustainable buildings?
- What new sets of skills and roles do architects have/need?

8.5.7 Developing VPL model for operational and daylighting

The original outcome from the exploratory case study and literature review, presented in chapters 2 and 3, was that a multi-optimisation model needs to be developed to allow architects to take sustainable performance-based decision. For optimisation of design decisions, a dynamic model needs to be developed for operation and daylighting as well at an early stage; and concurrently with their other ongoing design decisions . A reasonable approach to tackle this issue would be to develop a VPL model in a BIM authoring tool, by exploring Rhino.inside

Revit platform. This conclusion is made because Grasshopper is more highly developed for simulating operational energy and daylighting using VPL. The packages developed in Grasshopper can be investigated for Revit using Rhino.inside Revit. If a multi- optimisation VPL model is achieved, research can take place to further investigate the use of such models on the decision-making process in a real case study project.

8.6 List of publications

During the time period of this research the author has published the list of publications shown below. Abstracts and further details on the publications can be found in Appendix 8.

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Appendices

Appendix 1 - Case study interviews and example of coded interview

1. BREEAM Assessor

Part 1: Project circumstances and effect of team dynamics

The internal and external factors affected the project process, team dynamics and procurement divided by stage. (Team and client awareness, Contractual agreement effect, team prior experience with sustainable projects, BREEAM experience-client orientation and perspective).

1. How do the client orientation and perspective towards sustainability affect the project delivery?

2. Do the reason of green certification targeting mentioned by the client in the beginning of the project affect the project team interaction and vision towards BREEAM assessment? How?

3. For the case study project :
   What was the reason behind the client request for BREEAM certification?
   Did you have a previous experience of working with the project team?
   How do you evaluate their prior experience in delivering sustainable buildings?
   Do you find any project circumstances factor that you want to add that affects the project delivery?

Part 2: Problems in project delivery and lessons learnt

Early stage discussion

1. How were the sustainability aspirations discussed and translated into the development of: initial project brief, Quality objectives, and feasibility studies?
2. Who is responsible for doing these sustainability assessments?
3. How targets were set? Was they detailed enough? Do you have suggestions to improve the way the team is dealing with targets?
4. What were the points/topics that were discussed in the early meeting that you think is a great value for early collaboration?
5. What are the points/topics that were missed and discovered later that are considered loss to the project?

For the case study It is observed that the change in energy credits, 6 points lost through tracker files. Can you remember the reasons of variation that caused loss of points in energy category?

Part: technical

1. What are problems do you find in workflow, process, and data exchange?

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2. Do the responsibilities of providing evidence documents differs and generally ownership of BREEAM assessment differs from one project to another?

3. Do you deal with any models that the Architect or M&E do to give feedback or comments on the design or you just deal with reports, 2d drawings and specs?

4. Do they have intermediate checks before designing the whole detailed building?
5. What are the categories and credit that have high effect on the design decisions along all stages?
   Are their design decisions that really affects the sustainability?
6. What are the critical decision points that are cost effective if considered documented and streamed from the early stages of a project?
7. In what format do you exchange building information with other stakeholders?
8. Are you usually responsible for energy simulation and building performance calculations?
9. If yes, do you use building models developed by Architects, MEP?
10. Do you have an input in ensuring that specifications of the projects and detailed enough to deliver the BREEAM requirements?
11. Do you have technical problems or requirements?
12. Do you have any other lessons learnt and problems you want to share that you would like to develop collaboration in future projects?

2. <u>Lead Architect: Design Responsibilities</u>

Part 1

Understand the project circumstances and team dynamics from lead architect point of view.
Project process, team dynamics and procurement. (Team and client awareness, Contractual agreement effect, team prior experience with sustainable projects, BREEAM experience- client orientation and perspective towards sustainability)

Part 2

The generation and the development of the design with respect to sustainability aspects and BREEAM process.

(Setting sustainability targets, Decision timing, building performance based design, BREEAM categories and credits that have high impact on design, data exchange (graphical and non-graphical) between other team members and, process and workflow efficiency, communication , quantitative and qualitative analysis, dealing with BREEAM requirements documentation)

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Part 3

Potential of BIM and sustainability integration to serve the design development: Initial investigation on the areas of BIM contribution to develop green project delivery.

1. Representation :externalize ideas through visualization
2. Decision support: analysis, simulation…
3. Transaction / exchange: ease and support communication and collaboration, minimize data leakage between stages and between stakeholders.
4. Documentation, object based specification using classification and data extract : Intelligent, consistent, easily access history and archive (can be used for information and knowledge management as asset for future projects)
5. Automation: Plug in on models to be able to calculate credits, model checking verify/validate that certain information are there, compliance checker.
6. Standardization and common guide: building process and object libraries

Prioritize the importance of them from Architect point of view to increase the project delivery efficiency, investigate challenges and areas of development in order to reach successful integration.

3. Architect: Execution Responsibilities

Part 1

Understand the project circumstances and team dynamics from execution architect point of view.
Project process, team dynamics and procurement. (Team and client awareness, Contractual agreement effect, team prior experience with sustainable projects, BREEAM experience-client orientation and perspective towards sustainability, communication and coordination)

Part 2

Explore the current BIM implantation within the projects between project teams and specifically in sill project. And investigate better strategies for collaboration. (Problems, potentials and challenges)

1. Role of BIM model and information extract from conceptual stage until the as built.
2. Problems in Information leakage and loss of data.
3. Better strategies for collaboration and exchange of data through model sharing.
4. Missing attributes and parameters to serve/cover the sustainability aspects.
5. M &E, structure and architecture model interaction: informing and support design decisions, design model coordination, eliminating extra work,
6. Potentials and challenges in intelligent specification through NBS create according to uniclass and ways of development: (Shortage in object libraries, Manufactures and suppliers of green materials specification.

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7. Extra work/ documentation for BREEAM and potentials to include it within BIM model. Was the information in the model sufficient to delivery BREEAM requirements?

Part 3

The current use of the listed capabilities of BIM, importance of each for the project, ways of development in order to maximize the benefit and use of them.

Rating Applicability, Importance, relevance to sustainability and BIM integration of the potentials listed before in the other 2 interview structures.

<u>Example of thematically codded interview</u>

Dynamic and iterative design decisions and sustainability targets: Energy, Materials, (thermal and visual comfort)

The use of technology in the project:

"I worked with it right from the start from the completion design. both from demonstrating the design concept through to analysing how sun path patterns might work on it how the thermal model might work on it through to that coordination of M&E and structural and making sure it's all designed as efficiently as possible through to getting the calculations and quantities of the likes of the breeam carbs that's amazing tool to have."

Architects:

"We depend on our previous experience and knowledge to design high performance fabric, we model it on Revit and then give the model to the M&E in order to do the analysis and design of building systems but they use different modelling and simulation software. Afterwards, the decisions are made with them according to the accurate simulation results. "

Documentation and intelligent specification

"Best intentions when people are busy I think sometimes the works done but it's just the **compiling of the information content take time**. Yeah, absolutely and then BREEAM assessor do a great job to flag these things and try to keep trying to remind people and how people you know, and I think you know the likes of seal have quite useful tools of standard checklist and forms, which all help too. To get the information together because BREEAM have to have things presented in very specific ways. And I think the BIM helps of example the **MAT points,** you know, in terms of all the materials technical, you know, the technical justifications. Matt was able to pull off all Code and things like that quite in and you know easily of BIM so just really help with that side of Information"

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Representation

Architect and client

*I suppose it'd be more in terms of sustainability. I mean, it's you it's useful as **a graphic tool** just to demonstrate what the building looks like in three dimensions and being able to rotate it and cut section through as a way you want. And use it as a method of but the other thing that's quite useful as you can you can plot on **the sun at various points of the day and time of year and you can demonstrate how the sun's going to be hitting into the building now**, it's going to work around, you know, so that kind of solar influence.*

"I think it's pretty useful. I think we did a few sort of solar paths or. Illustrations to demonstrate. Yeah, these solar canopies are going to work in this location here. Are you going to lose some issues about what this elevation have some glare on it and we were able to demonstrate were actually but shape coming in across here.So very useful for this demonstrates the clients on those sides of things."

" I mean, I think there's different. Criteria and strategies that clients can set I think a lot of them say they want zero carbon, but they don't really fully understand what that is or the implications of what that is. And so I do think the Breeam until is really useful because it does set **very clear standards** and it gives you a **benchmarks** that you know to go against."

Transaction and exchange

Architect and M&E

" this causing difficulties with Engineers as well in the absolutely like further into the process of you know, Coordinating the services and the most efficient sort of roots and looking at the kind of buildup **in U values sorts of things** so in yeah, just the fact that you can integrate. The m&e models from the architectural model and discover if there's any inefficiencies, you know or crashes. "

Architect and contractor

"BIM model was really helpful for them to sort of understand the **building in 3D**, but that collaborative process of do the two-stage tender of working with them and for them being able to input into that model.

So things like the atrium design for example, which is **quite a complex**. **Is sloping in three different dimensions**, you know for them to be able to really interrogate the buildability aspect of us and for us to have that opportunity to do that with them through a **two-stage tender process** that it wasn't a fait accompli, they could help they could influence the design, we could use the BIM model to the system.

BIM model allowed early collaboration and input from contactor through two-stage contract

So if it's the atrium is a good example of money we had because we value engineering exercise. So looking at serving money. We were able to still keep the basic overall shape of the action

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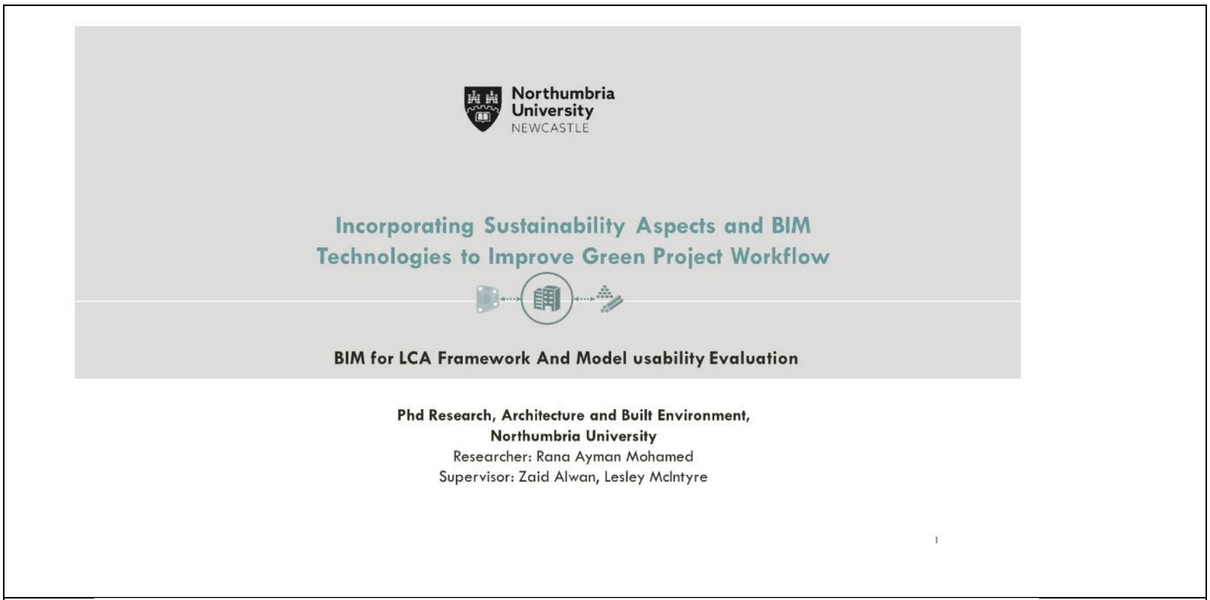
but standardize the panel sizes for example, and that helped with their input and their subcontractors input quite an early stage, you know.

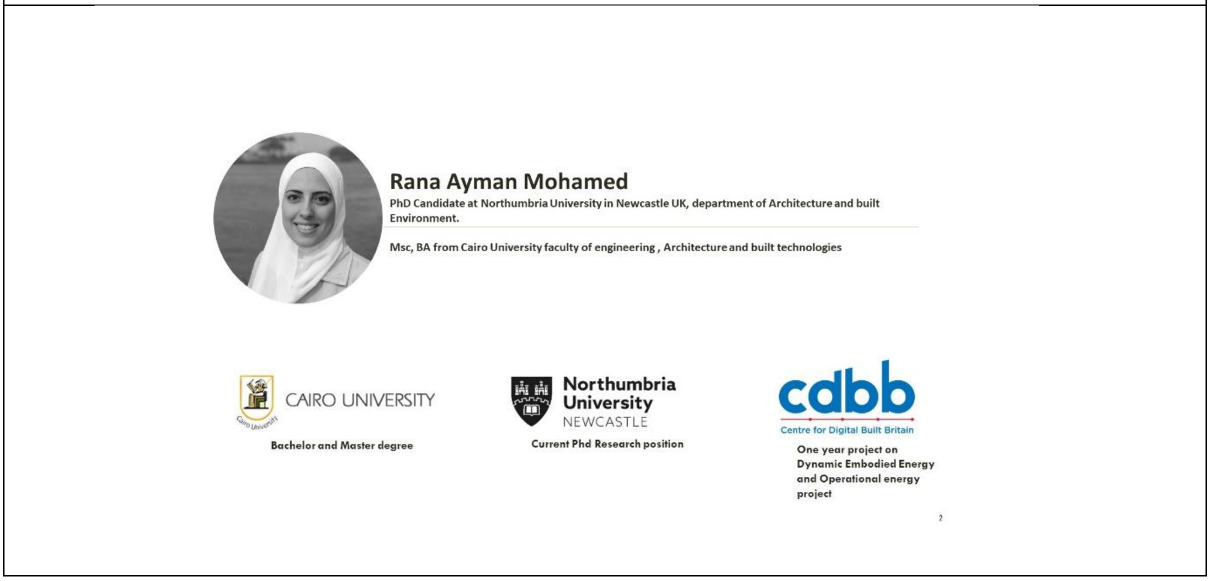
Rather than it being too far down the line and it gave us an opportunity to bridge to be built into the **production information** rather than having to do everything twice.

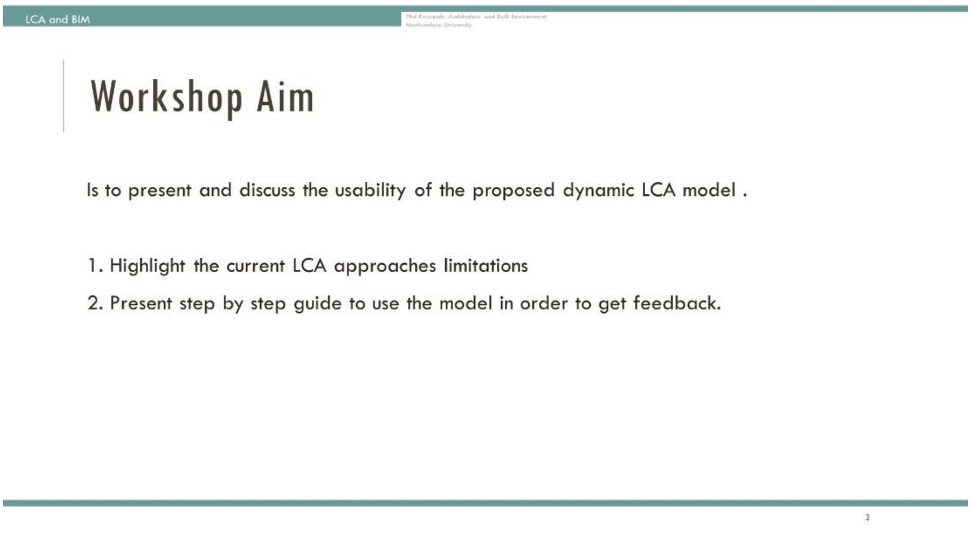
BIM allowed to generate, exchange and have feedback with more detailed information at early stage

" I think what ends up happening with BIM as you put you end up inevitably putting way more detailed information in at an earlier stage than you would have done traditionally with two-dimensional drawings, you know, so the level of information we had in on the planning drawings was Way Beyond what you would have normally done for a planning application years ago."

Appendix 2 - Workshop presentation







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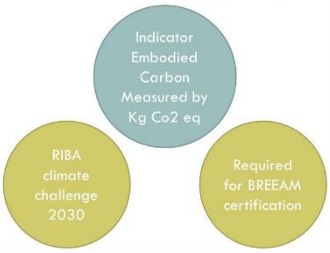
Presentation outline

1. Research brief and significance
2. LCA Approaches and challenges
3. Proposed model Roadmap and outline
4. Guideline steps for model use.
5. Feedback, discussion, questionnaire.

What is Life cycle assessment ?

"Life cycle assessment is a cradle-to-grave or cradle-to-cradle analysis technique to assess **environmental impacts** associated with all the stages of **a product's life**, which is from raw material extraction through materials processing, manufacture, distribution, and use."

(Iyyanki V. Muralikrishna, Valli Manickam, in Environmental Management, 2017)



85%-90% of total embodied carbon

Product / Manufacture Stage [A1-A3]			Construction Process Stage [A4-A5]		Use [B1-B7]							End-of-Life Stage [C1-C4]				Benefits & Loads Beyond [D]
					Building Fabric					Operation of the Building						
Raw Material Extract / Process / Supply	Transport	Manufacture	Transport to the Site	Assembly / Install in the building	Use / Application of Installed Products	Maintenance	Repair	Replacement	Refurbishment	Operational Energy Use	Operational Water Use	Deconstruction / Demolition	Transport to Waste Process	Reuse-Recovery-Recycle	Disposal	Reuse-Recovery-Recycle Potential
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
Cradle-to-Gate			Gate-to-Grave													
Cradle-to-Grave																
Cradle-to-Cradle																
System Boundaries																

Embodied energy and carbon Analysis:

Evaluation of the selection of material
according to the impact of the material on environment (LCA)

Approach 1:	SimaPro, GaBi Database Content
Approach 2:	eTool, Athena Impact Estimator for Buildings
Approach 3:	One Click LCA, tally

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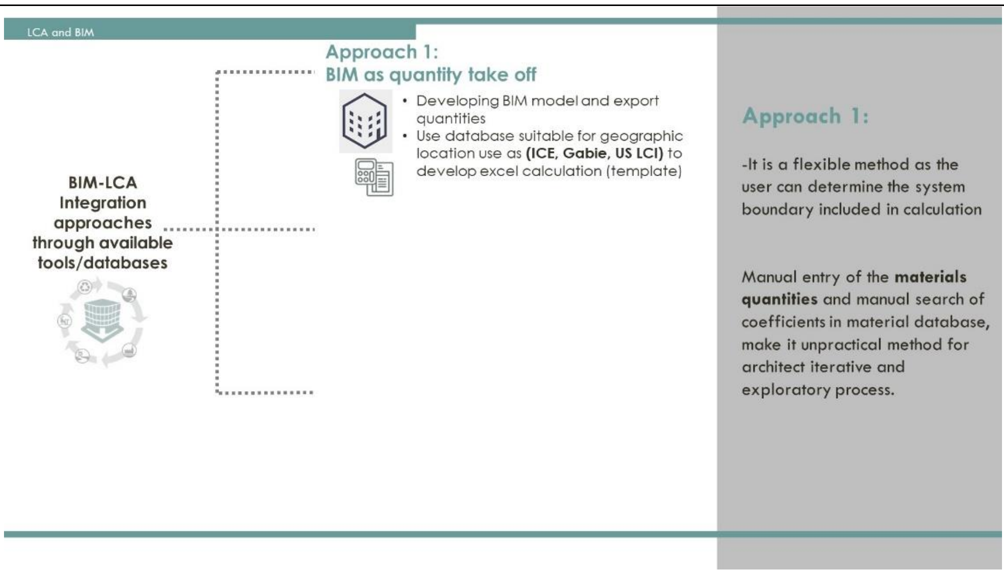
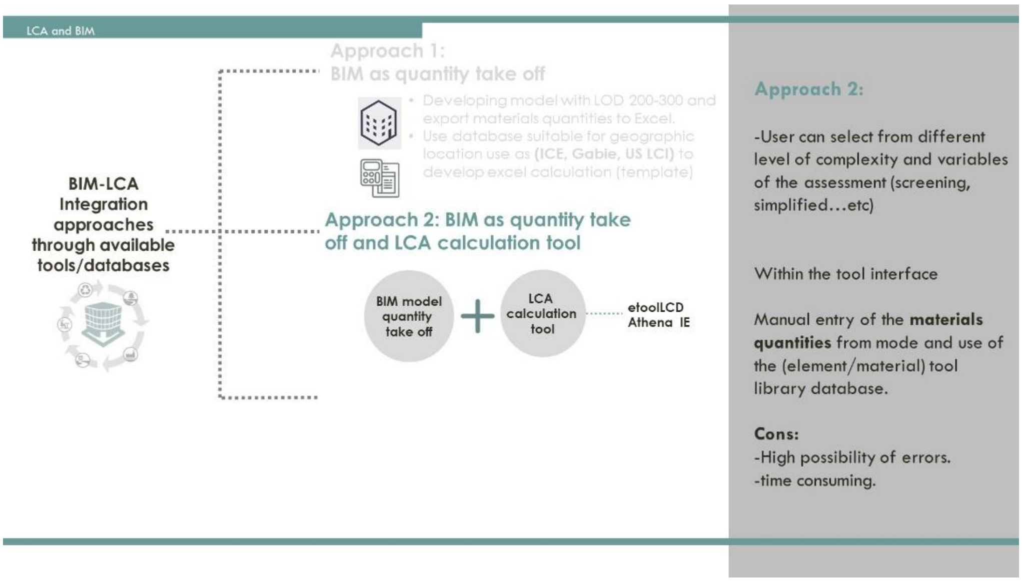
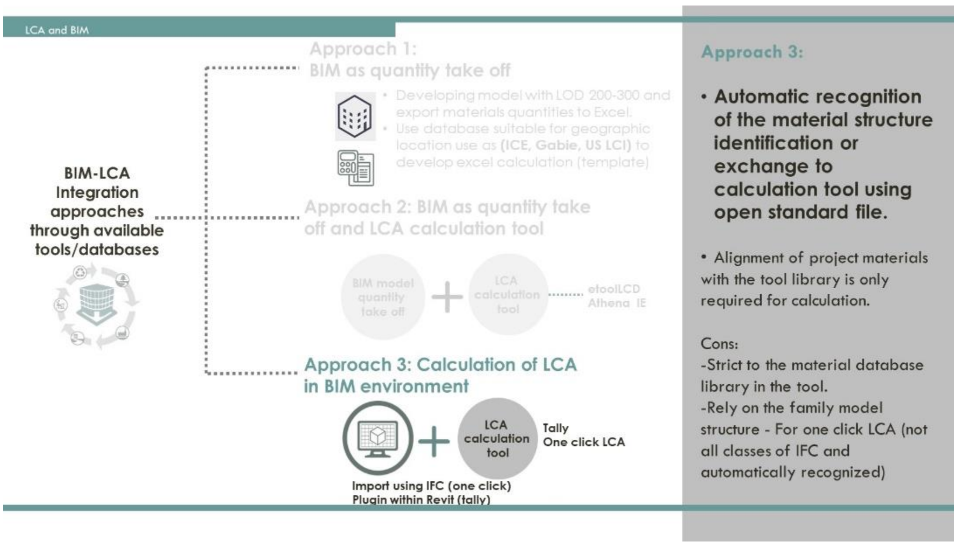

LCA and BIM
Approach 1:
BIM as quantity take off
• Developing BIM model and export quantities
• Use database suitable for geographic location use as (ICE, Gabie, US LCI) to develop excel calculation (template)
BIM-LCA Integration approaches through available tools/databases
Approach 1:
-It is a flexible method as the user can determine the system boundary included in calculation
Manual entry of the materials quantities and manual search of coefficients in material database, make it unpractical method for architect iterative and exploratory process.


LCA and BIM
Approach 1:
BIM as quantity take off
• Developing model with LOD 200-300 and export materials quantities to Excel.
• Use database suitable for geographic location use as (ICE, Gabie, US LCI) to develop excel calculation (template)
BIM-LCA Integration approaches through available tools/databases
Approach 2: BIM as quantity take off and LCA calculation tool
BIM model quantity take off
LCA calculation tool
etoolLCD
Athena IE
Approach 2:
-User can select from different level of complexity and variables of the assessment (screening, simplified…etc)
Within the tool interface
Manual entry of the materials quantities from mode and use of the (element/material) tool library database.
Cons:
-High possibility of errors.
-time consuming.

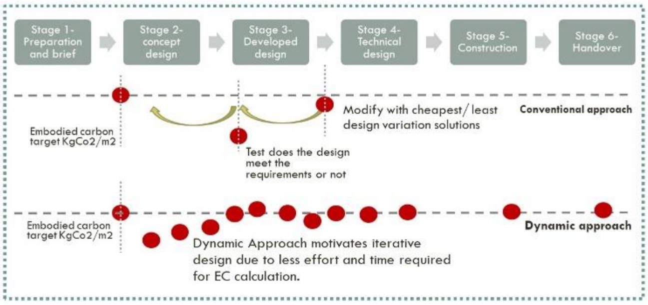

LCA and BIM
Approach 1:
BIM as quantity take off
• Developing model with LOD 200-300 and export materials quantities to Excel.
• Use database suitable for geographic location use as (ICE, Gabie, US LCI) to develop excel calculation (template)
BIM-LCA Integration approaches through available tools/databases
Approach 2: BIM as quantity take off and LCA calculation tool
BIM model quantity take off
LCA calculation tool
etoolLCD
Athena IE
Approach 3: Calculation of LCA in BIM environment
LCA calculation tool
Tally
One click LCA
Import using IFC (one click)
Plugin within Revit (tally)
Approach 3:
• Automatic recognition of the material structure identification or exchange to calculation tool using open standard file.
• Alignment of project materials with the tool library is only required for calculation.
Cons:
-Strict to the material database library in the tool.
-Rely on the family model structure - For one click LCA (not all classes of IFC and automatically recognized)

LCA and BIM

Summary of challenges

Challenges of conducting Multiple LCA analysis acts as a barrier to iterative design for Embodied carbon optimization.

1. Any update to quantities of a material must be re-entered manually (complex and time consuming).
2. Calculated output is no longer in BIM environment.
3. Increased possibility of errors due to multiple manual entries.
4. Shortage of Material Library in tools.



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LCA and BIM

Aims of Developing a Dynamic BIM for LCA tool

1. **Real-Time LCA**
2. **Time efficient process (eliminate manual work)**
3. **Minimize manual entry to eliminate LCA mistakes**
4. **Affordability and flexibility**
5. **Ease of use.**
6. **Use within BIM environment (same designer interface)**
7. **Support decision making (visualization, different detailing of output, benchmarking)**
8. **Possibility to Reuse and expand the library in multiple projects**
9. **Adding more LCA indicators in future with same concept if required in the same system.**

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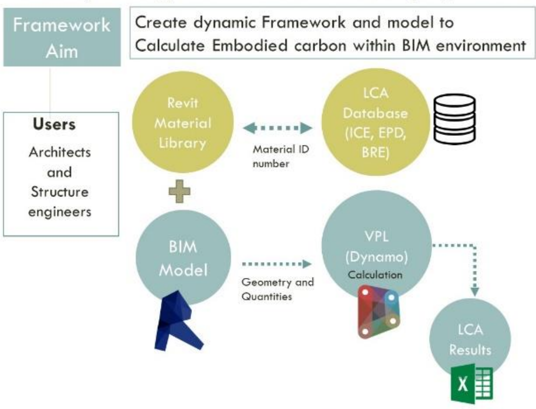
LCA and BIM

Usability testing and Evaluation of the proposed Framework and model



Functionality

1. Create Adequate **BIM Material library** for Embodied carbon Reusable, flexible, suitable for LOD in each stage

2. **Automatic calculation and eliminate multiple manual mapping,** which allow iterative assessments within design

3. **Visualize and benchmark results** to inform decision making.

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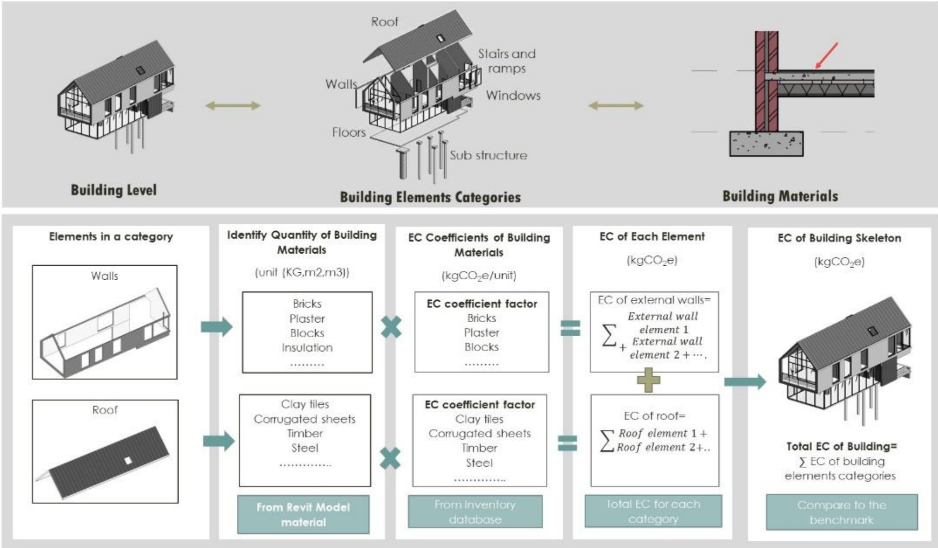
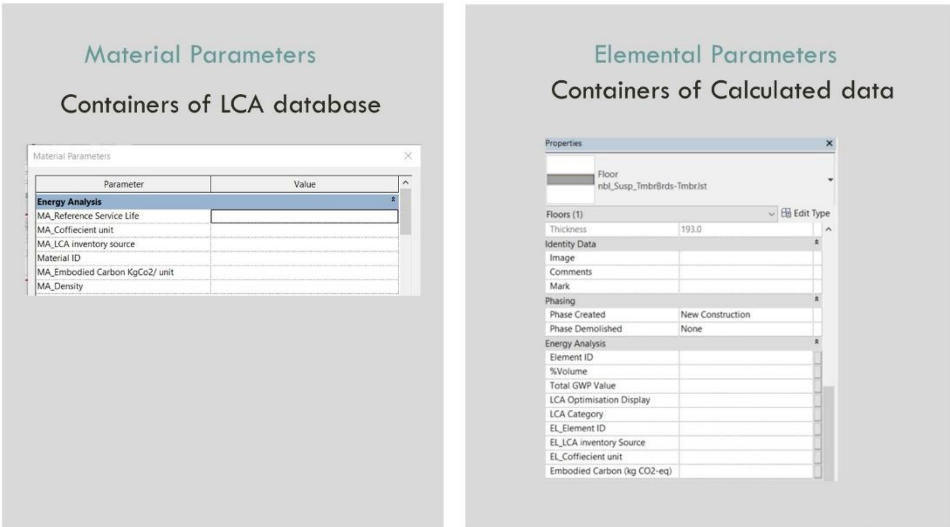
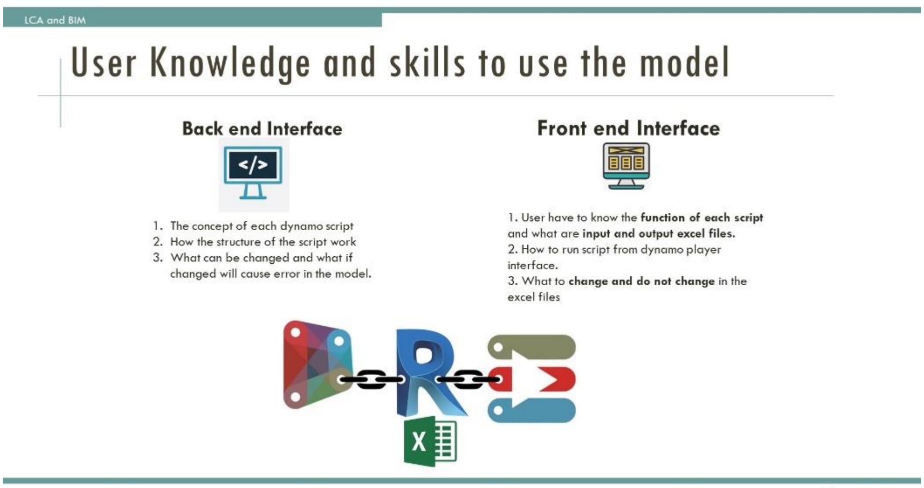


Roof
Stairs and ramps
Walls
Windows
Floors
Sub structure
Building Level
Building Elements Categories
Building Materials
Elements in a category
Walls
Roof
Identify Quantity of Building Materials
(unit (KG,m2,m3))
Bricks
Plaster
Blocks
Insulation
Clay tiles
Corrugated sheets
Timber
Steel
From Revit Model material
EC Coefficients of Building Materials
(kgCO2e/unit)
EC coefficient factor
Bricks
Plaster
Blocks
EC coefficient factor
Clay tiles
Corrugated sheets
Timber
Steel
From Inventory database
EC of Each Element
(kgCO2e)
EC of external walls=
EC of roof=
Total EC for each category
EC of Building Skeleton
(kgCO2e)
Total EC of Building=
∑ EC of building elements categories
Compare to the benchmark



Material Parameters
Containers of LCA database
Parameter
Value
Energy Analysis
MA_Reference Service Life
MA_Coffiecient unit
MA_LCA inventory source
Material ID
MA_Embodied Carbon KgCo2/ unit
MA_Density
Elemental Parameters
Containers of Calculated data
Properties
Floor
nbl_Susp_TmbrBrds-TmbrJst
Floors (1)
Edit Type
Thickness
193.0
Identity Data
Image
Comments
Mark
Phasing
Phase Created
New Construction
Phase Demolished
None
Energy Analysis
Element ID
%Volume
Total GWP Value
LCA Optimisation Display
LCA Category
EL_Element ID
EL_LCA inventory Source
EL_Coffiecient unit
Embodied Carbon (kg CO2-eq)



LCA and BIM
User Knowledge and skills to use the model
Back end Interface
1. The concept of each dynamo script
2. How the structure of the script work
3. What can be changed and what if changed will cause error in the model.
Front end Interface
1. User have to know the function of each script and what are input and output excel files.
2. How to run script from dynamo player interface.
3. What to change and do not change in the excel files

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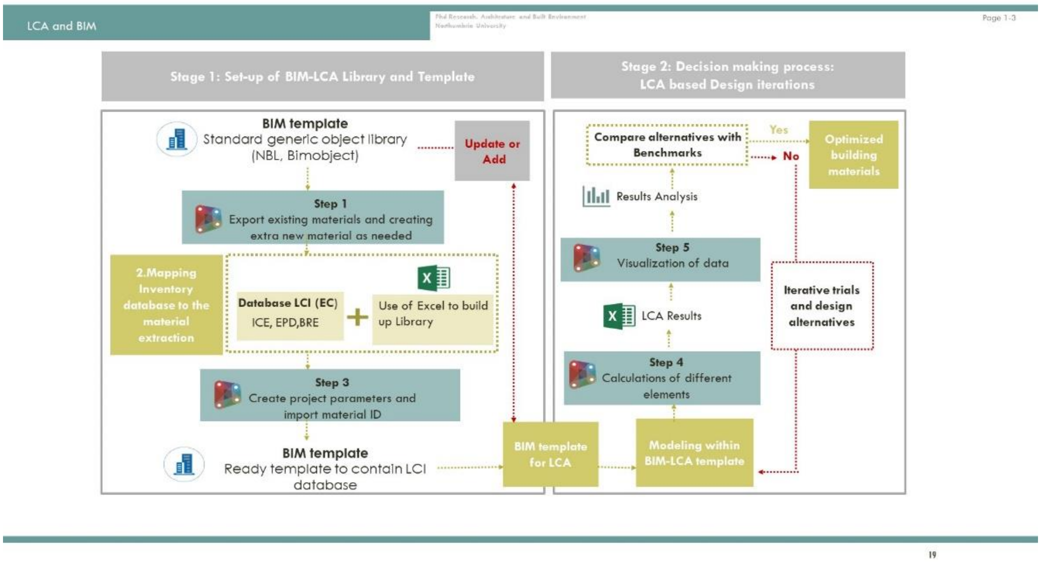

Stage	Script	Function	User Input	Output
Stage 1 –Create template with Library	**Script 1-Create Project Material**	Automatic creation of Materials from Excel sheet to eliminate manual creation.	Excel sheet with input Material name	Material creation in Revit library
	Script 2- Export All materials	Export all Materials in Revit Library	Excel sheet output file path.	Excel sheet with all Materials name and Revit IDS
	Manual mapping of Material ID on Excel			
	Script 3- Create project parameters	Create the required global, elemental and material parameters which are containers to database and calculations.	No input	Project parameters created in template file
	Script 4- Import Material ID and Information in standard file family	Read from standard inventory and write back in Revit material parameters.	Standard database excel file path	Standard file Inventory database and Material IDs imported to Material library
Stage 2.1 Calculation and Analysis	**Script 5- Walls**	Analysis and calculation of different element categories Through reading database from Excel standard file and filtering materials with coefficients m2,Kg,m3 then applying suitable equation accordingly.	Standard database excel file path	Writing back to elemental parameters the calculated values (% volume- embodied carbon- optimization LCA category)
	Script 6- Envelope			
	Script 7- Floors			
	Script 8- Interior			
	Script 9- Doors			
	Script 10- Structure			

Stage	Script	Function	User Input	Output
Stage 2.2 Representation	**Script 11- Report total EC per category**	Collect all calculated EC for each element and apply summation to present the data EC per category	File path for total EC per category excel sheet	**Excel sheet with EC values per category and bar chart.**
	Script 12-Report Detailed EC per Element	Present detailed calculated EC to examine and highlight the high EC contributors and act as check on the model calculations and missing elements.	File path for Detailed EC excel sheet	**Excel sheet with EC values per category and bar chart.**
	Script 13- LCA benchmarking	Compare the total EC/ gross floor area to Benchmark	File path for LCA benchmark excel file	**Excel sheet with design total EC per gross floor area benchmark comparison.**

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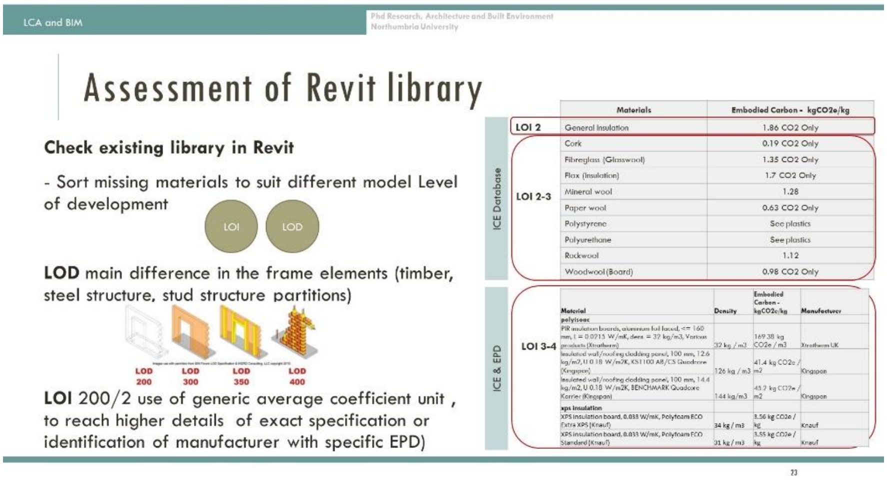
LCA and BIM
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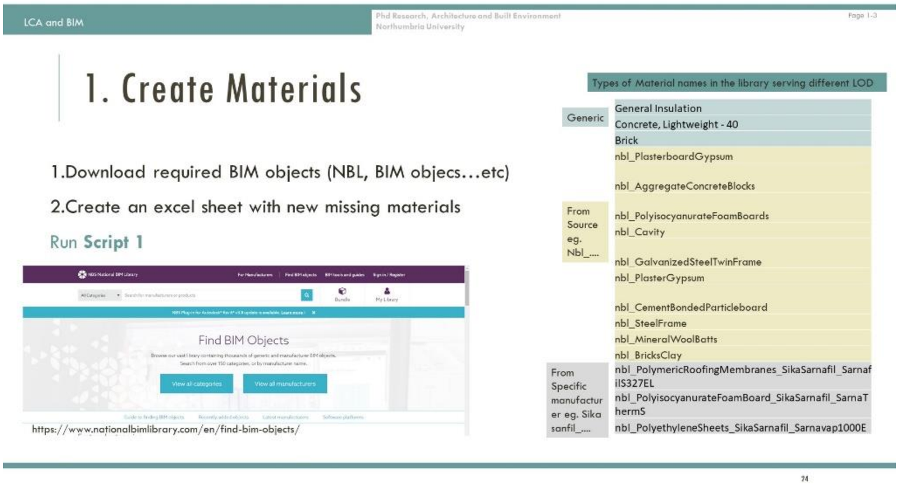
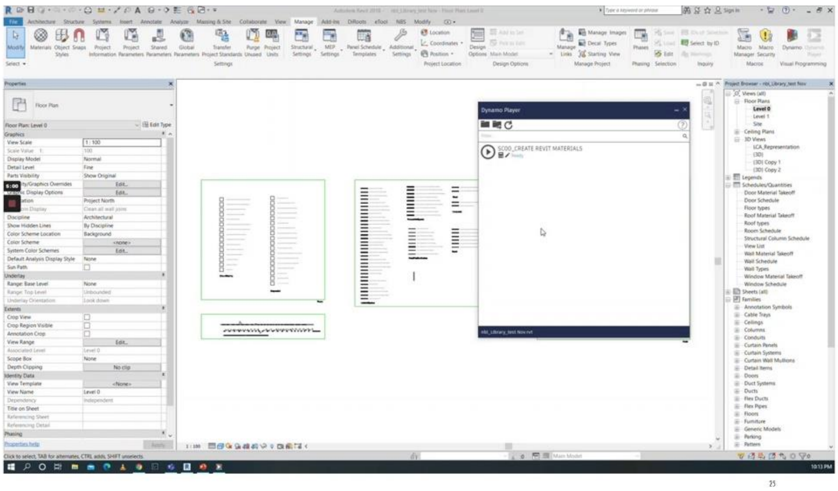
Northumbria University
Assessment of Revit library
Check existing library in Revit
- Sort missing materials to suit different model Level of development
LOI
LOD
LOD main difference in the frame elements (timber, steel structure, stud structure partitions)
LOD 200
LOD 300
LOD 350
LOD 400
LOI 200/2 use of generic average coefficient unit , to reach higher details of exact specification or identification of manufacturer with specific EPD)
ICE Database
Materials | Embodied Carbon - kgCO2e/kg
LOI 2
General Insulation | 1.86 CO2 Only
LOI 2-3
Cork | 0.19 CO2 Only
Fibreglass (Glasswool) | 1.35 CO2 Only
Flax (Insulation) | 1.7 CO2 Only
Mineral wool | 1.28
Paper wool | 0.63 CO2 Only
Polystyrene | See plastics
Polyurethane | See plastics
Rockwool | 1.12
Woodwool (Board) | 0.98 CO2 Only
ICE & EPD
LOI 3-4
Material | Density | Embodied Carbon - kgCO2e/kg | Manufacturer
polyisoc
PIR insulation boards, aluminium foil faced, <= 160 mm, l = 0.0215 W/mK, dens = 32 kg/m3, Various products (Xtratherm) | 32 kg / m3 | 169.38 kg CO2e / m3 | Xtratherm UK
Insulated wall/roofing cladding panel, 100 mm, 12.6 kg/m2, U 0.18 W/m2K, KS1100 AB/CS Quadcore (Kingspan) | 126 kg / m3 | 41.4 kg CO2e / m2 | Kingspan
Insulated wall/roofing cladding panel, 100 mm, 14.4 kg/m2, U 0.18 W/m2K, BENCHMARK Quadcore Karrier (Kingspan) | 144 kg/m3 | 43.2 kg CO2e / m2 | Kingspan
xps insulation
XPS insulation board, 0.033 W/mK, Polyfoam ECO Extra XPS (Knauf) | 34 kg / m3 | 3.56 kg CO2e / kg | Knauf
XPS insulation board, 0.033 W/mK, Polyfoam ECO Standard (Knauf) | 31 kg / m3 | 3.55 kg CO2e / kg | Knauf
23


LCA and BIM
Phd Research, Architecture and Built Environment
Northumbria University
Page 1-3
1. Create Materials
1.Download required BIM objects (NBL, BIM objecs…etc)
2.Create an excel sheet with new missing materials
Run Script 1
Find BIM Objects
View all categories
View all manufacturers
https://www.nationalbimlibrary.com/en/find-bim-objects/
Types of Material names in the library serving different LOD
Generic
General Insulation
Concrete, Lightweight - 40
Brick
From Source eg. Nbl_....
nbl_PlasterboardGypsum
nbl_AggregateConcreteBlocks
nbl_PolyisocyanurateFoamBoards
nbl_Cavity
nbl_GalvanizedSteelTwinFrame
nbl_PlasterGypsum
nbl_CementBondedParticleboard
nbl_SteelFrame
nbl_MineralWoolBatts
nbl_BricksClay
From Specific manufacturer eg. Sika sanfil_....
nbl_PolymericRoofingMembranes_SikaSarnafil_SarnafilS327EL
nbl_PolyisocyanurateFoamBoard_SikaSarnafil_SarnaThermS
nbl_PolyethyleneSheets_SikaSarnafil_Sarnavap1000E
24


Dynamo Player
SC00_CREATE REVIT MATERIALS
25

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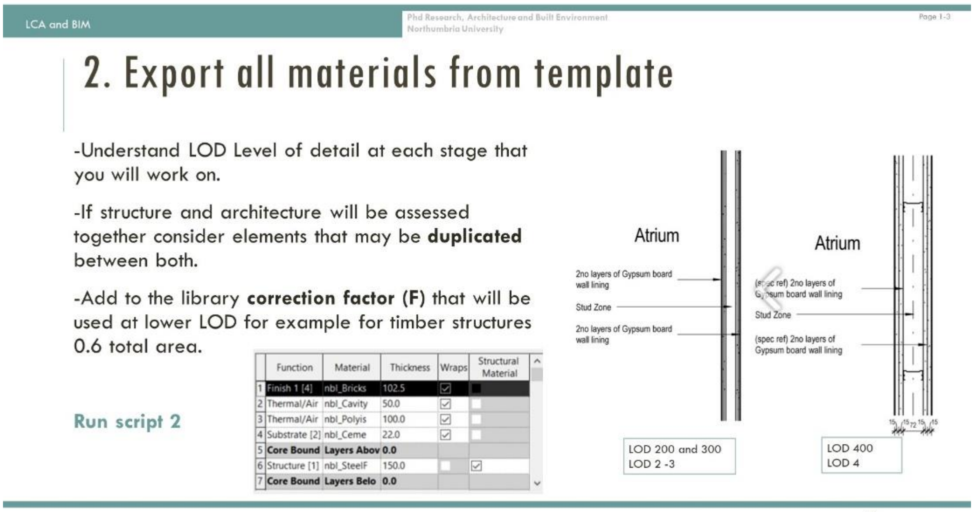
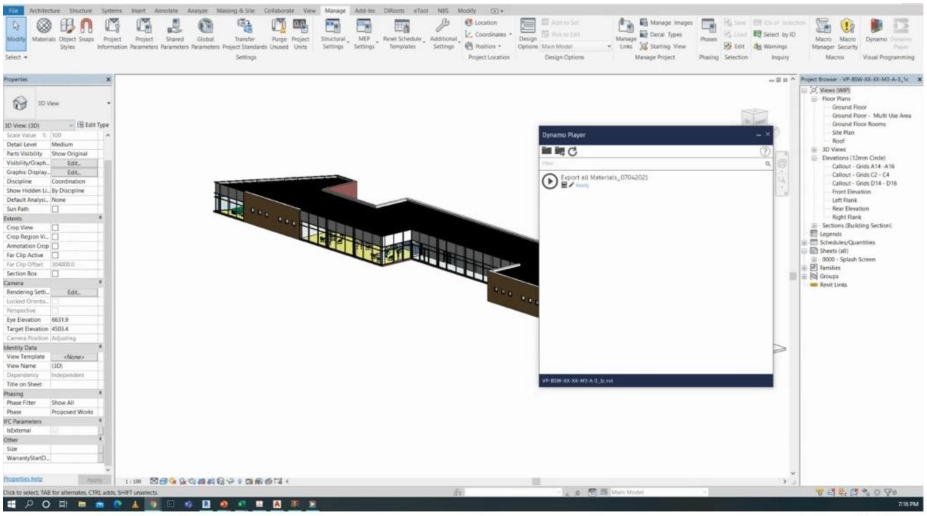
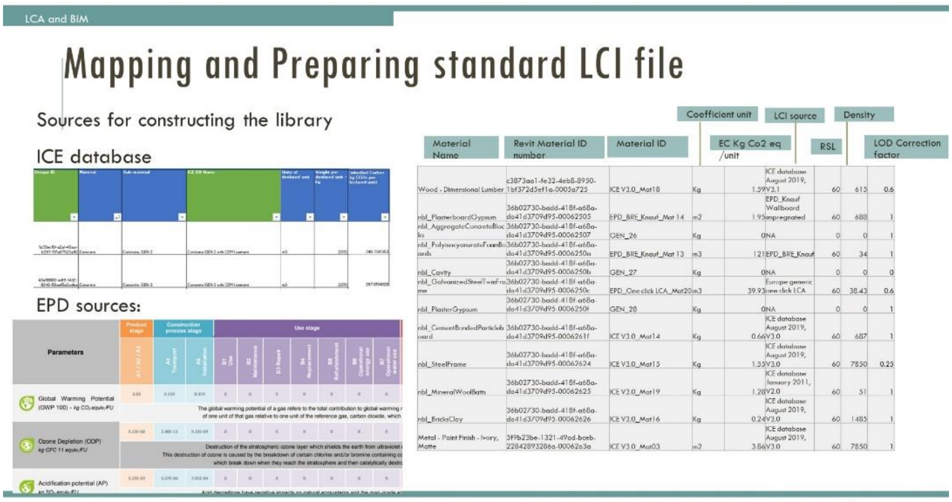


	Function	Material	Thickness	Wraps	Structural Material
1	Finish 1 [4]	nbl_Bricks	102.5	☑	
2	Thermal/Air	nbl_Cavity	50.0	☑	
3	Thermal/Air	nbl_Polyis	100.0	☑	
4	Substrate [2]	nbl_Ceme	22.0	☑	
5	Core Bound	Layers Abov	0.0		
6	Structure [1]	nbl_SteelF	150.0		☑
7	Core Bound	Layers Belo	0.0		





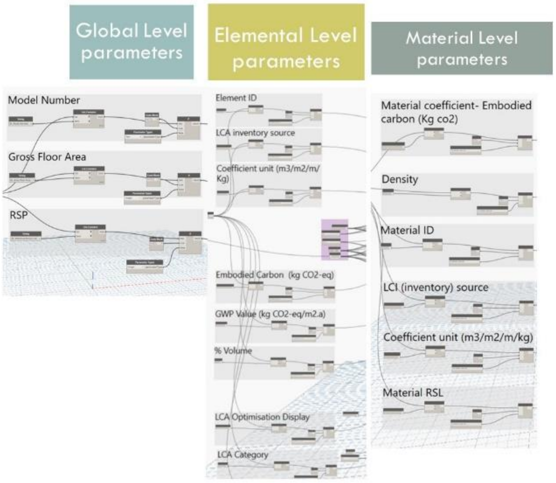
Material Name	Revit Material ID number	Material ID	Coefficient unit	EC Kg Co2 eq /unit	LCI source	RSL	Density	LOD Correction factor
Wood - Dimensional Lumber	c3873aa1-fe32-4eb8-8950-1bf372d5ef1a-0005a725	ICE V3.0_Mat18	Kg	1.59	ICE database August 2019, V3.1	60	615	0.6
nbl_PlasterboardGypsum	36b02730-badd-418f-a68a-da41d3709d95-00062505	EPD_BRE_Knauf_Mat 14	m2	1.95	EPD_Knauf Wallboard impregnated	60	688	1
nbl_AggregateConcreteBlocks	36b02730-badd-418f-a68a-da41d3709d95-00062507	GEN_26	Kg	0	NA	0	0	1
nbl_PolyisocyanurateFoamBoards	36b02730-badd-418f-a68a-da41d3709d95-0006250a	EPD_BRE_Knauf_Mat 13	m3	121	EPD_BRE_Knauf	60	34	1
nbl_Cavity	36b02730-badd-418f-a68a-da41d3709d95-0006250b	GEN_27	Kg	0	NA	0	0	0
nbl_GalvanizedSteelTwinFrame	36b02730-badd-418f-a68a-da41d3709d95-0006250c	EPD_One click LCA_Mat20	m3	39.93	Europe generic one click LCA	60	38.43	0.6
nbl_PlasterGypsum	36b02730-badd-418f-a68a-da41d3709d95-0006250f	GEN_28	Kg	0	NA	0	0	1
nbl_CementBondedParticleboard	36b02730-badd-418f-a68a-da41d3709d95-0006261f	ICE V3.0_Mat14	Kg	0.66	ICE database August 2019, V3.0	60	687	1
nbl_SteelFrame	36b02730-badd-418f-a68a-da41d3709d95-00062624	ICE V3.0_Mat15	Kg	1.55	ICE database August 2019, V3.0	60	7850	0.25
nbl_MineralWoolBatts	36b02730-badd-418f-a68a-da41d3709d95-00062625	ICE V3.0_Mat19	Kg	1.28	ICE database January 2011, V2.0	60	51	1
nbl_BricksClay	36b02730-badd-418f-a68a-da41d3709d95-00062626	ICE V3.0_Mat16	Kg	0.24	ICE database August 2019, V3.0	60	1485	1
Metal - Paint Finish - Ivory, Matte	5f9b23be-1321-49ad-bceb-22842893286a-00062a3a	ICE V3.0_Mat03	m2	3.86	ICE database August 2019, V3.0	60	7850	1

`

3. Create Project Parameters

Revit file parameters are considered Information containers

Run script 3



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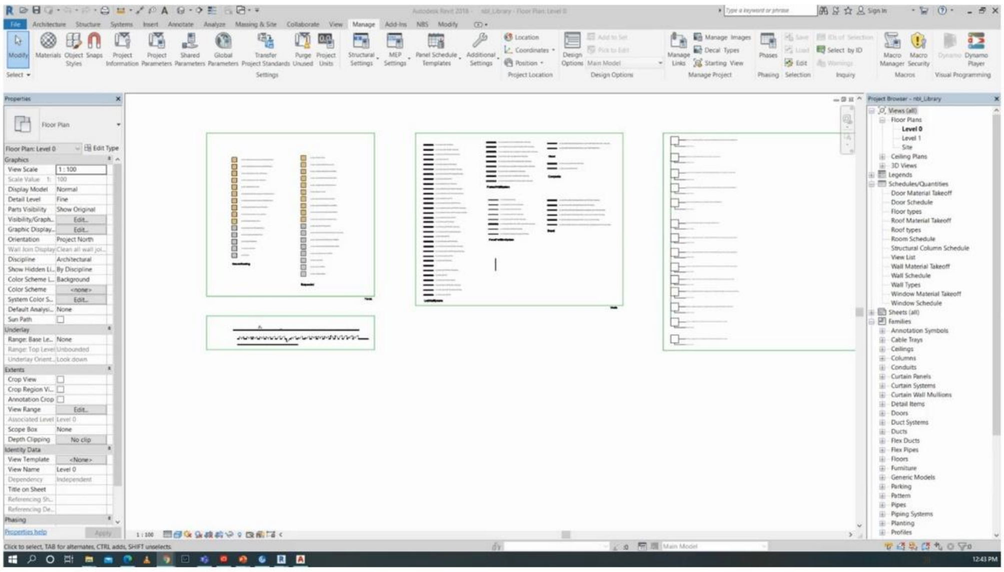


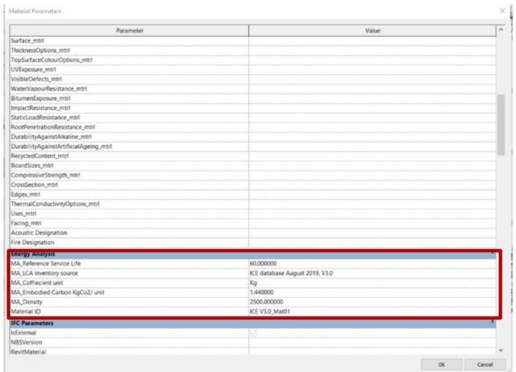
4. Import LCI

Important notes

Don't change the rows and columns order of any excel sheet

Script work on reading from specific index for each value

Any added Materials will be added from the bottom of the standard Material LCI file



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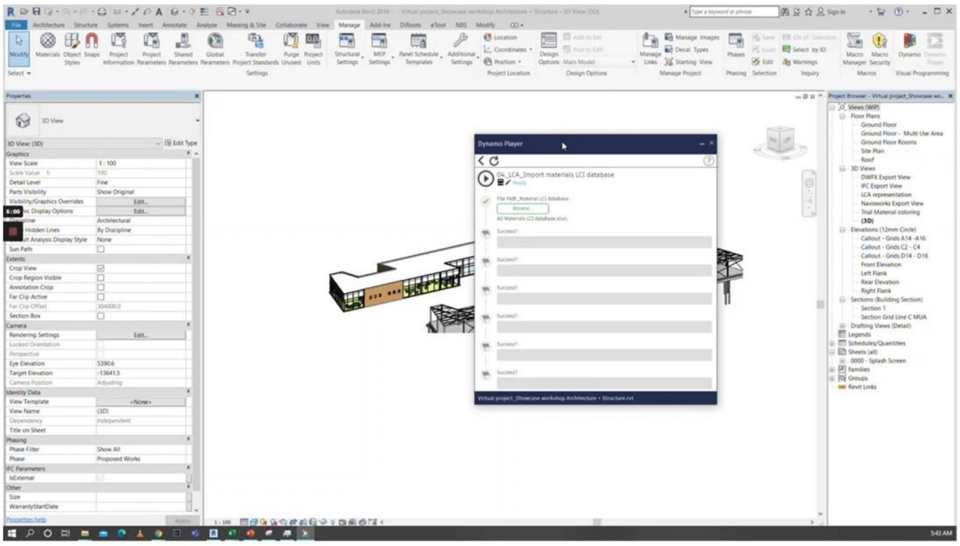
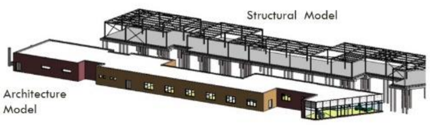


32

Modeling



Notes to consider:

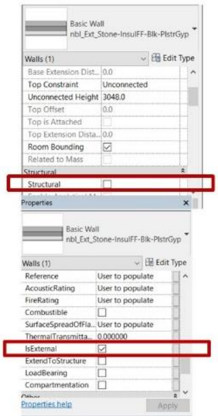
In order to identify internal from external walls and floors

Each element need to check on IFC parameters

Structural

IsExternal

As script will filter them accordingly

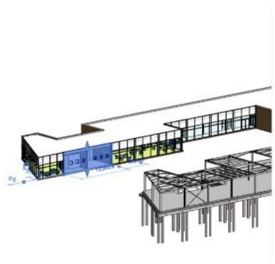


34

4. Calculation

Filters of Kg,m2,m3 materials and then apply the suitable equation.

Then write back the output on the elemental parameters.



35

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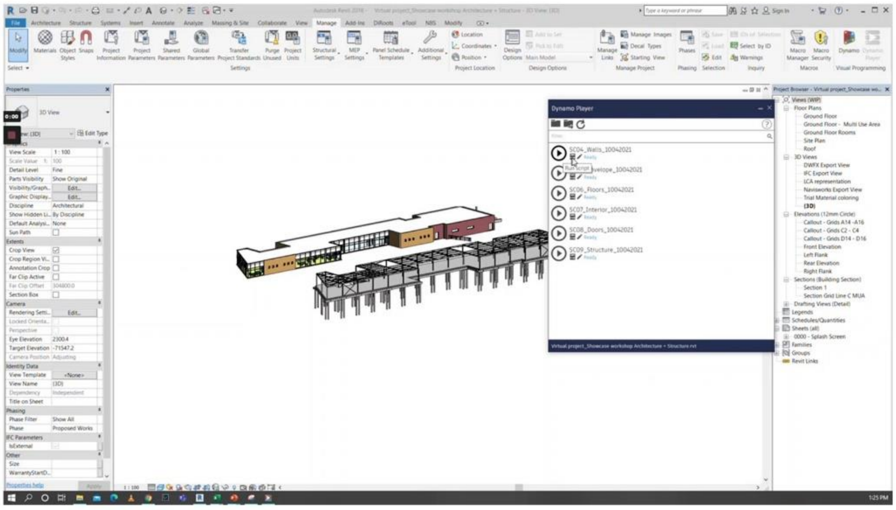
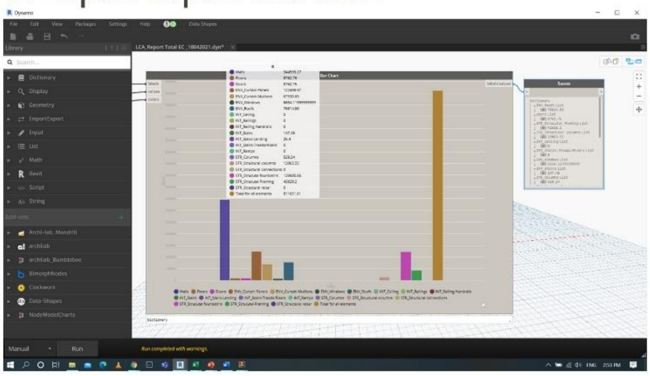


5. Export Report and chart



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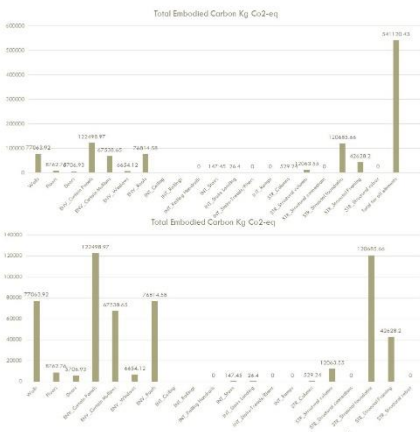
5. Export Report & chart

Category	Total Embodied Carbon Kg Co2
Walls	77063.92
Floors	8762.76
Doors	5706.93
ENV_Curtain Panels	122498.97
ENV_Curtain Mullions	67538.65
ENV_Windows	6654.12
ENV_Roofs	76814.58
INT_Ceiling	
INT_Railings	
INT_Railing Handrails	0
INT_Stairs	147.45
INT_Stairs Landing	26.4
INT_Stairs-Treads/Risers	0
INT_Ramps	0
STR_Columns	529.24
STR_Structural columns	12063.55
STR_Structural connections	0
STR_Strucutal foundatins	120685.66
STR_Strucutal Framing	42628.2
STR_Structural rebar	0
Total for all elements	541120.43



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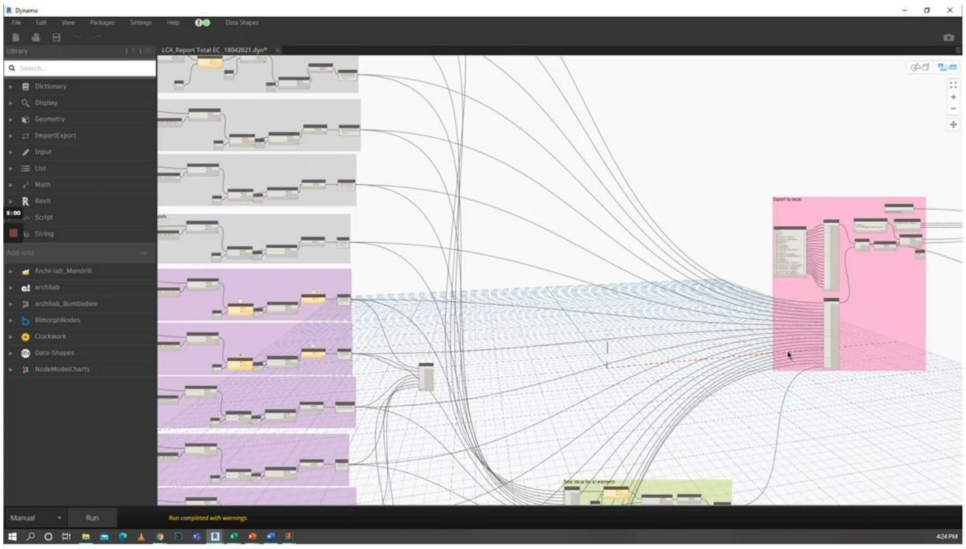

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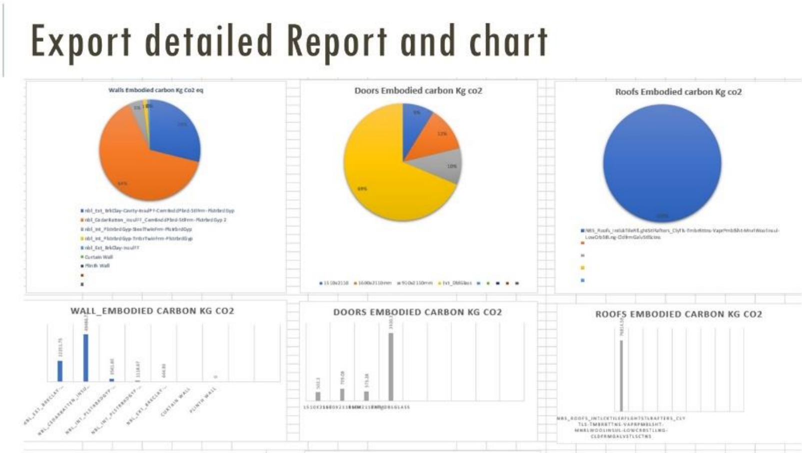

Export detailed Report and chart
Walls Embodied carbon Kg Co2 eq
Doors Embodied carbon Kg co2
Roofs Embodied carbon Kg co2
WALL_EMBODIED CARBON KG CO2
DOORS EMBODIED CARBON KG CO2
ROOFS EMBODIED CARBON KG CO2

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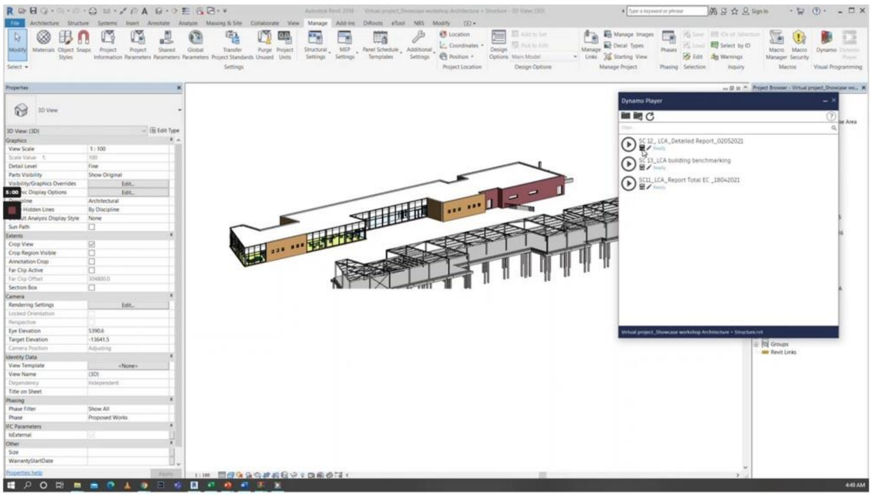

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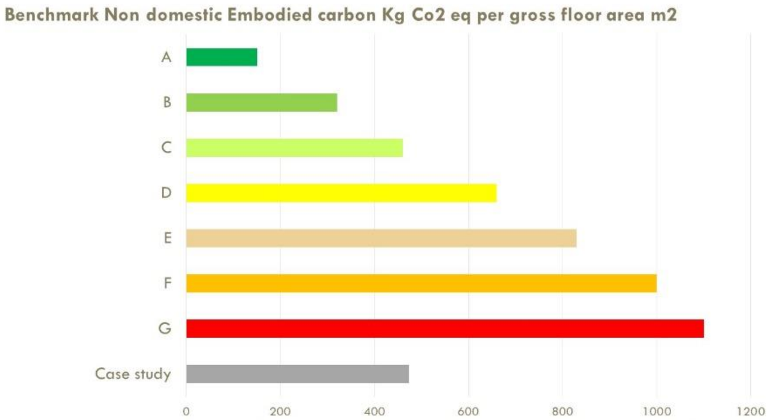
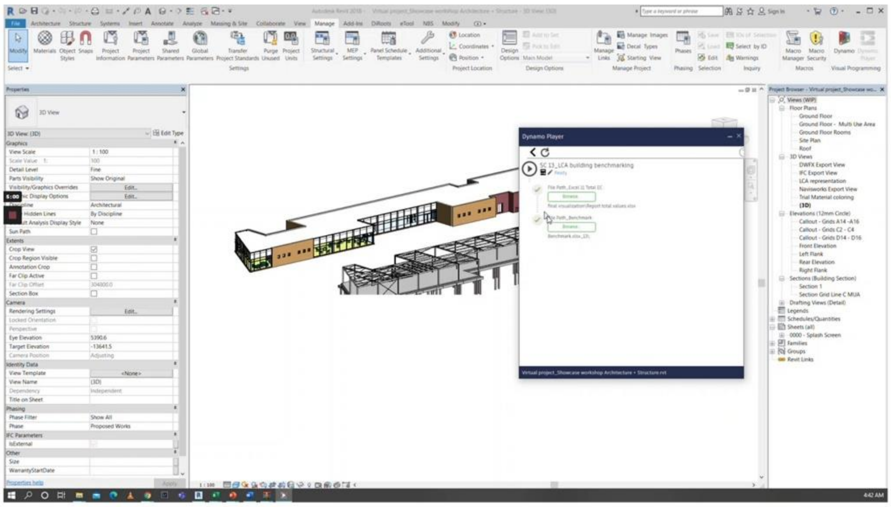
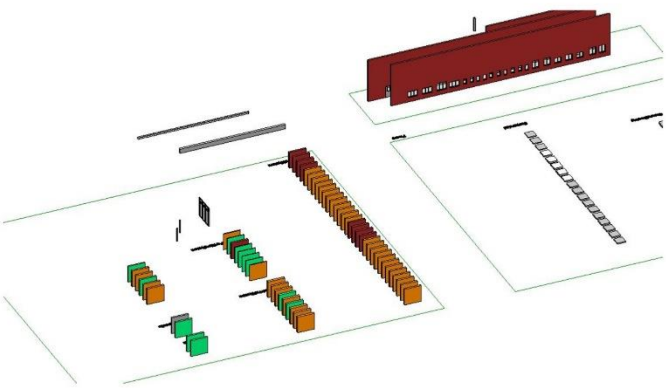


	Case study	G	F	E	D	C	B	A
Benchmark Non domestic Embodied carbon Kg Co2 eq per gross floor area m2	473.4211986	1100	1000	830	660	460	320	150

42





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Appendix 3- Guideline file

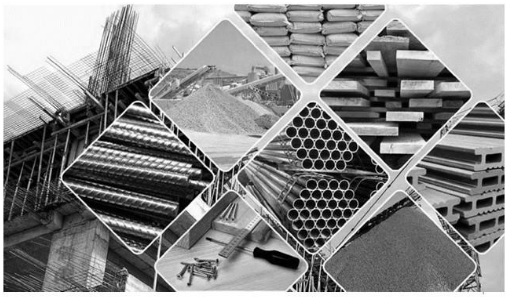
This was provided to the user as a guideline file to use the scripts and all details needed to run the model

Northumbria University
NEWCASTLE

Incorporating Sustainability Aspects And BIM Technologies to Improve Green Project Workflow

Phd Research, Architecture and Built Environment, Northumbria University
Researcher: Rana Ayman Mohamed
Supervisor: Zaid Alwan, Lesley McIntyre

Dynamic EC calculation framework
User guide



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Document outline

This document will present the framework functionality and then is used as a user manual guide to run the model

Outline

LCA and BIM | Phd Research, Architecture and Built Environment Northumbria University | Page 2

1. Introduction and Significance

What is Life cycle assessment ?

"Life cycle assessment is a cradle-to-grave or cradle-to-cradle analysis technique to assess **environmental impacts** associated with all the stages of **a product's life**, which is from raw material extraction through materials processing, manufacture, distribution, and use." (Iyyanki V. Muralikrishna, Valli Manickam, in Environmental Management, 2017)

What is System boundary included in this framework?

85%-90% of total embodied carbon

Product / Manufacture Stage [A1-A3]			Construction Process Stage [A4-A5]		Use [B1-B7]: Building Fabric					Use [B1-B7]: Operation of the Building		End-of-Life Stage [C1-C4]				Benefits & Loads Beyond [D]
Raw Material Extract / Process / Supply	Transport	Manufacture	Transport to the Site	Assembly / Install in the building	Use / Application of Installed Products	Maintenance	Repair	Replacement	Refurbishment	Operational Energy Use	Operational Water Use	Deconstruction / Demolition	Transport to Waste Process	Reuse-Recovery-Recycle	Disposal	Reuse-Recovery-Recycle Potential
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
Cradle-to-Gate			Gate-to-Grave													
Cradle-to-Grave																
Cradle-to-Cradle																
System Boundaries																

Due to the shortage of the EC database in Uk that covers the whole life cycle of the building materials, the EC coefficients that will be used in the framework will cover **(A1-A3) cradle to gate** as main database that will be used id ICE V3.0 which has same system boundary. This stage also contributes with 85-90% of the total EC of the buildings, therefore it is the most crucial value. Still this system is flexible once open source generic database (not specific to manufacture) that includes whole life cycle of material, system boundary for materials could be expanded. It is important for the user to understand that consistent system boundary for all materials is crucial specially when combining different sources of EC inventory database in the same LCA.

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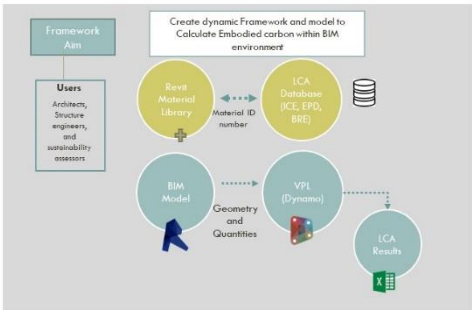
2. The proposed Framework and Model Aim

The framework proposed in this research aims to allow the architects and structure engineers to develop an adequate BIM Material library and use Visual programming language to calculate and visualize embodied carbon (EC) of their design decisions. This approach allows dynamic and iterative evaluation of EC and enable the reuse of information on other projects.

Functionality

1. Create Adequate **BIM Material library** for Embodied carbon Reusable, flexible, suitable for LOD in each stage.
2. **Automatic calculation and eliminate multiple manual mapping,** which allow iterative assessments within design
3. **Visualize and benchmark results** to inform decision making.



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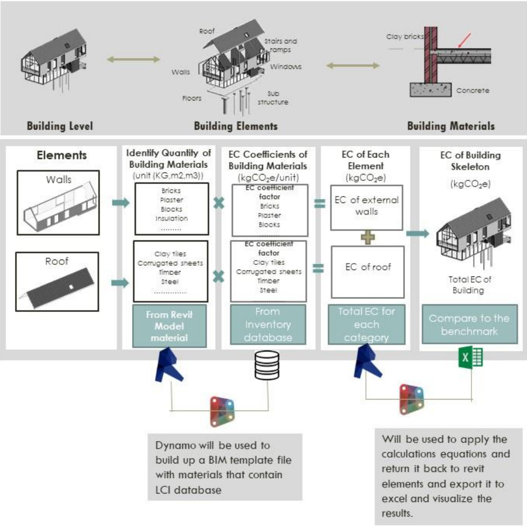
3. Break down of the LCA calculation method

Dynamo scripts function is to eliminate manual work required to build up the system (Revit template file with the library) and the manual work required to apply the right equation according to the EC coefficient unit. It collects the material quantities and filter the materials according to coefficient factor unit and then apply the suitable equation accordingly.

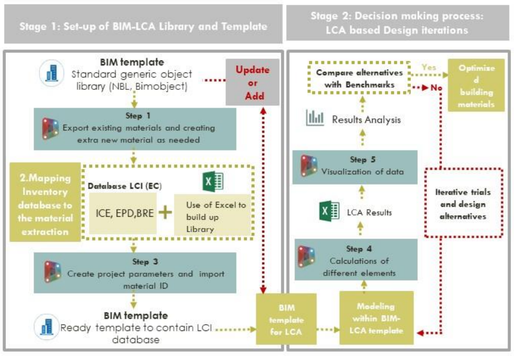
Bellow is the breakdown of how LCA calculations are done.



4. Road map for the main 2 stage model

The framework consists of 2 stages :

The first stage is to set up an adequate BIM Library using compliant databases and tools. Then in stage two the BIM for LCA template will be used to model several design alternatives and be able to compare and visualize. The framework allows the reuse of the generated data and provided a framework to built up, reuse and update BIM library for LCA. The use of scripts eliminate the manual mapping of materials and reduce extra work. Illustration bellow shows the workflow of the two stages.



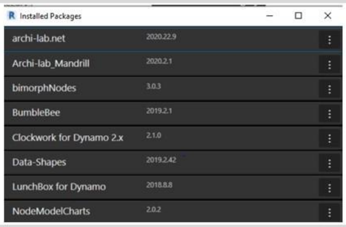
5. Summary guide table for each script function, input and output

Stage	Script	Function	User Input	Output
Stage 1 –Create template with Library	**Script 1-Create Revit Material**	Automatic creation of Materials from Excel sheet to eliminate manual creation.	Excel sheet with Material name	Material creation in Revit library
	Script 2- Export All materials	Export all Materials from Revit Library	Excel sheet output file path.	Excel sheet with all Materials name and Revit IDS
	Manual mapping of Material ID on Excel			
	Script 3- Create project parameters	Create the required global, elemental and material parameters which are containers to database and calculations.	No input	Project parameters created in template file
	Script 4- Import Material ID and Information in standard file family	Read from standard inventory and write back in Revit material parameters.	Standard database excel file path	Standard file Inventory database and Material IDs imported to Material library
Stage 2.1 Calculation	**Script 5- Walls** **Script 6- Envelope** **Script 7- Floors** **Script 8- Interior** **Script 9- Doors** **Script 10- Structure**	Analysis and calculation of different element categories Through reading database from Excel standard file and filtering materials with coefficients m2,Kg,m3 and applying suitable equation accordingly.	Standard database excel file path	Writing back to elemental parameters the calculated values (% volume-embodied carbon-optimization LCA category)
Stage 2.2 Representation	**Script 11- Report total EC per category**	Collect all calculated EC for each element and apply summation to present the data EC per category	File path for total EC per category excel sheet	**Excel sheet with EC values per category and bar chart.**
	Script 12-Report Detailed EC per Material	Present detailed calculated EC to examine and highlight the high EC contributors and act as check on the model calculations and missing elements.	File path for Detailed EC excel sheet	**Excel sheet with EC values per category and bar chart.**
	Script 13- LCA benchmarking	Compare the total EC/ gross floor area to Benchmark	File path for LCA benchmark excel file	**Excel sheet with design total EC per gross floor area benchmark comparison.**

6. Required installation For the use of the dynamo scripts

Programs to be installed before use of the model:

-Revit 2018 or above version .
- Dynamo 2.0.3 (this is very important)
-Packages in Dynamo with versions listed below



Useful links to help in installations

1.Install dynamo for revit (**version is very important** please install from pre release link down the webpage version 2.0.3) or install it direct from attachment provided in the email.
https://www.youtube.com/watch?v=jF-AUWYByb4
http://dynamobim.org/download/

2. Install packages within dynamo listed above
https://www.youtube.com/watch?v=fwvjcTWk0ol

3. Install packages manually (use only incase online package manager is not working
(https://www.youtube.com/watch?v=mQDpQalXbVo)

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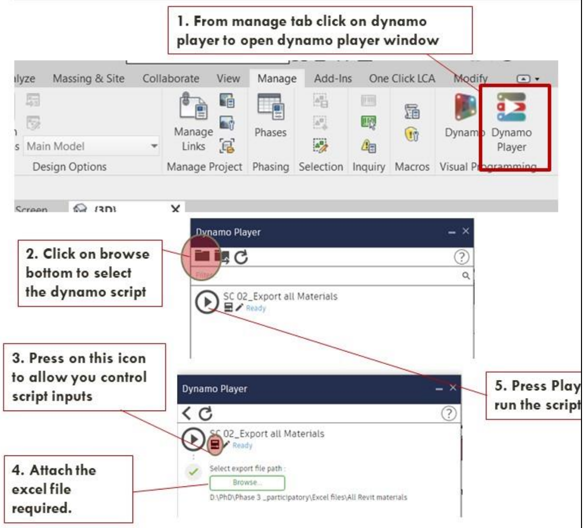
7.Detailed guidelines and considerations

How to run the script ?

All the steps are illustrated in videos in google drive link attached to this user guide.

The Model consists of folders with dynamo file and excel file needed as input or output for the dynamo script. Run scripts as illustrated bellow.



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7.Detailed guidelines and considerations

Routes of applying the model

The Aim of this framework is to make it flexible for the user to start at any point. It is the user choice to select between building Revit library and template integrated with the company system. Or use the template file provided.

Route 1	Route 2
Skip stage 1 and use the ready template and the materials in the revit file.	Build your own library as required and needed with the company system and naming convention.
Only scripts from 5-13 are needed.	All Scripts are needed with manual excel mapping.

Or You can use the template to begin with then add and update library if more materials are needed.

Next Section will explain in detail the function of each script and how to use it.

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7. Detailed guidelines and considerations

1. Script 1-Create Revit Materials

Create new material names in revit library.

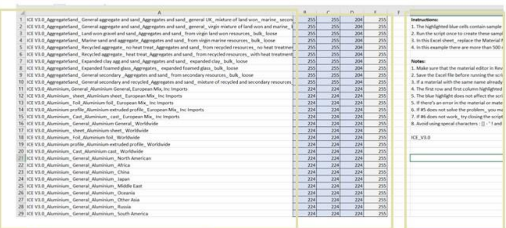
In excel sheet 1: Insert all new names of materials need to be added in your revit template library.

- This script is used to build up library in Revit file template and also used when update is needed (new added materials).

Used files

Dynamo : SC01_CREATE REVIT MATERIALS.dyn

Excel: 01_Create Revit Materials.



List of New material names	RGB and alpha	Instructions
New materials that the user want to create in Revit library – I used here all ICE-V3.0 names Use naming convention of Source_material name Eg. ICE V3.0_Aluminium_ sheet_Aluminium sheet_ Worldwide	These are the RGB values required to be set in the revit library display- alpha keep it with value 255	Read and follow the instructions to run the script and add more materials in the future.

See video 1

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7. Detailed guidelines and considerations

2. Script 2- Export All materials

Export all materials in the Revit template

All the material In revit template (existing materials +New materials) names and Revit ID.

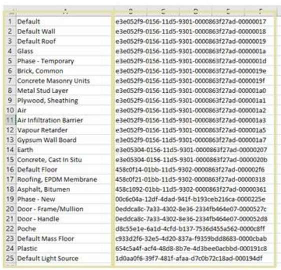
Important notes:

- The order of the materials rows should not be changed (don't delete any material row), because it will be imported with same order.
- This excel file will be used to build up the "standard manual mapped LCI database"
- If you have a material name that will not have an EC value keep it zero but don't delete it from excel only, it has to be exact as revit library order.

Used files

Dynamo : SC 02_Export all Materials.dyn

Excel: 02_Export All Materials.



Material Names | Reference Revit ID

See video 2

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7. Detailed guidelines and considerations

Manual Mapping

Prepare the "Standard file LCI Material database"

In this step the user will take the excel extracted from the previous step script and use it to complete the standard database file.
The user will only fill the materials that are used in modelling, other materials such as default or cavity ….etc will be kept in the file but with zero value and NA value.

Important Notes:

- Sources are : ICE database, BRE greenbooklive, Manufacturers EPD.
https://circularecology.com/embodied-carbon-footprint-database.html
https://www.greenbooklive.com/search/scheme.jsp?id=260
- Don't change the row arrangement from the exported excel sheet.
- Don't change the column arrangement as it will be read to import database properly to the material parameters.
- Make sure you add the correction factor with understand of use with different LOD. Check in the Appendix

Material Name	Revit Material ID number	Material ID	Coefficient unit	EC Kg Co2 eq /unit	LCI source	RSL	Density	Correction factor
Wood - Dimensional Lumber	c3873aa1-fe32-4eb8-8950-1bf372d5ef1a-0005a725	ICE V3.0_Mat18	Kg	1.59	ICE database August 2019, V3.1	60	615	0.6
nbl_Plasterboard Gypsum	36b02730-badd-418f-a68a-da41d3709d95-00062505	EPD_BRE_Knauf_Mat 14	m2	1.95	EPD_Knauf Wallboard impregnated	60	688	1
nbl_PolyisocyanurateFoamBoards	36b02730-badd-418f-a68a-da41d3709d95-0006250a	EPD_BRE_Knauf_Mat 13	m3	121	EPD_BRE_Knauf	60	34	1
nbl_Cavity	36b02730-badd-418f-a68a-da41d3709d95-0006250b	GEN_27	Kg	0	NA	0	0	0
nbl_SteelFrame	36b02730-badd-418f-a68a-da41d3709d95-00062624	ICE V3.0_Mat15	Kg	1.55	ICE database August 2019, V3.0	60	7850	0.25
nbl_MineralWoolBatts	36b02730-badd-418f-a68a-da41d3709d95-00062625	ICE V3.0_Mat19	Kg	1.28	ICE database January 2011, V2.0	60	51	1
nbl_BricksClay	36b02730-badd-418f-a68a-da41d3709d95-00062626	ICE V3.0_Mat16	Kg	0.24	ICE database August 2019, V3.0	60	1485	1

7. Detailed guidelines and considerations

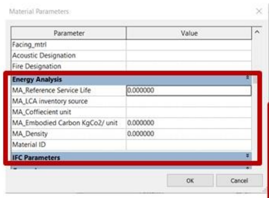
3. Script 3- Create project parameters

This script will create the required **global, elemental and material parameters,** which are **containers to database and calculations.**

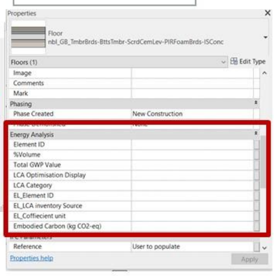
Used files
Dynamo : SC03_Create Project Parameter
Excel:_ parameters

No Inputs or output files- Run the script then check in the material and elements properties that the parameters are created

Material Parameters



Elemental Parameters



See video 3

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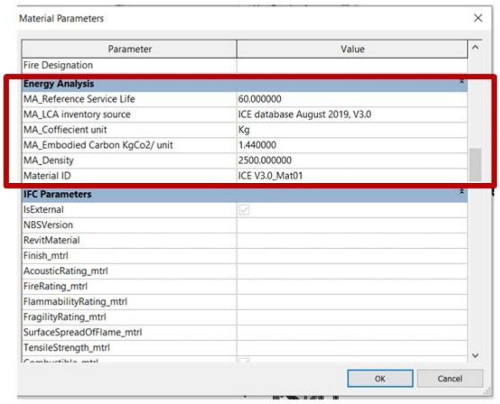
7. Detailed guidelines and considerations

4. Script 4_ Import Material ID and Information in standard file family

This dynamo script will import all "All Materials LCI database" which are prepared manually in previous step, into the material parameters.

Check that they are imported correctly.

Used files
Dynamo : SC 04_LCA_Import materials LCI database.dyn
Excel: 04_All Materials LCI database



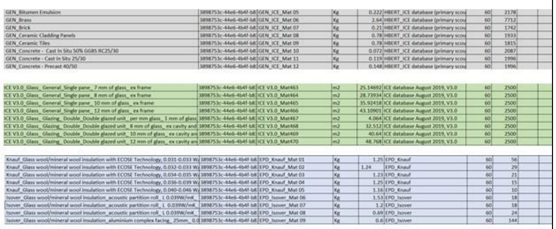
See video

7. Detailed guidelines and considerations

If you are using the template start from here

Revit User template: Model in Revit using Only use materials of these 3

General material **GEN_Material Name**	ICE database materials **ICE_Material Name**	**EPD materials Manufacture_Material Name** Eg. Knauf_Glasswool
Suitable at LOD 2	**Suitable at LOD 2 & 3**	**Suitable at LOD 3 & 4**



This is how they are grouped in the excel standard file. "04_ALL Materials LCI database" .

Don't change the row order inside of the file if you need to add more materials first create then using SC_01 then export them using SC02 . Any new material will be added at the bottom.

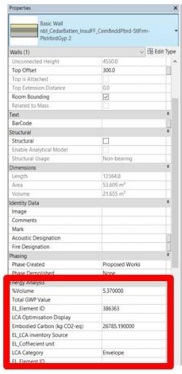
`

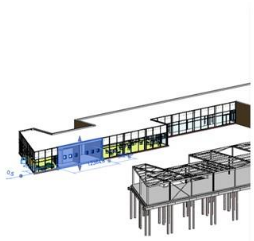
7. Detailed guidelines and considerations

5. Script 5- Walls ,Script 6- Envelope ,Script 7- Floors , Script 8- Interior , Script 9- Doors ,Script 10- Structure

This Script will apply the analysis and calculation of different element categories.
Through reading database from Excel standard file and filtering materials with coefficients m2,Kg,m3 and applying suitable equation accordingly.

Used files
Dynamo : SC05_Walls.dyn, SC06_Envelope, SC07_Floors, Script 8-Interior, Script 9-Doors, Script 10-Stucture.
Excel: 04_All Materials LCI database





The results will written back to the output on the elemental parameters.

See video 4

7. Detailed guidelines and considerations

6. Script 11- Report total EC per category

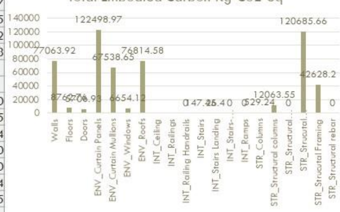
This script will collect all calculated EC for each element and apply summation to present the data EC per category.

Select the output script file 11_report total values.

Used files
Dynamo : SC11_LCA_Report Total EC
Excel: 11_Report total values

These are the results in the excel sheet (total EC per category)

Category	Total Embodied Carbon Kg Co2
Walls	77063.92
Floors	8762.76
Doors	5706.93
ENV_Curtain Panels	122498.97
ENV_Curtain Mullions	67538.65
ENV_Windows	6654.12
ENV_Roofs	76814.58
INT_Ceiling	
INT_Railings	
INT_Railing Handrails	0
INT_Stairs	147.45
INT_Stairs Landing	26.4
INT_Stairs-Treads/Risers	0
INT_Ramps	0
STR_Columns	529.24
STR_Structural columns	12063.55
STR_Structural connections	0
STR_Strucutal foundatins	120685.66
STR_Strucutal Framing	42628.2
STR_Structural rebar	0
Total for all elements	541120.43



See video 5

Detailed guidelines and considerations

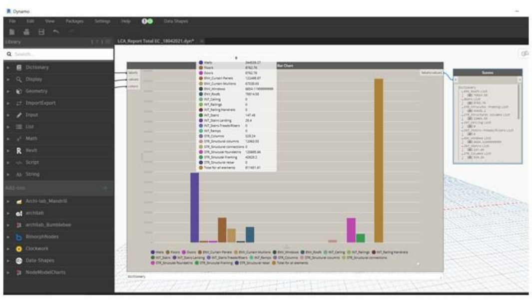
6. Script 11- Report total EC per category

This script will collect all calculated EC for each element and apply summation to present the data EC per category.

Select the output script file 11_report total values.

Used files
Dynamo : SC11_LCA_Report Total EC
Excel: 11_Report total values

These are the results as chart from inside of dynamo, you can save as jpeg.



See video 5

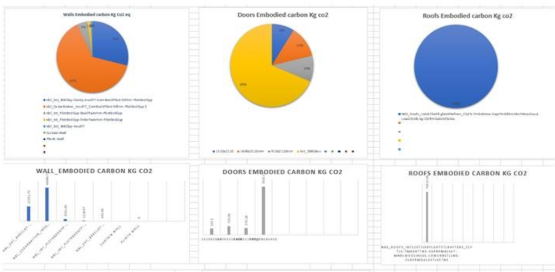
7. Detailed guidelines and considerations

6. Script 12- Report total EC per category

This script will Present detailed calculated EC to examine and highlight the high EC contributors and act as check on the model calculations and missing elements.
Select the output excel file 12_Report detailed values.

Used files
Dynamo : SC 12_LCA_Detailed Report
Excel: 12_Report detailed values

These are the results presented in excel sheet to analyze the EC per material inside the category.



See video 6

7. Detailed guidelines and considerations

6. SC 13_LCA building benchmarking

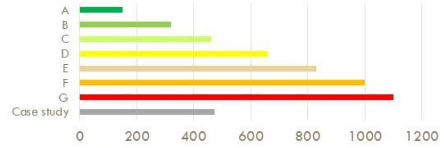
This script will Compare the total EC/ gross floor area to Benchmark

Select the Input excel file 11_report total values And the output 13_Benchmark Non domestic

Used files
Dynamo : SC 13_LCA building benchmarking
Excel: 11_Report detailed values + 13_Benchmark Non domestic or 13_Benchmark domestic

Select the excel file with the suitable building typology category, below is the output chart.

Benchmark Non domestic Embodied carbon Kg Co2 eq per gross floor area m2



	Case study	G	F	E	D	C	B	A
Benchmark Non domestic Embodied carbon Kg Co2 eq per gross floor area m2	473.4212	1100	1000	830	660	460	320	150

See video 7

Appendix

Example of how to structure naming convention for different LOD for insulation

		Materials	Embodied Carbon - kgCO2e/kg
ICE Database	LOI 2	General Insulation	1.86 CO2 Only
	LOI 2-3	Cork	0.19 CO2 Only
		Fibreglass (Glasswool)	1.35 CO2 Only
		Flax (Insulation)	1.7 CO2 Only
		Mineral wool	1.28
		Paper wool	0.63 CO2 Only
		Polystyrene	See plastics
		Polyurethane	See plastics
		Rockwool	1.12
		Woodwool (Board)	0.98 CO2 Only

		Material	Density	Embodied Carbon - kgCO2e/kg	Manufacturer
ICE & EPD	LOI 3-4	**polyisoac**			
		PIR insulation boards, aluminium foil faced, <= 160 mm, L = 0.0215 W/mK, dens. = 32 kg/m3, Various products (Xtratherm)	32 kg / m3	169.38 kg CO2e / m3	Xtratherm UK
		Insulated wall/roofing cladding panel, 100 mm, 12.6 kg/m2, U 0.18 W/m2K, KS1100 AB/CS Quadcore (Kingspan)	126 kg / m3	41.4 kg CO2e / m2	Kingspan
		Insulated wall/roofing cladding panel, 100 mm, 14.4 kg/m2, U 0.18 W/m2K, BENCHMARK Quadcore Karrier (Kingspan)	144 kg/m3	45.2 kg CO2e / m2	Kingspan
		xps insulation			
		XPS insulation board, 0.033 W/mK, Polyfoam ECO Extra XPS (Knauf)	34 kg / m3	3.56 kg CO2e / kg	Knauf
		XPS insulation board, 0.033 W/mK, Polyfoam ECO Standard (Knauf)	31 kg / m3	3.55 kg CO2e / kg	Knauf

The naming convention in the revit material library should cover the three levels (generic, material specific, then last level is manufacturer specific

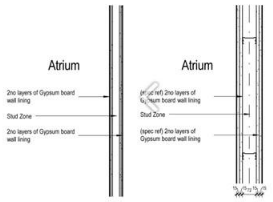
Appendix

Understand different LOD and LOI and it's impact of the calculation

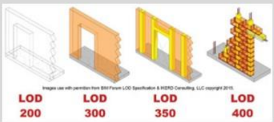
1. Understand LOD Level of detail at each stage that you will work on.

2.If structure and architecture will be assessed together consider elements that may be **duplicated** between both.

3.Add to the library **correction factor (F)** that will be used at lower LOD for example for timber structures 0.6 total area.



LOD main difference in the frame elements (timber, steel structure, stud structure partitions)



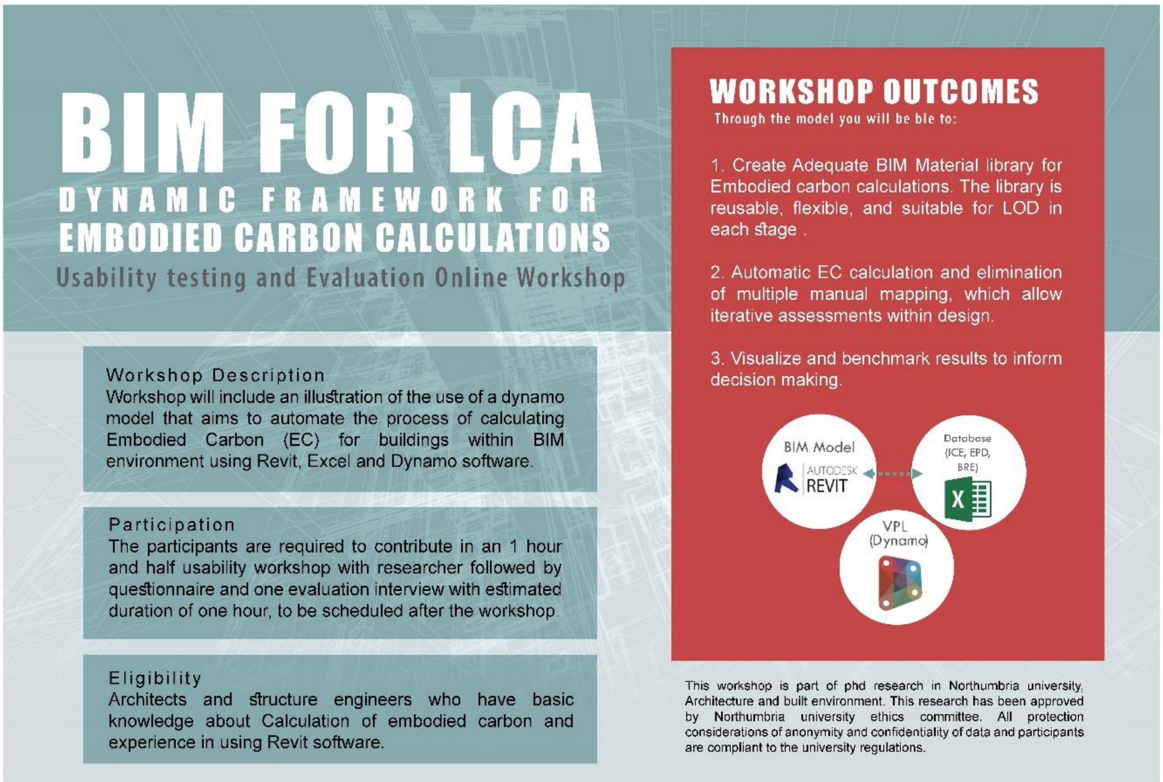
LOI 200/2 use of generic average coefficient unit , to reach higher details of exact specification or identification of manufacturer with specific EPD)

Research team is Looking forward for Collaboration and Happy to discuss any Inquires

Contact Details:
Rana.ayman@Northumbria.ac.uk

`

Appendix 4- Project brief, recruitment flyer and Consent forms



If you are interested, please contact us through: Rana.ayman@northumbria.ac.uk

`

Appendix 5- Usability Questionnaire

Usability of a dynamic BIM-LCA framework for Embodied carbon Evaluation

User Consent

Purpose
The Informed Consent Form is designed to confirm that the participant has been given all relevant
information about the research and their role within it, and how both the researcher and participant are
protected. Please read the following statements fully and carefully. By proceeding to take the
questionnaire, you are giving your consent.

Summary
I volunteer to take part in this PhD research questionnaire. I understand that the research aims to collect
data on user Evaluation of a dynamic BIM for LCA framework and model. The data collected in this questionnaire will be used in a PhD thesis and help expand the knowledge base for dynamic BIM for LCA software in AEC sector.

1. I confirm that I have been given a copy, and read, the Participant Information Sheet and fully
understood the information it contained.
2. I understand that my participation in this project is voluntary. I will not be paid for my involvement. I am
free to withdraw from the project at any time, without reason.
3. I have read and understood that all data provided will be treated in strict confidence, and that my name
and organisation will be anonymised. I understand that my data will be kept, securely, for a period of 5
years after the interview, in accordance with the Data Protection Act 1998. .
4. I understand that this research has been approved by Northumbria University Ethics Committee.
5. I have read and understood the explanation of the research project provided to me. I have had the
opportunity to ask any questions and they have been answered to my satisfaction.
By proceeding to take this questionnaire, I agree to take part in this research project and to the above
statements. Any statements I have concern with I will discuss with the principle researcher prior to
commencing.

This questionnaire is part of Phd research in Northumbria University

Northumbria University NEWCASTLE

Section 1- General User Information

This is a general section which will collect information about the user previous experience

1. How many years of experience do you have in practice?

   Mark only one oval.

   - 0-5 years
   - 6-10 years
   - 11-15 years
   - 16-20 years
   - Other: ______________________

2. How many years have you been using BIM in your projects?

   Mark only one oval.

   - Less than 1 year
   - At least 1 year but less than 5 years
   - At least 5 years but less than 10 years
   - 10 years or more
   - Other: ______________________

3. How many years have been using Revit or similar software?

Mark only one oval.

- Never used
- less than one year
- At least 1 year but less than 5 years
- At least 5 years but less than 10 years
- 10 years or more
- Other: ____________________

4. Did you use dynamo or dynamo player before?

Mark only one oval.

- Yes
- No

5. Have you been involved in project that involved assessment of Embodied Yes carbon?

Mark only one oval.

- Yes
- No

6. If yes what are the tools and material database used?

7. If Yes, At what stage did the Embodied carbon have been assessed? You can use more than one answer

Mark only one oval.

- Early Conceptual design stage
- Design Development stage
- Technical development stage
- Construction stage
- Post construction stage
- Other: ____________________

8. If yes, Approximately how many times the assessment was repeated?

____

9. What problems/challenges did you find in Embodied Carbon evaluation to be repeated to inform design decision? You can use more than one answer

Check all that apply.

- [ ] Time consumption
- [ ] Complex and Require expert
- [ ] Material database and library shortage
- [ ] Not reliable results
- [ ] Manual Mapping is prone to errors
- [ ] Results are not informative to design development
- [ ] All of the above
- [ ] Non of the above

Other: [ ] ____________________

Section 2- Overall Model Satisfaction

In this section user is evaluating the satisfation of the framework features.

Rate your experience and satisafation to use the system , by selecting how much do you agree with the statment.

1-Strongly disagree - to 5- strongly agree

10. 1. I think that I would like to use this system frequently.

Mark only one oval.

	1	2	3	4	5	
Strongly disagree	◯	◯	◯	◯	◯	Strongly disagree

11. 2- I found the system unnecessarily complex.

Mark only one oval.

	1	2	3	4	5	
Strongly disagree	◯	◯	◯	◯	◯	Strongly agree

12. 3- I thought the system was easy to use.

Mark only one oval.

	1	2	3	4	5	
Strongly disagree	◯	◯	◯	◯	◯	Strongly agree

13. 4- I think I would need the support of technical person to be able to use this system.

Mark only one oval.

	1	2	3	4	5	
Strongly disagree	◯	◯	◯	◯	◯	Strongly agree

14. 5. I found the various functions in this system were well integrated.

Mark only one oval.

	1	2	3	4	5	
Strongly disagree	◯	◯	◯	◯	◯	Strongly agree

15. 6. I thought there was too much inconsistency in this system.

Mark only one oval.

	1	2	3	4	5	
Strongly disagree	◯	◯	◯	◯	◯	Strongly agree

16. 7. I would imagine that most people would learn to use this system very quickly.

Mark only one oval.

	1	2	3	4	5	
Strongly disagree	◯	◯	◯	◯	◯	Strongly agree

17. 8. I found the system very complex to use.

Mark only one oval.

	1	2	3	4	5	
Strongly disagree	◯	◯	◯	◯	◯	Strongly agree

18. 9. I felt very confident using the system.

Mark only one oval.

	1	2	3	4	5	
Strongly disagree	◯	◯	◯	◯	◯	Strongly agree

19. 10. I need to learn a lot before I could get going with this system

Mark only one oval.

	1	2	3	4	5	
Strongly disagree	◯	◯	◯	◯	◯	Strongly agree

Section 3- Evaluation of Model Features

Using scale 1-not satisfied at all 5-fully satisfied evaluate the features of the tool, Also mention select is it important feature or not.

20. 1. Link the geometrical data and project quantities to the embodied carbon database

Mark only one oval.

	1	2	3	4	5	
Not Satisfied at all	◯	◯	◯	◯	◯	Fully Satisfied

21. 2. Provide an ontology for mixing product database and create company library that can be reused

Mark only one oval.

	1	2	3	4	5	
Not Satisfied at all	◯	◯	◯	◯	◯	Fully Satisfied

22. 3. Being able to track the source of the used material inventory data

Mark only one oval.

	1	2	3	4	5	
Not Satisfied at all	◯	◯	◯	◯	◯	Fully Satisfied

23. 4. Minimize data input which is simple and intuitive

Mark only one oval.

	1	2	3	4	5	
Not Satisfied at all	◯	◯	◯	◯	◯	Fully Satisfied

24. 5. Provide enough material library to overcome shortage

Mark only one oval.

	1	2	3	4	5	
Not Satisfied at all	◯	◯	◯	◯	◯	Fully Satisfied

25. 6. The Output is Simple and visual, easy to interpret, and clear

Mark only one oval.

	1	2	3	4	5	
Not Satisfied at all	◯	◯	◯	◯	◯	Fully Satisfied

26. 7. The output provides supportive information for design decisions suitable for early stage of design and design development

Mark only one oval.

	1	2	3	4	5	
Not Satisfied at all	◯	◯	◯	◯	◯	Fully Satisfied

27. 8. The output provides well segregated results on elemental and material level

Mark only one oval.

	1	2	3	4	5	
Not Satisfied at all	◯	◯	◯	◯	◯	Fully Satisfied

28. 9. The output can be compared to benchmarks

Mark only one oval.

	1	2	3	4	5	
Not Satisfied at all	◯	◯	◯	◯	◯	Fully Satisfied

Appendix 6- Post workshop usability interviews

- **Semi structured interviews:**

  - Do you agree that this tool provide a dynamic ability is efficient enough to save the user time and reduce error of manual material mapping?
  - Do you agree that this tool provide a dynamic ability is efficient enough to save the user time and reduce error of manual material mapping?
  - To what extend do you agree that the framework could instantly calculate the embodied carbon with the BIM model and would be effective in enhancing the design process?
  - Could you predict a framework and tool such as dynamo for LCA being adopted in your practice? Why?
  - Do you have any problem with the framework and use of tools?
  - Do you have any suggestions for improvements?

`

Appendix 7- Sample from workshop discussion interviews transcription

The participant is encouraged to comment on the following statements.

System related aspects:

1. Link the geometrical data and project quantities to the embodied carbon database.

It is brilliant to be able to have a framework that has this level of intelligence and be able to link our library to a EC inventory database such as Ice database is in valuable and it takes out manual error and perhaps it can be encountered with the hakin brown plugin.

Once the system is being able to pick up the volumes and areas in the model to be able to sit down and work out all of that manually every time it will take forever, so I see the value and efficiency in adopting such a system to do calculations with the change in model.

2. Provide an ontology for mixing product database and create company library that can be reused.
3. Being able to track the source of the used material inventory data.
   I imagine that this point is covered through adding sufficient supporting parameter.
4. Minimize data input which is simple and intuitive
5. Provide enough material library overcome shortage

`

We used other plugins the advantage that they provide ready to use library but always with limitation of we can't add more materials.

6. The Output is Simple and visual, easy to interpret, clear.

   I think the output is very clear and simple to interpret, but it would be better to add also colour code on the model to indicate the values in the graph.

   The graphs of the output are simple and easy to communicate with other team members and clients but Last point when you showed potential for future visualization options on BIM model is worth development. Architects usually prefer more model visuals than just graphs

   I found that navigating through the model and being able to check the value for each element by selecting it is great.

7. The output is well segregated results on elemental and material level

   I think the output provided an understanding where the biggest amount of embodied carbon is, It looks like the tool you have shown us works quit effectively in split down of the element and then split down materials to show which is the biggest contributor to EC because you can really pull them apart.
8. The output can be compared to benchmarks

   It is great to automatically have embedded comparison with current benchmarks UK benchmarks, it saves the team time to search for the right values by searching in regulations, it is not an information that we use on daily basis.

Process Related aspects:

1. Quickly and easily create and test alternatives which encourage iterations

   Yes, I agree It allows to run periodic millstones along the project timeline easily.

   I would recommend if it can also compare alternatives together automatically.

2. Adaptable to / in tune with design stages (time and work)

`

With this model we will be able to have feedback at each stage of the project, unlike all the tools that we are all plugins that we can't control the level of detail we are working with, so I think this is really useful and I can say it will inform the design and specification at each stage unlike other methods.

3. Flexible and can accommodate additional indicators with same concept
4. Library is reusable and buildable through projects.

   Effort required to do the assessment decreases overtime and more use over projects as the library will mostly cover all materials that we need.
5. Suitable to different level of development models.

   Considering the LOD is very good as you don't have to wait till you reach a technical stage to get any feedback, I think that allows you to get feedback right at the start of deciding materials and knowing that it doesn't have to be fully accurate at stage 2 but at least you get an idea that can help inform the design stage.
6. The use of the model reduces manual mapping and repetitive tasks.

   I think you automated a lot of tasks which is really useful and it reduces the time you need to sit down and work through the model if it also calculated automatically and reduce possibility of errors.

Semi structured interviews:

- Do you agree that this tool provide a dynamic ability is efficient enough to save the user time and reduce error of manual material mapping?

  I think there is a lot of mileage in that the visual representation of the Ec is brilliant, it gives anyone working on a project in BIM environment. And gives insights of what to resolve.
- To what extend do you agree that the framework could instantly calculate the embodied carbon with the BIM model and would be effective in enhancing the design process?

I this will this model we will be able to have feedback at each stage of the project, unlike all the tools that we are all plugins that we can't control the level of detail we are working with, so I think this really useful and I can say it will inform the design and specification at each stage unlike other methods.

`

I think it works effectively in breaking down the elements and even split down materials ‘to see which is the biggest contribution in EC

- Could you predict a framework and tool such as dynamo for LCA being adopted in your practice? Why?

  I think yes, in comparison with other plugins this one seems to be much more intuitive. Main challenge to adopt such a model is being able to update the scripts in tune with the progression of the packages used in the script, So the maintenance aspects that comes along with updating the Revit version. I see this aspect is not always straight forward.

  I think if it is an open source it is more likely to be adopted more.

  Education and resources platform Architectural technologist: to take more of a spread uptake and to increase usability of it is good to blog these videos that you are showing and having step by step guide something like slides on linkdin leading or training program, as an architect who has no experience with dynamo it could be overwhelming to use it so this visual kind of aids that you can follow would be very useful. So, I think by trying to train a few people by preparing for them visual guidance will increase possibility of adoption. In our office a have a learning platform called clinical so we can upload our content to that platform

  We can use it to upload these content to our platform and it could be the start for a people within our studio to integrate that process into projects so Visual guidelines will be great..

- Do you have any problem with the framework and use of tools?
- Keeping the team informed with this process, so it is an education aspect , but as an actual thing
- Main challenge I see now is educating the wider in our studio about EC as calculation itself, I think it is fairly new to most people, I don’t think that most architects came across it. It became more familiar this year

  Then I guess teaching people the process of integrating that into the model and use it as a tool because it is not something that you have normally think about, you think about sustainability broadly but you don’t think about it on material level.

  Tool like this is going to help us to be educated about important aspects that is up cross our profession.

`

How would I work with a reference model on a master plan as we have 2 apartment buildings (typical and 68 town houses). We have a town house file that is linked to a plot land file. Can we apply these scripts on linked files. To overcome that we can take a town house and do calculation for it then multiply by the number within the land plot to get the total. EC per town house and then multiply by number of town house.

- Do you have any suggestions for improvements?

-Having a ready template to begin with To be able to filter current families in BIM environment according to their EC value using colour code and visual presentation. This will also allow us as architects to learn more about EC visually.

If there is a possibility to be able to compare alternatives together within the tool, I know that you can do that with the data that you are exporting out that, but if it can be within same interface.

BIM manager: The visual reference with colour codding you proposed as recommended addition, I think there is so much value in that. I would be very useful if we can check by any elements if any parameter is not completed represents as red object, so that people could look at the model again and see what was content and also check if any elements doesn't have any value in them yet. That would be an immediate visual indicator, as someone can on to a project that doesn't work on it previously and didn't probably know the principle that are going along, so it gives the project lead the ability to use this visual 3D model as a reference that all of the parameters are in and populated with some value. Visual indicators as a model checking that any added material or element contain parameters values

Alternative suggestion It could be nice if you can interrogate the material that is causing the biggest contribution to carbon with alternative suggestion or alternative material spec. that you could use instead to make it more environmentally friendly. Because for us as an architects it is not about finding out how much EC is there in a building, it is more to addressing that and find alternative options as you specify materials may be so it could be done as filter for example if you are looking for an insulation a drop down menu can be filtered from low to high attached with other important key specification as U value and Embodied Energy to select an alternative.

`

Appendix 8- Publication abstracts and citation

ARCHITECTURAL SCIENCE REVIEW
https://doi.org/10.1080/00038628.2019.1669525

BIM for sustainable project delivery: review paper and future development areas

Rana Ayman, Zaid Alwan and Lesley McIntyre

Architecture and Built Environment, Northumbria University, Newcastle upon Tyne, UK

ABSTRACT

The evolution of Building Information Modelling (BIM) is transforming practice in the Architecture, Engineering and Construction (AEC) industry. BIM provided revolutionary ways of generating, visualizing, exchanging, predicting and monitoring information. Over the last decade, delivering sustainable projects has become a high priority along with the recognition of the role the BIM plays to improve efficiency. However, BIM-enabled sustainability practices are still relatively immature and inconsistent. Previous research has identified challenges in the delivery of green-rated buildings, that include: dealing with documentation, evidencing requirements, monitoring progress, and decision making. Limited studies focused on linking workflow obstacles of green projects to potential improvements using current BIM capabilities. Through interrogating existing research via a systematic literature review, this paper takes the original approach of constructing an 'analysis map' to 'bridge the gap' and highlight current limitations and successes between BIM and sustainability practices. The findings are formulated through two parallel investigation tracks: the first is design task/BIM capability analysis, and the second is green project delivery problem/BIM enabled sustainability application. This research highlights future potential investigation areas, which are categorized into six clusters: representation; performance simulation; transaction and exchange; documentation; automation and standardization and guidance.

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KEYWORDS
Building information modelling; sustainable construction; green rating systems; BIM and green practices synergies; Green BIM; systematic review

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Factors Motivating the Adoption of BIM- based Sustainability Analysis

Rana Ayman[1], Zaid Alwan[2], Lesley McIntyre[3]

[1] PhD Student at Architecture and Built Environment, Northumbria University.
[2] Senior Lecturer at Architecture and Built Environment, Northumbria University.
[3] Senior Lecturer at Architecture and Built Environment, Northumbria University.

Key words:

BIM technologies, BIM based sustainability, Environmental Assessment methods, Sustainability drivers and barriers.

Abstract

The delivery of sustainable and green certified buildings such as BREEAM and LEED is a highly-discussed topic with significant interest growth between the Architecture Engineering and Construction (AEC) industry. At the same time, professionals in the AEC have started to recognize the importance of the synergy between Building Information Modelling (BIM) and the assessment of green building strategies to the construction industry. Several studies demonstrated BIM as a platform for collaboration in the AEC sector in general, rather than to deliver green buildings. Thus fewer researchers have tended to investigate the external and internal problems/factors that affects the delivery of green buildings, and role of digital tools and BIM based strategy in solving them. Through thematic coding of existing literature, this paper formulates a critical review of the key drivers for the change needed in AEC industry. It maps knowledge, makes recommendations for improved collaboration, and offers general insight into the delivery of green building design. This review will act as a base to address the critical factors affecting the delivery of green buildings, and investigate how integrating BIM with sustainability aspects could overcome workflow problems towards better collaboration. The investigation concluded that the practice adoption to BIM-based applications is affected by the immature level of integration and lack of consistent framework that is based on the problems in the workflow, process and gap in communication strategies captured from the field work.

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Framework for parametric assessment of operational and embodied energy impacts utilising BIM

Zaid Alwan [a,*], Amalka Nawarathna [a], Rana Ayman [a], Mingyu Zhu [b], Yomna ElGhazi [c]

[a] Faculty of Engineering and Environment, Northumbria University, Newcastle, NE1 8ST, UK
[b] School of Engineering, Newcastle University, Newcastle Upon Tyne, NE1 7RU, UK
[c] School of Architecture, Planning & Landscape, Newcastle Upon Tyne, NE1 7RU, UK

ARTICLE INFO

Keywords:
Building information modelling
Operational energy
Embodied energy
Life cycle assessment
Parametric design

ABSTRACT

In recent years advances in digital tools have been leading the way in the construction of cleaner, more energy-efficient buildings. Furthermore, improvements in Building Information Modelling (BIM) have resulted in various tools being used to assess building performance and overall Life Cycle Analysis (LCA). This work offers a unique insight into the development of a parametric LCA BIM tool, focusing on both operational and embodied energy perspectives through case study analysis of a commercial and a domestic building in the UK. A mixed research method was employed combining a literature review, qualitative and quantitative LCA case study analysis, and parametric modelling. The results indicate that embodied energy is much more critical in the early stages of the building's life, then is quickly overtaken by operational energy. In addition, many variations exist in energy outputs between domestic and commercial buildings. Operational energy takes a significant share in domestic buildings compared to commercial buildings. These variations are attributed to different design methods, construction materials, occupancy patterns and energy demands. The study proposes an LCA-BIM interactive user-led method of addressing energy hotspots for both operational and embodied elements, which can provide more instant identification of energy critical areas. Such an approach can offer real alternative BIM-based analysis tools during the design stages, compared to those currently being used, which focus mainly on either LCA of operational or embodied energy.

To cite**: Alwan, Z., Nawarathna, A., Ayman, R., Zhu, M., & Elghazi, Y. (2021). Framework for parametric assessment of operational and embodied energy impacts utilising BIM. Journal of Building Engineering, 102768.**

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