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Developing Eco Self-Build Community Housing as a Sustainable and Scalable Housing Solution in the UK

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A dissertation submitted to the University of Bristol
in accordance with the requirements for award of the degree of
Doctor of Philosophy in the Faculty of Engineering.

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Abstract

The government has set out targets for the UK to be net-zero carbon by 2050 and supply 300,000 new homes per year, yet conventional new build housing is struggling to achieve these aims. To address these challenges, this thesis proposes eco self-build community (ESBC) housing as an alternative solution and investigates the key factors in enabling it to become a sustainable and scalable housing solution in the UK. It uses Water Lilies, a 33-home scheme in Bristol, as the case study. The thesis comprises three main research areas. First, it investigates potential consumer preferences for ESBC housing, who are found to prioritise the provision of eco-housing with a low environmental impact and a sense of community, which is distinct from consumers of conventional self-build and custom-build housing, who prioritise location and the need to tailor the house design to the owner's unique aesthetic and lifestyle preferences. Second, it conducts a whole life cycle assessment of a typical ESBC housing shell and compares the impact of different insulation options and energy scenarios on embodied and operational carbon emissions. The results show that an ESBC building shell using hemp fibre insulation produces the least carbon emissions in both the operationally net-zero carbon Water Lilies Community Energy (WLCE) scenario and the best-case Future Energy Scenario (FES), Leading the Way, whereas the baseline polyisocyanurate insulation produces the least carbon emissions in the worst-case FES, Steady Progression. Furthermore, across all design options, the WLCE scenario demonstrates up to 68% carbon reductions compared to Steady Progression. Third, it provides a comprehensive evaluation of neighbourhood sustainability assessment tools (NSATs) and selects the Value Toolkit to evaluate Water Lilies. For this tool, it establishes a framework that provides unique sustainability indicators and benchmarks to drive future improvements in the design and delivery of future ESBC housing schemes.

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Special thanks go to my partner, Hannah, who has been my rock throughout this journey.

Author’s Declaration

I declare that the work in this dissertation was carried out in accordance with the requirements of the University's *Regulations and Code of Practice for Research Degree Programmes* and that it has not been submitted for any other academic award. Except where indicated by specific reference in the text, the work is the candidate's own work. Work done in collaboration with, or with the assistance of, others, is indicated as such. Any views expressed in the dissertation are those of the author.

SIGNED: PABLO NEWBERRY DATE: 23/03/2023

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List of Publications

This thesis integrates a series of publications as chapters, following guidance in Annex 5 of the University of Bristol's *Regulations and Code of Practice for Research Degree Programmes* (University of Bristol, 2023). This is explained in further detail in section 1.3. The thesis is based on the journal papers listed below.

1. **Newberry, P.**, Harper, P. and Morgan, T. (2021) 'Understanding the Market for Eco Self-Build Community Housing', *Sustainability*, 13(21), p. 11823.
2. **Newberry, P.**, Harper, P. and Norman, J. (in press) 'Carbon assessment of building shell options for eco self-build community housing through the integration of building energy modelling and life cycle analysis tools', *Journal of Building Engineering*.
3. **Newberry, P.** and Harper, P. 'Selecting and applying a Neighbourhood Sustainability Assessment system to evaluate an eco self-build community housing project', *Journal of Cleaner Production*. Manuscript in preparation.

Journal papers 1, 2, and 3 are presented in Chapter 4, 5, and 6, respectively. Any modifications to the original manuscripts to support the overall coherence of the thesis are highlighted at the beginning of each chapter.

The research for journal paper 1 proved to adhere to good ethical principles following a review post-completion. A favourable opinion was granted on 10/06/2022 with the reference number 10889. The research for journal paper 3 was granted ethics approval on 03/02/2022 with the reference number 9885. The research for journal paper 2 did not require ethics approval.

List of Abbreviations

AHP	Analytical hierarchy process
ASGE	Assessment Standard for Green Eco-districts
AusLCI	Australian National Life Cycle Inventory Database
BCIS	Building Cost Information Service
BECCS	Bioenergy with carbon capture and storage
BEIS	Department for Business, Energy and Industrial Strategy
BEM	Building energy modelling
BIM	Building information modelling
BREEAM	Building Research Establishment Environmental Assessment Method
CAD	Computer-aided design
CAMSUD	Comprehensive Assessment Method for Sustainable Urban Development
CASBEE-UD	Comprehensive Assessment System for Building Environmental Efficiency for Urban Development
CEPRO	Community Energy Prospector
CIEH	Chartered Institute of Environmental Health
CO_2	Carbon dioxide
DCLG	Department for Communities and Local Government
DHW	Domestic hot water
DIY	Do it yourself
EPD	Environmental Product Declaration
ESBC	Eco self-build community
ESG	Environmental, Social and Governance
EU	European Union
FES	Future Energy Scenario
FSC	Forest Stewardship Council
GIA	Gross internal area

GLA	Greater London Authority
GRI	Global Reporting Initiative
GW	Glass wool
GWP	Global warming potential
HF	Hemp fibre
HVAC	Heating, ventilation, and air conditioning
IES VE	Integrated Environmental Solutions Virtual Environment
IFC	Industry Foundation Classes
ISO	International Organization for Standardization
IStructE	Institution of Structural Engineers
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LEED-ND	Leadership in Energy and Environmental Design for Neighbourhood Development
LETI	London Energy Transformation Initiative
LOD	Level of development
MCDA	Multi-criteria decision analysis
MHCLG	Ministry of Housing, Communities and Local Government
MS	Microsoft
MVHR	Mechanical ventilation with heat recovery
NaCSBA	National Custom and Self Build Association
NHF	National Housing Federation
NMA	Non-material amendment
NSAT	Neighbourhood sustainability Assessment
NSBRC	National Self Build and Renovation Centre
OS	Outcome statement
OSB	Oriented strand board

PIR	Polyisocyanurate
PUR	Polyurethane
PV	Photovoltaic
RIBA	Royal Institute of British Architects
RICS	Royal Institute of Chartered Surveyors
RW	Rock wool
SAP	Standard Assessment Procedure
SCR	Sustainable Community Rating
SFCA	Standard Form of Cost Analysis
SPeAR	Sustainable Project Appraisal Routine
SWEMWS	Short Warwick-Edinburgh Mental Wellbeing Scale
TRNSYS	Transient System Simulation Tool
UGF	Urban Greening Factor
UK	United Kingdom
UKGBC	United Kingdom Green Building Council
UN	United Nations
US	United States
USA	United States of America
USLCI	United States Life Cycle Inventory
WHO	World Health Organization
WLCE	Water Lilies Community Energy
WLEMC	Water Lilies Estate Management Company
WRAP	Waste and Resources Action Programme

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Chapter 1 – Introduction

1.1 Background and Motivation

The UK government has committed to reaching net-zero carbon by 2050 (BEIS, 2021) whilst seeking to deliver 300,000 homes per year by the mid-2020s to provide for an increasing population and address years of under-supply (MHCLG, 2018). The housing sector is responsible for 27% of national energy demand (Martiskainen and Kivimaa, 2019) and approximately 15% of greenhouse gas emissions in the UK (BEIS, 2019). It is projected that building-related greenhouse gas emissions could rise to 21% unless immediate action is taken (Yeatts *et al.*, 2017). Therefore, if the UK is to meet the 2050 target, there must be an urgent transition toward energy efficient, zero-carbon homes and communities (Committee on Climate Change, 2019).

In order to decarbonise UK housing by 2050, it is clear that existing stock must be retrofitted with improved energy efficiency measures and zero-carbon technologies (Gillich, Saber and Mohareb, 2019). For example, on average, 60% of energy demand from the residential sector comes from space-heating, which can largely be attributed to poor thermal integrity of the building envelope in existing housing stock (Sousa *et al.*, 2017). However, whilst existing stock needs desperate improvement, delivering new energy efficient and zero-carbon homes is also imperative in the decarbonisation challenge (Heffernan *et al.*, 2015). The Energy Saving Trust (2017) calculated that, if just 200,000 homes were to be built each year between 2019 and 2032 without a ‘2050-ready’ homes policy, these would emit 43 million tonnes of avoidable CO_2 emissions between 2019 and 2050. Since there is a backlog of 4.3 million homes in Britain (Watling and Breach, 2023), seriously addressing this shortfall without appropriate carbon reduction measures in place would result in an even higher amount of CO_2 emissions. A report by the Committee on Climate Change (2019) asserts that it is not prohibitively expensive to build homes to the required design specification so as to meet carbon reduction targets, and it is much cheaper than forcing retrofit later. As well as considering the operational energy impact of homes, the embodied energy impacts of materials used in construction must also be taken into account, which can contribute up to one-fifth of whole-life carbon impacts (Ajayi, Oyedele and Ilori, 2019).

Presently, the mainstream model of speculative housebuilding in the UK is not ready to build homes to the standard necessary to ensure the 2050 net-zero carbon target is achieved, and current policy and regulations are not fit to support the decarbonisation transition with respect to housing (Parvin *et al.*, 2011; Energy Saving Trust, 2017; Martiskainen and Kivimaa, 2019). The profit-driven nature of the speculative housebuilder model (Nicol and Hooper, 1999) does not facilitate the delivery of sustainable homes (Maliene and Malys, 2009) nor does it create homes or communities that are designed to meet the specific needs of the end-users (Parvin *et al.*, 2011; Lane *et al.*, 2020). As set out in the Government's 2017 Housing White Paper, *Fixing Our Broken Housing Market*, the UK aims to move towards innovative, diverse and sustainable housing solutions and proposes to foster self-build and community-based approaches (DCLG, 2017).

Group self-build housing presents a bottom-up approach that can provide more environmentally and socially sustainable homes and empowered communities (Daly, 2017; Heffernan and de Wilde, 2020) in which homes are designed for the specific needs of occupants (Hamiduddin and Gallent, 2016) and a sense of community is cultivated by providing shared spaces, establishing common values, and encouraging social interaction and mutual support between residents (Williams, 2005; Vestbro, 2010; Chiodelli and Baglione, 2014; Ruiu, 2016). However, whilst group self-build housing may be part of the solution, such community-led models are not able to deliver at the scale necessary to meet the decarbonisation challenge (Hamiduddin and Gallent, 2016). Their degrees of success vary, with common problems encountered related to finding and buying land, planning, financing, skills gaps and self-governance (Tummers, 2016; Ward and Brewer, 2018). Furthermore, it is difficult to replicate certain approaches due to specific project challenges and different funding mechanisms, often with a reliance on government grants (Chatterton, 2013). As a result, group self-build and community-led housing only contribute a small proportion of new housing in the UK (Heffernan and de Wilde, 2020). The self-build sector delivers 8% of new homes in the UK (Lane *et al.*, 2020) and the community-led housing sector delivers 0.6% (Heywood, 2016).

Eco self-build community (ESBC) housing provides an alternative solution that gives people the opportunity to design and build their own home as part of a sustainable housing community. It was established by the developer, Bright Green Futures, following research suggesting it could be a financially viable housing solution that had the potential to significantly reduce carbon emissions in the UK (Broer and Titheridge, 2010; Broer, 2012). ESBC housing offers self-build and custom-build homes that integrate sustainable construction materials, high energy efficiency measures and renewable energy systems with access to communal spaces and facilities on-site. During the design and build process, the developer facilitates one-to-one sessions and community workshops to support the group. The developer takes on the project risks so individuals can create their homes and community without needing to form the group, identify land, obtain planning permission, contract construction, and secure finance (Hughes, 2020).

Water Lilies is Bright Green Futures' flagship 33-home ESBC housing project. It is a net-zero carbon scheme consisting of self-finish and custom-build homes based around a shared garden and community building. The scheme has developed from the planning stage through to construction during the course of this research project. Water Lilies combines a net-zero design approach with a unique delivery method (described in detail in Chapter 2), providing a potential proof of concept as a scalable housing model that can deliver sustainable homes and communities in the UK. However, previous research has not provided insights regarding the market for ESBC housing and whether Water Lilies satisfies this market, the life cycle carbon impacts of a typical ESBC home, and the multiple dimensions of sustainability that need to be evaluated to assess the performance of ESBC housing.

1.2 Research Objectives

This research uses Water Lilies as a case study to investigate the key factors in enabling ESBC housing to become a sustainable and scalable housing solution in the UK. The research is broken down into three main areas: investigating potential consumer preferences in the ESBC housing market and how effectively these are met by current ESBC schemes such as Water Lilies; investigating the environmental impacts of ESBC housing compared to alternative design options; and investigating how a comprehensive evaluation of the Water Lilies project can be conducted to drive future improvements in the design and implementation of ESBC housing schemes. Based on the motivation for the work and the detailed literature review presented in Chapter 3, the following more detailed research objectives were defined, where 1 and 2 are linked to understanding consumer preferences, 3 and 4 are linked to investigating environmental impacts; and 5 and 6 are linked to developing a robust evaluation framework for Water Lilies:

1. To identify the factors that influence the purchasing decisions of potential ESBC housing consumers and how they compare to the market for conventional self-build and custom-build housing.

2. To evaluate the extent to which the ESBC development model satisfies the market and what further development of ESBC schemes is needed to facilitate their future expansion.
3. To develop a method that integrates building energy modelling and life cycle assessment tools to conduct a whole life cycle assessment of a typical ESBC housing shell.
4. To evaluate and compare the 60-year life cycle carbon impacts of different construction materials and energy scenarios on a typical ESBC terraced building shell.
5. To provide a comprehensive evaluation of neighbourhood sustainability assessment tools and select the most suitable for ESBC housing using a method of multi-criteria decision analysis.
6. For the selected neighbourhood sustainability assessment tool, develop an implementation framework for a comprehensive evaluation of Water Lilies and other similar ESBC housing schemes.

The research conducted to address these objectives features a variety of novel aspects in relation to both self-build and sustainable community housing schemes:

- It provides insights to the market for ESBC housing compared to conventional self-build and custom-build housing.
- It demonstrates a method of integrating specific building energy modelling and life cycle assessment tools to perform a whole life cycle assessment.
- It utilises projected scenarios for the carbon intensity of the UK's national grid to assess operational carbon emissions over time.
- It provides a comprehensive evaluation of neighbourhood sustainability assessment tools using an original framework that can support decision-makers to select a suitable tool to evaluate their development project.

1.3 Thesis Structure

The structure of the thesis follows 'guidance on the integration of publications as chapters' in Annex 5 of the University of Bristol's *Regulations and Code of Practice for Research Degree Programmes* (University of Bristol, 2023). This states that publications (e.g., journal articles, conference proceedings or official reports) can be included as individual chapters within the thesis, provided it remains as a coherent, single document. Furthermore, the student may be the sole or co-author of the publications. For co-authored publications, the student must make a substantial contribution, and this must be clearly stated in the thesis. Therefore, my contribution as lead author of each publication is stated at the beginning of Chapters 4, 5 and 6.

This thesis contains seven chapters. Following this chapter, Chapter 2 provides an overview of the case study Water Lilies project, Chapter 3 is a literature review, Chapters 4, 5 and 6 are adapted versions of journal papers that investigate the research objectives defined in section 1.2, and Chapter 7 draws together the main conclusions from the research, including recommendations for the future design and delivery of ESBC housing, and important further research required. To ensure a coherent narrative, at the start of Chapters 4, 5 and 6 a brief rationale for the research based on findings from the literature review and/or the preceding paper is provided. A detailed description of each chapter is provided below.

- **Chapter 2: Case Study Overview**

  This chapter describes the Water Lilies project as the case study for this research. It introduces the main aspects of the scheme and provides details on the site and location, the masterplan, sustainable building design features, renewable energy technology, self-finish and custom-build home typologies, community workshops and support provided by the developer, and lifestyle carbon emission reductions. Finally, it explains the stages of the development process.

- **Chapter 3: Literature Review**

  This chapter provides an extensive literature review consisting of four sections. Section 3.1 defines ‘sustainable housing’ in the context of this research and highlights the key drivers and barriers to sustainable housing in the UK. Section 3.2 describes housing delivery models including conventional speculative housebuilding as the dominant model and self-build and custom-build, group self-build, and community-led housing as alternative models. Furthermore, it presents data demonstrating demand for these alternative models and outlines examples of projects, like ESBC housing, that are led by a developer to facilitate the delivery of sustainable self-build, custom-build and community housing. Section 3.3 discusses the literature on building life cycle assessments, including the methodology, its limitations, and tools to conduct assessments. Moreover, it highlights that residential building lifecycle assessment rarely assess both embodied and operational carbon emissions or account for the energy mix of the grid in their calculations. The integration of building information modelling and building energy modelling tools in the life cycle assessment process is highlighted as an effective method of performing a whole life cycle assessment. Finally, section 3.4 reviews the literature on neighbourhood sustainability assessment tools. It makes the distinction between third-party rating systems and plan-embedded tools and provides examples. It discusses the strengths and weaknesses of neighbourhood sustainability assessment tools with respect to a range of criteria.

- **Chapter 4: Understanding the Market for Eco Self-build Community Housing**

This chapter presents a modified version of journal paper 1 in 'List of Publications' and addresses research objectives 1 and 2 set out in section 1.2. This paper gains a broad understanding of the market for ESBC housing by analysing and comparing survey data from potential ESBC housing consumers with data from a similar survey targeted at the market for conventional self-build and custom-build housing. It identifies the factors that influence the purchasing decisions of potential ESBC housing consumers, which are compared to the market for conventional self-build and custom-build housing. Furthermore, it evaluates the extent to which the ESBC development model satisfies the market and highlights opportunities for scaling up the delivery of ESBC housing.

- **Chapter 5: Carbon Assessment of Building Shell Options for Eco Self-Build Community Housing Through the Integration of Building Energy Modelling and Life Cycle Analysis Tools**

This chapter presents a modified version of journal paper 2 in 'List of Publications' and addresses research objectives 3 and 4 set out in section 1.2. This paper developed a method that integrates building energy modelling and life cycle assessment tools, IES Virtual Environment and One Click LCA, to perform a whole life cycle assessment of a typical ESBC housing building shell. It evaluates and compares the 60-year life cycle operational and embodied carbon impacts of design options using different insulation materials to the baseline case study building shell. The results are based on the application of different scenarios for the proportion of renewables in the energy supply over time, using the best- and worst-case Future Energy Scenarios for connection to the national grid and the Water Lilies Community Energy scenario for connection to a localised operationally net-zero carbon microgrid.

- **Chapter 6: Selecting and Applying a Neighbourhood Sustainability Assessment System to Evaluate an Eco Self-Build Community Housing Project**

This chapter presents a modified version of journal paper 3 in 'List of Publications' and addresses research objectives 5 and 6 set out in section 1.2. This paper provides a comprehensive evaluation of neighbourhood sustainability assessment tools and selects the most suitable for application to Water Lilies by using the analytical hierarchy process as a method of multi-criteria decision analysis. Furthermore, it defines the specific implementation measures for the selected tool that are required to successfully evaluate Water Lilies. This provides insights to the unique sustainability indicators for ESBC housing and how they are prioritised and evaluated, thus establishing a framework with performance benchmarks to deliver sustainable schemes in the future.

- **Chapter 7: Conclusions and Further Work**

This chapter presents the overall conclusions stemming from Chapters 4, 5 and 6, including recommendations to make eco self-build communities a sustainable and scalable housing solution in the UK, and highlights future work that could support this case.

1.4 Research Methodologies

The overarching methodology for this research is a case study approach, using a mix of methods to address the research objectives set out in section 1.2. The following section, 1.4.1, briefly describes the case study approach, including a justification for using it in this research and the limitations of using Water Lilies to generalise about ESBC housing and its relatability to other contexts. Then, section 1.4.1 summarises the specific methods applied in Chapters 4, 5 and 6, discussing their suitability and limitations. A detailed explanation of the specific methods is provided in Chapters 4, 5 and 6.

1.4.1 Case Study Approach

A case study approach facilitates the exploration of a phenomenon within its context through a variety of lenses and using a variety of data sources to reveal and understand multiple facets of the case (Baxter and Jack, 2008). According to Yin (2018), the case study approach might be a favourable method when: (a) the form of the research question is a "how" or "why" question; (b) the researcher has little or no control over behavioural events;

and (c) the research focuses on contemporary rather than entirely historical phenomena. This research is suited to a case study approach because it aims to explore how ESBC housing can become a sustainable and scalable housing solution in the UK. As such, Water Lilies, provides a discreet case study to investigate multiple facets of the housing model, using a mix of methods to address the research objectives described in section 1.3, and gain generalised knowledge about ESBC housing as a contemporary phenomenon. A common concern about case study research is the inability to generalise from a single-case study (Yin, 2018) but for certain research, it is a necessary and sufficient method that one can often generalise from (Flyvbjerg, 2006). For this research project, it is a necessary method because Water Lilies is the first example of ESBC housing in the UK and the learning gained from its implementation can help inform the approach used for similar schemes in the future.

Regardless, issues related to generalisation should be acknowledged with respect to this research. First, the Water Lilies development is situated in the physical, social, and economic context of northwest Bristol. Hence, any findings and conclusions will be guided by that context. For instance, a large proportion of people interested in purchasing a home in Water Lilies may be situated in or near Bristol because they have encountered the scheme through word of mouth or local media. The appetite for self-build and custom build community housing and socio-economic circumstances of individuals differs across the UK. Therefore, the research should be careful in how it uses market data to generalise about ESBC housing preferences and inform the development of future schemes. In addition, political support for innovative housebuilding approaches and specific policy related to self-build and custom build housing and net-zero carbon development can affect the viability of ESBC housing development. So, these market and policy factors should be understood within the context of Bristol.

Second, the Water Lilies site has certain physical characteristics and constraints that affect the way in which the scheme is delivered, including its shape and size, ground conditions, green and blue infrastructure, and local climate. These factors shape the development in terms of design (e.g., foundation types, building forms, material choices, renewable and low carbon technologies), access (for the main building contractor and self-builders and their sub-contractors), and construction (e.g., labour and machinery). As such, general insights gained from evaluating aspects of Water Lilies need to be understood within the context of the site characteristics.

Third, the Water Lilies design and delivery team, including the developer (Bright Green Futures), main building contractor, and project architect are involved in developing the first ESBC housing scheme of its kind. They are implementing novel approaches to development and learning what does and does not work as the project progresses. This means that insights regarding ESBC housing design and delivery should be understood within the context of the delivery team's experience of developing Water Lilies, as well as their capacity and resources to undertake the development. Therefore, the knowledge acquired but not necessarily implemented in Water Lilies should be considered in future ESBC housing.

Whilst acknowledging the limitations of generalisation, it is essential to investigate ESBC housing through Water Lilies as a case study since it serves as a proof-of-concept. Furthermore, it provides a live scheme that has been through multiple stages of delivery during the course of this research project, from planning permission through to fit-out. This exposed the researcher to a range of development processes and stakeholders and facilitated an in-depth understanding of multiple facets of the project that either contextualise or are directly relevant to the main areas of research.

1.4.2 Summary of Methods

The papers presented in Chapters 4, 5 and 6 require completely different methods in response to the research objectives set out in section 1.2. Chapter 4 adopted a survey methodology to understand the market for ESBC housing. Two surveys were used. Survey 1 was an online survey, embedded on the Bright Green Futures website, using non-probability convenience sampling to target people registering an interest in an ESBC home, such as Water Lilies (i.e. the market for ESBC housing). Survey 2 was an online survey using non-probability purposive sampling to target people that want to design and/or build their own home or are in the process of doing so (i.e. the market for conventional self-build and custom-build housing). By comparing the results of Survey 1 and Survey 2, the factors that might influence purchasing decisions could be identified, highlighting potential differences between the markets. A significant limitation is that a disproportionate number of people responding to Survey 1 would be based in or intend to move to Bristol because this is where Water Lilies and the developer, Bright Green Futures, are situated, compared to Survey 2, which is not linked to a specific location and housing scheme. Therefore, any conclusions should acknowledge that the understanding of the market for ESBC housing is currently limited by the reach of Bright Green Futures and Water Lilies. However, as the market for ESBC housing has not been investigated before, for Survey 1, non-probability convenience sampling using a website survey was considered the most suitable method to both identify and collect data on a yet established population.

Chapter 5 developed a method to model and simulate a whole life cycle carbon assessment of a typical ESBC housing shell. The integration of building energy modelling and life cycle assessment tools, IES Virtual Environment and One Click LCA, was considered a suitable method of calculating both operational and embodied carbon emissions in a streamlined manner, building on the literature reviewed in section 3.3. Furthermore, it enables a flexible and efficient method for evaluating different construction options at an early design stage. A limitation of applying this method to the case study regards the time and location in which Water Lilies is being developed. These factors influence the case study in terms of climate, site conditions, material availability, manufacturing processes and transportation distances, and the carbon intensity of the national grid. Hence, generalised insights regarding the life cycle carbon impacts of ESBC housing should be considered within the time-location context of Water Lilies, and data should be adjusted accordingly for assessing developments on future sites.

Chapter 6 adopted a three-phase methodology to select a suitable neighbourhood sustainability assessment tool (Phase 1), specify the implementation measures for the selected tool (Phase 2), and evaluate Water Lilies using the tool (future research for Phase 3). This was considered a robust method for assessing a range of neighbourhood sustainability assessment tools; selecting one that is most suitable for evaluating ESBC housing within the context of Water Lilies; establishing and prioritising sustainability indicators and performance benchmarks; and using this framework to evaluate the scheme. Grounding this method in the context of Water Lilies enabled the needs of ESBC housing to be reflected in the tool selection process and the definition of implementation measures. It demonstrates a method that is replicable in different contexts. However, applying the same tool and implementation measures to other ESBC housing developments could be problematic because the needs of Water Lilies may differ to those in future schemes (e.g. changes in the capacity and resources of the developer and the requirements of the development). Therefore, specific indicators and performance benchmarks may have different levels of importance in different contexts. Nevertheless, using Water Lilies as a case study provides the opportunity to establish a robust method for selecting a neighbourhood sustainability assessment tool and a process for defining the factors considered most important to the development of ESBC housing across multiple dimensions of sustainability.

1.5 Summary

This chapter established the background and motivation for the research into ESBC housing as a potentially scalable model that can deliver sustainable homes and communities in the UK. This led to the formulation of research objectives that use the Water Lilies development as a case study. The explanation of the thesis structure provided an overview of what to expect in each chapter. Finally, it outlined the case study approach as an overall methodology, justifying its use and summarising the distinct research methodologies used in its application, which are described in detail in Chapters 4, 5 and 6. The following chapter provides an overview of the Water Lilies case study.

Chapter 2 – Case Study Overview

The case study for this research was Water Lilies, a 33-home eco self-build community housing scheme in Bristol being developed by Bright Green Futures. The scheme enables residents to design (and build) their home, shape their community, and lead sustainable lifestyles (Bright Green Futures, 2022). The scheme consists of 21 self-finish houses and 12 custom-build flats designed around a central community garden and community building that are owned and managed by residents through a not-for-profit company, Water Lilies Estate Management Company (WLEMC). WLEMC is made up of members and an elected board of directors, and all members can participate in group decision-making. The purpose of WLEMC is to manage the community assets and maintain them to a high quality in perpetuity to benefit the residents of Water Lilies and the wider community (Bright Green Futures, 2021e). Water Lilies aims to be net-zero carbon by utilising energy efficient building design, low carbon materials, renewable energy connected to a community microgrid, and battery storage (Bright Green Futures, 2021a, 2021c). As of March 2023, most homeowners had completed and were living in their homes. Water Lilies is the first ESBC housing development of its kind; it can potentially provide a blueprint for future ESBC schemes and demonstrate a scalable housing model to deliver sustainable homes and communities in the UK.

2.1 Site and Location

The site is located on a former reservoir site of approximately 0.5 hectare in Kings Weston, Bristol (see Figure 1). It is on a west facing slope that overlooks the Severn Estuary and South Wales. The surrounding hillsides are covered predominantly by inter-war and post-war terraced housing with the exception of rough grass and woodland on the adjacent hilltop to the south-east (Marshall and Kendon Architects, 2017).

Figure 1. Water Lilies site location in Kings Weston, Bristol

2.2 Masterplan

The scheme was designed following cohousing principles (UK Cohousing Network, 2021), including features such as a community garden, community building, and shared facilities, to encourage community cohesion. The community building provides a physical space for group decision-making and a multitude of uses that can also serve the wider community. The existing reservoir (L: 50m x W: 15m x D: 4m) was converted into underground parking with a concrete deck above for the community garden and pond. The houses, with their own private gardens, face the community garden and work with the topography by stepping down the north-west slope. There is visitor parking at the single point of access for vehicles to the north, and another point of access for pedestrians from the public footpath to the east. Figure 2 shows the Water Lilies site plan.

Figure 2. Water Lilies site plan

2.3 Sustainable Building Design

The houses, in the style of townhouses, are two- to three-storey and the rows of terraces have roof terraces overlooking the community garden. The house building shells use sustainably sourced timber (labelled FSC mix) as the primary structural material, which sequesters carbon during the tree growth and provides a load-bearing frame that allows self-builders to design their internal layout flexibly (Darren Evans Building Energy Efficiency, 2017). The houses are designed as A-rated for energy efficiency and environmental performance. This is achieved through highly energy efficient building fabrics that have Passivhaus standard U-values and an airtightness of $2m^3/h/m^2$@50pa, which further prevents heat loss. Mechanical Ventilation with Heat Recovery (MVHR) is an optional addition for self-builders to help maintain comfortable temperatures and optimise air quality. The external wall and roof elements follow the same construction principles including two layers of energy efficient PIR insulation outside the timber frame. The walls are finished with render on carrier board and the roof is finished with a profiled galvanised steel roof covering. The windows and doors are double- or triple-glazed and have a wood-aluminium frame. These consistent external features provide the homes with a coherent appearance. All the buildings are oriented to maximise passive solar gain. Further detail on building design is in section 5.2.1.

2.4 Renewable Energy Technology

Water Lilies has the UK's first net-zero carbon residential microgrid. This localised electricity network combines national grid electricity with renewable energy generated by solar PV panels on south-east and south-west facing roofs. The energy is stored on-site in a high-capacity battery and is shared across the site, providing low-carbon, cost-effective energy to residents. Houses have air source heat pumps (ASHPs) and water saving products, minimising the electricity required to provide hot water for both their heating system and hot water supply. Any residual emissions (e.g. energy imported during darker periods of the year when solar PVs are less effective) are offset by procuring additional renewable energy (e.g. off-site wind farms) through the microgrid company (Bright Green Futures, 2021d), following guidance from "Renewable Energy Procurement & Carbon Offsetting: Guidance for net zero carbon buildings" by UK Green Building Council (UK Green Building Council, 2021).

2.5 Lifestyle Carbon Emission Reduction Measures

Further to building materials and energy, Water Lilies seeks to minimise carbon emissions related to residents' lifestyles through the following measures:

- Travel-related carbon emissions are reduced as residents can integrate offices or studios to work from home or use the community building for co-working. Furthermore, the shared garden and community building provide spaces for social activities and childcare on-site. Finally, it provides the minimum number of car parking spaces permitted along with electric vehicle plug-in stations and secure bicycle storage, as well as a car-share scheme.
- Waste-related carbon emissions are reduced by integrating a communal recycling facility and setting up a community recycling scheme with the local authority.
- Consumable-related carbon emissions can be reduced as residents may arrange for local and sustainable food to be sourced communally through WLEMC and community-based living encourages household items to be shared.

2.6 Self-Finish and Custom-Build

Water Lilies has a mixture of 21 self-finish houses and 12 custom-build flats. With self-finish, residents design the layout of their home with the project architect. The building shell is constructed by the main contractor then the residents fit-out the home through a combination of employing contractors, project management, and DIY. Table 1 shows what is included in the self-finish building shell at handover and what the homeowners need to install to complete the fit-out.

Table 1. Self-finish building shell at handover and fit-out requirements

Self-finish building shell at handover	Self-finish fit-out requirements
• Foundations • Ground floor (excluding insulation and screed) • Upper floors • External walls • Roof • Balconies (if present) • Capped services, including electricity and water • Telephone line and internet cables • Air source heat pump	• Kitchen • Bathrooms • Internal walls and doors • Stairs, balustrades, and handrails • Mezzanine floor structures (if wanted) • Plumbing, electrics, and heating (e.g. radiators or underfloor heating) • Any additional fixtures and fittings

On the other hand, with custom-build, residents work with the project interior designer to choose various fit-out options (including door finishes, paint colours, kitchen and bathroom tiling, kitchen cupboard doors and worktop finishes, and flooring materials), then the flats are built to completion by the main contractor (Newberry, Harper and Morgan, 2021).

2.7 Community Workshops and Individual Support

The developer, Bright Green Futures, engages the community in decision-making during the design and construction process. It expands the conventional role of a housing developer by facilitating individual design and mentoring sessions and workshops to provide support to the community group, covering topics such as sustainable building materials, heating and energy systems, project management, and employing tradespeople (Bright Green Futures, 2019). Expertise from contractors working on the project is employed to engage residents on issues such as technical design, construction, and project management.

2.8 Development Process

The Water Lilies delivery model operates within mainstream housebuilding practices and returns profits for investment in future schemes without relying on grant funding. Once the homes are complete and residents move in, ownership of the site and its community assets is transferred to the community. Table 2 describes the ESBC development process as applied to Water Lilies. In practice, there are overlaps between stages (e.g. marketing and sales may continue throughout project until all the homes are sold).

Table 2. ESBC housing development process

Stage	Description
1. Funding	ESBC developer receives investment towards project in the same way a conventional speculative housebuilder would, promising a return to investors.
2. Land acquisition	ESBC developer finds a site and negotiates a deal with the landowner(s).
3. Development design	ESBC developer works closely with the project architect to design a scheme that delivers environmental and social sustainability.
4. Planning permission	ESBC developer applies for planning permission for the scheme design.
5. Marketing and sales	ESBC developer markets the homes and customers buy into the scheme, forming the community group.
6. Individual design sessions	Self-finishers design internal layouts with the project architect. Any significant changes require a non-material amendment (NMA) planning application. Custom builders make design choices with the interior designer.
7. Community workshops	ESBC developer facilitates a series of workshops with the community group to support them at various stages of their project and encourages participation and collaboration.
8. S106 and building regulations	The project undergoes Section 106 agreements and building regulations approval.
9. Tendering	ESBC developer tenders for construction and a main contractor is appointed.
10. Main contractor construction	Main contractor constructs the building envelopes ('shells') of the self-finish houses with services attached, the custom-build flats (fit-out by separate contractor), and the community infrastructure.
11. Estate Management Company	ESBC developer works with the community to develop a self-management structure. This is set out contractually in an estate management company.
12. Fit-out	Self-finishers complete the fit-out of their homes through a combination of project management, DIY, and subcontractor employment. A separate contractor completes the custom-build apartments to customer design specifications.
13. Move-in	Residents move into their homes, taking ownership of community assets including a shared garden and community building.

14. Reinvestment in new projects	ESBC developer aims to gain 15–20% profit and reinvest this into another ESBC housing project.

2.9 Summary

This chapter provided an overview of the case study, Water Lilies, outlining the site and location, the masterplan, sustainable building design, renewable energy technology, lifestyle carbon reduction measures, self-finish and custom-build housing options, community workshops and individual support, and the development process. The following chapter is the literature review, which informs the research undertaken in this thesis.

Chapter 3 – Literature Review

3.1 Towards Sustainable Housing in the UK

The United Nations Brundtland Commission (World Commission on Environment and Development, 1987, p. 1) provides a widely accepted definition of sustainable development as being able to “meet the needs of the present without compromising the ability of future generations to meet their own needs.” However, there are struggles over the definition of ‘sustainable housing’ with calls for a more specific definition (Lovell, 2004). The Brundtland Report’s definition has been adapted by Priemus (2005, p. 6) to define sustainable housing as “housing that is geared to meeting the needs of the current residents without compromising the ability of future generations of residents to meet their own needs”. Yet, sustainable housing has often been considered in relation to environmental sustainability, omitting social and economic dimensions (Bhatti, 2001; Lovell, 2004; Priemus, 2005).

Choguill (2007, p. 145) argues the Brundtland Report’s definition is too simplistic to apply in practice and seeks to operationalise it across multiple dimensions of sustainability, stating that sustainable housing initiatives “must be economically viable, socially acceptable, technically feasible and environmentally compatible”. As such, this definition identifies a series of dimensions across which housing needs to perform for it to be considered sustainable. It does not, however, offer a calibration of the levels of performance required. Furthermore, Egan (2004, p. 7) defines ‘sustainable communities’ as being able to “meet the diverse needs of existing and future residents, their children and other users, contribute to a high quality of life and provide opportunity and choice. They achieve this in ways that make effective use of natural resources, enhance the environment, promote social cohesion and inclusion, and strengthen economic prosperity.”

These definitions help ensure that the issues associated with providing sustainable housing and communities are considered and evaluated in this research. The following sub-sections discuss the environmental, social, and economic impact of housing, and the drivers and barriers to delivering sustainable housing.

3.1.1 Environmental, Social and Economic Impact of Housing

As highlighted in section 1.1, the UK government has committed to reaching net-zero carbon by 2050 (BEIS, 2021) whilst delivering 300,000 homes per year by the mid-2020s (MHCLG, 2018). Many years of under-supply has led to rising costs and greater need for housing that people can afford (McManus, Gaterell and Coates, 2010). According to an estimate commissioned by the National Housing Federation (NHF) and Crisis from Heriot-Watt University (Bramley, 2019), there needs to be a supply of approximately 150,000 affordable homes per year in England (around 90,000 from new social housebuilding, 27,000 from shared ownership, and 33,000 from intermediate affordable rent). The problem of affordability is compounded by rising energy prices, with domestic gas prices increasing by 95% and domestic electricity prices by 54% from June 2021 and June 2022 (Harari *et al.*, 2022). This has substantially increased the cost of living and put household budgets under strain.

In terms of environmental impact, the housing sector is responsible for 27% of national energy demand (Martiskainen and Kivimaa, 2019) and approximately 15% of greenhouse gas emissions in the UK (BEIS, 2019), contributing significantly to climate change. 20% of the UK housing stock consists of pre-1919 homes, which are the least energy efficient, contributing 9.4 tCO_2e/year compared to 1.5 tCO_2e/year in current new build housing (Kaveh *et al.*, 2018). While investment to retrofit over 20 million dwellings in the UK is essential to reducing energy consumption and carbon emissions (Alabid, Bennadji and Seddiki, 2022), this research focuses specifically on the role of new housing development.

As well as planetary health, housing has a significant impact on human health, including physical, mental, and social wellbeing. The World Health Organization's (WHO, 2018) understanding of housing is broken down into a four-layer model: (1) the *home*, which brings a sense of belonging, security, and privacy; (2) the physical properties of the *dwelling* and their impact on physical health, such as being structurally sound, providing comfortable temperatures, adequate sanitation and lighting, sufficient space and connection to utilities, and protection from mould and pests; (3) the *community*, which supports health and wellbeing through social interactions and; (4) the *immediate housing environment*, which has an impact on health through the quality of urban design, including access to services, green space, and active and public transport.

These aspects of housing have been widely discussed in the literature in relation to their social impact. Bonnefoy (2007) asserts that the *home* represents a refuge from the outside world and can develop a sense of identity and attachment for individuals or families, whilst Kearns *et al.* (2000, p. 389) highlight the social-psychological aspects of the home "as a haven, as a site of autonomy, and providing social status". Fuller-Thomson, Hulchanski and Hwang (2000) describe how physical properties of the *dwelling*, such as building type and layout, can impact mental health (e.g. depression), and dampness and mould, indoor air quality and temperature and ventilation, can impact physical health (e.g. respiratory conditions). Furthermore, the socio-economic status of a household plays a significant role in the quality of its housing situation, with low-income households paying a higher percentage of their income for relatively low quality housing compared to higher income households (Fuller-Thomson, Hulchanski and Hwang, 2000). In terms of *community*, Shaw (2004) emphasises the ability of social networks to encourage people to support one other and the influence of community and social trust on health. With respect to the *immediate housing environment*, one study found that access to green spaces and community facilities were amongst the most important factors in the physical environment that people associated with mental wellbeing (Guite, Clark and Ackrill, 2006).

Demand for new housing, including a large proportion of affordable dwellings, combined with the urgent need to decarbonise the sector, underlines the importance of building a cost-effective, energy efficient, and low carbon supply at speed. Furthermore, the literature demonstrates the social impact of housing on people and communities and can inform the way new housing developments are designed to promote healthy living. The following sub-section highlights some of the mechanisms that can help drive the delivery of sustainable housing in the UK and confront the environmental, social, and economic challenges discussed, as well as the barriers.

3.1.2 Drivers and Barriers of Sustainable Housing

A range of policies, regulations, and industry-led tools and initiatives have supported, and continue to support the development of sustainable housing in the UK. Firstly, the Code for Sustainable Homes was introduced by the UK's Labour government in 2007 "as a voluntary national standard to improve the overall sustainability of new homes by setting a single framework within which the home building industry can design and construct homes to higher environmental standards." (DCLG, 2009b, p. 3). The Code consisted of nine categories: energy and CO_2, pollution, water, health and wellbeing, materials, management, surface water run-off, ecology, and waste, which could be rated from 1–6, with 1 being the lowest and 6 the highest rating, demonstrating exemplary performance (Gibbs and O'Neill, 2015). As the categories focus predominantly on environmental aspects of sustainability, it is argued that the Code treated social and economic aspects as peripheral (Prochorskaite and Maliene, 2013). Furthermore, the additional costs of meeting requirements of the Code were prohibitive, particularly for social housing (McManus, Gaterell and Coates, 2010). Although the UK government had planned to make the highest level of the Code mandatory for all new homes by 2016 (Fischer and Guy, 2009), it was withdrawn in 2015 by the Conservative and Liberal Democrat coalition government (MHCLG, 2015a).

To achieve the ambition to be net-zero carbon by 2050, the UK government now plans to introduce the Future Homes Standard to improve the environmental performance of new homes through changes to Part L (conservation of fuel and power) and F (ventilation) of Building Regulations that will come into effect from 2025 (MHCLG, 2019). As a result of these changes, it is expected that an average home built with high building fabric standards and a low carbon heating system will have 75-80% less carbon emissions than one built to current energy efficiency standards (MHCLG, 2019). In response to consultation on the Future Homes Standard, the Chartered Institute of Environmental Health (CIEH, 2020) argues that the anticipated carbon reductions are insufficient and that the Standard must ensure new homes are built to zero carbon by focusing more on fabric standards than relying too heavily on the decarbonisation of the electricity grid. Furthermore, it should consider carbon emissions across the whole life cycle of the building (CIEH, 2020).

The construction industry is also increasingly willing to deliver net-zero carbon buildings, as demonstrated by the UK Green Building Council’s partnership with a range of industry stakeholders, including trade associations, professional institutions, private organisations (including developers and manufacturers), and non-profit organisations, to develop a definition for net-zero carbon buildings in the UK. This led to the publication of *Net Zero Carbon Buildings: A Framework Definition*, freely available guidance for “building developers, designers, owners, occupiers and policy makers to inform the development of building tools, policies and practices” (UKGBC, 2019, p. 9). Furthermore, the Royal Institute of British Architects (RIBA) produced the *RIBA Plan of Work 2020 Overview*, which provides a consistent framework, based on nearly seven years of feedback from the construction industry, guiding clients on outcomes, tasks, statutory processes, procurement routes, and information exchanges across eight stages of a building project, including briefing, designing, delivering, maintaining, and operating (RIBA, 2020). This includes tasks aligned to the RIBA Sustainable Outcomes Guide, which defines measurable outcomes including net-zero operational carbon, net-zero embodied carbon, sustainable water cycle, sustainable connectivity and transport, sustainable land use and biodiversity, good health and wellbeing, sustainable communities and social value, and sustainable life cycle cost, each of which are underpinned by UN Sustainability Goals, and ways to achieve and evaluate them (RIBA, 2019).

In terms of reducing carbon emissions in the housing sector, the life cycle assessment methodology is being increasingly adopted to optimise design and reduce the environmental impacts of buildings (Anand and Amor, 2017; RICS, 2017) with several tools available to calculate embodied and operational carbon emissions (Islam, Jollands and Setunge, 2015). The literature on building life cycle assessments is reviewed in section 3.3. Furthermore, standards have been established to support the integration and evaluation of environmental, social, and economic sustainability in development projects using a range of methods and metrics. BREEAM (Building Research Establishment Environmental Assessment Method), founded in 1990, is a third-party sustainability assessment and certification system that aims to improve the performance of an asset across its life cycle in terms of net-zero design, health and social impact, circularity and resilience, and biodiversity (BREEAM, 2023a). At the neighbourhood scale, BREEAM Communities was developed to assess and certify sustainable design in the development of new communities and regeneration projects (BREEAM, 2023b). The academic literature defines this framework as a ‘neighbourhood sustainability assessment tool’ (NSAT). These are described in detail in section 3.4.

Despite the drivers highlighted, risk is identified as a major barrier to developing sustainable housing. Siebert *et al.* (2018) highlights areas of technical, commercial, and financial risk associated with innovative sustainable solutions. High technical risk arises from new technologies being “unproven, open to the threat of competition, and potentially difficult to warranty” and will only be accepted if considered necessary, viable, and practical. High commercial risk comes from their dependence on changes to policies, tariffs, and regulations, the willingness of supply chain businesses to participate in their implementation, and the uncertainty of public acceptance. Finally, the cost of promoting innovative solutions and any training and reskilling required to deliver them comes with high financial risk.

3.1.3 Conclusion

This section highlighted definitions of ‘sustainable housing’ and ‘sustainable communities’ to help shape the way sustainability is considered in the context of this thesis. Furthermore, it covered some of the environmental, social, and economic impacts of housing to provide a backdrop to why striving for sustainable housing is important. Finally, it outlined key drivers and barriers to sustainable housing. The following section, 3.2, reviews different housing delivery models and suggests the extent to which they can deliver high quality, sustainable housing communities. Section 3.3 then discusses the use of building life cycle assessments to reduce the environmental impact of housing and section 3.4 examines NSATs to evaluate the performance of whole neighbourhood developments across the multiple dimensions of sustainability.

3.2 Housing Delivery Models

This section of the literature review has been extracted and modified from the published paper 'Understanding the Market for Eco Self-Build Community Housing' that is discussed more fully in Chapter 4.

To contextualise ESBC housing, the following subsections briefly discuss the literature on speculative housing and forms of grassroots and developer-led self-build, custom-build, and community-led housing. Firstly, it describes how speculative housebuilding can lead to issues with design, construction quality, sustainability, and community aspects because the model prioritises cost and efficiency. It then discusses self-build, custom-build, and forms of community-led housing as alternative models of housing that have the potential to address the problems associated with speculative housebuilding. It further highlights the key barriers that make it difficult for individuals and groups to initiate and complete self-build community projects. It provides examples of developer-led self-build, custom-build and community housing schemes which demonstrate that developers may be able to overcome the key barriers to deliver such housing at scale.

3.2.1 Speculative Housebuilding

The largest speculative housebuilders construct the majority of new homes in the UK—in 2017, speculative housebuilders delivered 63% of all new homes (Savills, 2018). As a result, these housebuilders have a great responsibility in shaping the development of homes and communities. The speculative housebuilder model is typically dependent on product and process standardisation (Payne and Barker, 2018) and limits innovation (Ball, 1999). Standardisation reduces design fees and labour costs through the use of familiar and repeatable construction methods that do not require further training, and enables labour to be subcontracted to deliver numerical flexibility and planning and building regulations to be achieved more easily on the basis of largely accepted house designs (Nicol and Hooper, 1999; Payne, 2015). Ultimately, this results in a cost-effective and efficient model of development which maximises profits (Nicol and Hooper, 1999) but can be lacking in terms of design quality (Tiesdell and Adams, 2004; Parvin *et al.*, 2011), construction quality (Parvin *et al.*, 2011) and sustainability (Maliene and Malys, 2009).

With respect to speculatively built homes, Nash (2016, p. 1) argues that "homes have no sense of place, do not encourage community spirit and offer extremely low space and design standards." It has been observed that speculatively built homes, more often on greenfield land, lack 'character and identity', and are 'indifferent to context' (Tiesdell and Adams, 2004). Parvin *et al.* (2011) claim that the speculative housebuilder model leads to a 'one-size-fits-all design' because the homes are designed for imaginary end-users, basing their ability to find buyers on local market data. In effect, this model has no input from future homeowners (Lane *et al.*, 2020). Furthermore, the way homes are designed in the UK have not been responsive to changes in lifestyles and the size of family groups, which can manifest as single-parent families, home-working, people living with parents, and aging people with limited mobility (Vize, 2019). As household structures and lifestyles have shifted, more varied and flexible house designs are required (Maliene and Malys, 2009).

As well as poor design quality, construction quality is also suffering. Parvin *et al.* (2011) assert that, due to the profit-driven nature of speculative housebuilding, developers seek to design structures that minimise both construction risks and build costs wherever possible, which in turn produces lower quality, lower energy performance homes that have less space and less flexibility. These issues can be exacerbated by economic shocks. For example, the UK housebuilding sector faced shortages in materials, skills, and labour because of the 2008 financial crisis (Hopkin *et al.*, 2016). According to Callcutt (2007), poor-quality design or construction will be the root of economic and social problems that will be expensive to resolve, with issues beyond the defects themselves. Considering housing represents 59% of the nation's wealth, producing high-quality housing is vital, otherwise the sector will become a drain on future investment (Callcutt, 2007).

Furthermore, Parvin *et al.* (2011) contend that the speculative housebuilder model isolates end-users as they play no part in the production process and future neighbours are whoever happens to live next-door. A 2019 study by Skipton Building Society (2019) reinforces this claim, showing that, in the UK, 73% of people do not know their neighbours by name and 20% would only interact with them if they needed something.

If, in contrast, developments are sustainable across economic, social, and environmental dimensions then homes should be designed and constructed to a high quality and created as part of a community where facilities, services and amenity spaces are easily accessible. Moreover, the neighbourhood environment should be designed and maintained to a high standard.

3.2.2 Self-Build and Custom-Build Housing

Self-build and custom-build housing are both routes to homeownership where individual buyers and groups are involved in the production of their own homes (Duncan and Rowe, 1993; Barlow, Jackson and Meikle, 2001; Wilson, 2017). Self-build and custom-build housing not only offer high-income households the opportunity to express free choice, but self-build also offers low-income households the ability to build smaller homes on smaller plots with lower build costs, thus providing an independent living situation and access to the housing market (Lloyd, Peel and Janssen-Jansen, 2015). According to Ash *et al.* (2013), 20% to 30% of build costs can be saved through models of self-build procurement, and group projects can save even more due to economies of scale.

Self-build procurement results in the development of homes with better energy performance because self-builders have a long-term interest in their home and therefore make decisions based on its whole life, considering running costs and comfort (Heffernan and de Wilde, 2017). Furthermore, the distinctive approach of developing self-build and custom-build homes results in greater architectural diversity and homes that are more closely matched with the needs of the initial occupants (Hamiduddin and Gallent, 2016).

3.2.3 Community-Led Housing: Cohousing and Group Self-Build

Cohousing is viewed as a means to achieve sustainable communities that foster meaningful relationships and social interaction as well as enabling low-carbon lifestyles (Wang and Hadjri, 2017). Such communities are founded and developed on the basis of particular values, which tend to be focused on solidarity, inclusion, social activism and mutual support, or environmental sustainability (Chiodelli and Baglione, 2014). Cohousing, as a product of its various approaches, can offer common space and shared facilities, collaboration by residents, emphasis on the collective organisation of services, and togetherness and sense of community (Vestbro, 2010). There are key design considerations including; density and layout, the division of public and private space, and the quality, type and functionality of communal space; which are intended to build trust, encourage social interactions, and develop social networks, social rules and norms between residents

(Williams, 2005). Based on core values and community-orientated design, cohousing can cultivate a sense of community, mutual support and sense of safety (Ruiu, 2016).

Furthermore, the dominant opinion within the industry is that group self-build housing is more likely than speculatively built housing to deliver homes that are energy efficient than speculatively built homes (Heffernan and de Wilde, 2020). It is common for cohousing communities to build with sustainable design and construction principles and techniques, including high levels of insulation, passive solar design, and the use of local construction materials and renewable energy systems (Daly, 2017).

An advantage of group self-build (or cohousing) over individual self-build developments is that it enables housing schemes of a similar scale to speculative housing projects (Heffernan and de Wilde, 2020): for example, Lilac, Leeds, a 20-home ecological, affordable cohousing community (Chatterton, 2013), Springhill Co-housing, Stroud, a 35-home new build cohousing scheme (Architype, 2011), and Ashley Vale, Bristol, a 39-home self-build community (Broer and Titheridge, 2010; Hamiduddin, 2017). In each of these developments, the residents were in some way involved in the planning, design, delivery, and management of their homes and communities.

Yet, whilst group self-build has the potential to provide sustainable communities of a significant scale, currently it only accounts for a small proportion of new housing in the UK (Heffernan and de Wilde, 2020). Community groups face common barriers and obstacles that stall or halt projects. Key factors include; difficulties in purchasing land and obtaining planning permission, issues with leadership and establishing a management structure, being able to finance equitably, and the initiators of projects leaving before they are complete (Tummers, 2016). Furthermore, suitable medium-sized and large-sized sites are scarce due to competition from speculative housebuilders pricing out self-builders and local authorities making little provision for these groups (Gingell and Shahab, 2021). External risks to community groups also exist, including policy changes, planning delays, contractors facing business difficulties, rising material and labour costs, and opposition to development (Ward and Brewer, 2018).

3.2.4 Demand for Self-Build and Community-Led Housing

The UK government brought in legislation through the Self-build and Custom Housebuilding Act 2015 in order to mobilise the self-build housing sector by placing a duty on local authorities to keep a register of individuals and associations that wish to acquire serviced plots of land for self- and custom-build housing in their administrative area (Gingell and Shahab, 2021). Furthermore, The Housing and Planning Act 2016 requires local authorities to grant sufficient development permissions to meet the demand, as demonstrated in its register (Gingell and Shahab, 2021).

The government's 2017 Housing White Paper, *Fixing Our Broken Housing Market*, contends that the UK should move towards innovative, diverse and sustainable housing solutions, with a focus on self-build and community-based approaches in their proposals (DCLG, 2017). This is exemplified by the Council-led 1,900-home self- and custom-build Graven Hill development highlighted in section 3.2.5. Furthermore, a Welsh Government initiative, the Self Build Wales scheme, targeted £210 million investment to remove the barriers and uncertainty involved in self-build, offering applicants self-build development loans that cover 75% of the cost of the plot and all build costs (Self Build Wales, 2020). The UK government also set up the Community Housing Fund, which made £163 million available up to March 2020, to boost the output of community-led housing several-fold (Homes England, 2018). These measures aimed to encourage growth in the self-build and community-led housing sectors and reduce the dependence on major housebuilders to meet the high demand for homes in the UK.

However, the self-build sector only contributes 8% of new homes in the UK (Lane *et al.*, 2020). This contrasts with the experience in many other European countries where it is commonplace: over 80% of homes in Austria developed through self-build and approximately 60% in Belgium, Italy, Sweden, Norway, Germany and France (Stevens, 2017). Considering 32% of people in the UK are interested in building their own home (NaCSBA and Building Societies Association, 2020), it suggests that self-build and custom-build housing could prosper with the right opportunities available. However, 83% of people are unaware of the self-build registers provided by local authorities (NaCSBA and Building Societies Association, 2020). This demonstrates how ineffective current legislative instruments have been in supporting people to take that first step to building their own homes. The community-led housing sector is even smaller, contributing only 0.6% of total housing output in the UK (Heywood, 2016) and delivering approximately 400 units per year in England (Homes England, 2018). Concurrently, there are more than 750 groups seeking to build (Stevens, 2017) and a variety of organisations that own, manage or develop community schemes. These organisations include 736 Housing Co-operatives, 113 Self Help Housing Organisations, 29 Development Trusts, 19 Community Land Trusts (CLTs) and 18 Cohousing communities (Gooding and Johnston, 2015). There is growth in the community-led housing sector with increasing Government backing and an increasing amount of information and guidance available, through organisations such as Locality, to support community groups and enablers to deliver homes.

3.2.5 Developer-Led Self-Build, Custom-Build, and Community Housing

There is evidence of developers taking on the major project risks outlined in section 3.2.3 to develop housing where residents participate in the design and management of their communities. For instance, Marmalade Lane is a 42-home developer-led cohousing scheme in Cambridge where the resident group K1 Housing collaborated with developers Town and Trivelhus, and Mole Architects (Mole Architects, 2018). The scheme innovates with sustainable pre-fabricated timber panels to create highly energy efficient homes and has communal spaces and facilities designed to foster community spirit and sustainable living (Mole Architects, 2018). Furthermore, the residents are members of an estate management company, Cambridge Cohousing Ltd., giving them a stake in communal areas and enabling them to contribute to the management of the community (Marmalade Lane, 2021). Another example is HomeMade, Heartlands, an upcoming 54-home custom-build development in Cornwall led by Igloo Regeneration, which has planning in place to allow people to buy a plot and choose one of six companies to design their home with and build their home to completion (HomeMade Heartlands, 2020). The customer can choose from six layouts and styles with the option to add extensions and install solar panels and electric car points (Kollewe, 2017). The customers are then involved in the design of the 'village green' as a shared community space (HomeMade Heartlands, 2020).

Each of these examples demonstrates that developers can realise socially and environmentally sustainable community housing schemes that enable residents to be involved in the design process and ongoing management of the community. While they are not necessarily a replacement for grassroots community-led housing projects, such schemes do illustrate more robust and dependable delivery models that overcome the major barriers that self-builders and community groups face. In many ways, it can be argued that these schemes carry the same benefits to customers as community-led projects in terms of personalised design, sense of community, and sustainable lifestyles.

Finally, on a much larger scale, Graven Hill in Bicester is the UK's first major self-build and custom-build development of 1900 homes being constructed over 10 years (Graven Hill, 2021a). The scheme is being led by Cherwell District Council (in the form of its own development company) to provide a mixture of homes to match demand, including for self-build and custom-build housing, and to accelerate the pace of local housing delivery (NaCSBA, 2021). The local authority was selected as one of eleven 'Vanguard' councils funded by the Government to support and enable self- and custom-build housing in order to speed up and diversify housing supply (Graven Hill, 2021b). The project provides 30% affordable housing, as well as a primary school, community hall, local shops, commercial space, allotments and a renewable energy centre (NaCSBA, 2021). Graven Hill appears to be successful in meeting demand for self-build and custom-build housing and generating a significant return and income stream for the local authority (NaCSBA, 2021); however, there is little emphasis on community participation and customers do not take ownership of the spaces and facilities on the site.

3.2.6 Conclusion

The literature discussed in this section firstly demonstrates that speculative housebuilding does not always meet people's needs, deliver quality, or shape socially and environmentally sustainable communities, whereas, grassroots self-build and cohousing drive user-centred design, energy efficiency, sustainable lifestyles, and community building. However, key barriers related to finance, planning, and land are making it difficult to meet demand for such housing in the UK. Furthermore, legislative instruments to mobilise the self-build and custom-build sector have proven to be relatively ineffective so far. This presents an opportunity for developers, that often have the resources and expertise to overcome these barriers and complexities, to innovate and deliver this unmet demand in a scalable way. Marmalade Lane, HomeMade, and Graven Hill demonstrate viable developer-led models of self-build, custom-build, and community development that have recently emerged. As shown by Water Lilies in Chapter 2, ESBC housing offers a potentially sustainable developer-led approach that combines self-finish and custom-build routes, community workshops, master planning based on cohousing principles, community-owned assets, sustainable construction, and renewable energy systems. Yet, since Water Lilies is only a potential proof of concept, this thesis seeks to investigate aspects of its sustainability and scalability. The following section, 3.3, reviews the literature on life cycle assessments to evaluate environmental sustainability based on building-related carbon emissions, and the final section of this chapter, 3.4, reviews the literature on neighbourhood sustainability assessment tools to evaluate the multiple dimensions of sustainability for a scheme across a range of indicators.

3.3 Building Life Cycle Assessment

LCA is a methodological framework used to evaluate the environmental impacts of a product from cradle-to-grave, including emissions associated with raw material extraction, production and transportation, use, and end-of-life treatment (ISO, 2006). The methodology analyses various strategies "to reduce energy and resource consumption and the environmental impacts of building materials" (Najjar *et al.*, 2017, pp. 116–117). Building LCAs are carried out in practice by urban designers, property developers, architects, engineers, and consultants (Hellweg and Canals, 2014). In the academic literature, there has been an increasing number of studies over the past 15 years as attempts are made to analyse and reduce the environmental impacts of the construction sector (Anand and Amor, 2017). Considering the whole life cycle of a building, including embodied and operational carbon emissions, enables the optimal combined opportunities for reducing lifetime emissions to be identified (RICS, 2017). Furthermore, it is suggested building performance can be optimised by adopting LCA during the design phase of a project because the embodied and operational carbon emissions of different types and quantities of materials can be identified and balanced accordingly before decisions are fixed (Paleari, Lavagna and Campioli, 2016).

3.3.1 LCA Methodology

LCA methodology follows four distinct analytical steps based on recognised standards set out in ISO 14040, including goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation of results (ISO, 2006). The first step, goal and scope definition, includes establishing the system boundary, functional unit, and lifespan of the building. The system boundary determines the products and processes to include within the LCA, in accordance with the goal of the study (Abd Rashid and Yusoff, 2015). There are four life cycle stages with associated carbon emissions that can be included: the product stage – modules A1–A3 (i.e. extraction, processing, manufacture, and transportation between these processes); the construction process stage – modules A4 and A5 (i.e. transportation of materials to site, on-site energy usage during construction, and the production, transportation, and end-of-life processing of materials wasted on site); the use stage – modules B1–B7 (i.e. use, maintenance, repair, replacement, and refurbishment, and operational energy and water use during the building's operation), and; the end-of-life stage – modules C1–C4 (i.e. deconstruction and/or demolition, transportation of materials away from the site, waste processing, and material disposal) (Gibbons and Orr, 2020).

A functional unit is quantified description of the function of a product and is essential to LCA to ensure impact can be assessed and compared with other studies (Arzoumanidis *et al.*, 2020). Different functional units are used in building LCA studies such as floor area (m^2), building element (e.g. roof, external walls, floors, etc.), and weight (e.g. kg, tonne, etc.) (Anand and Amor, 2017), but for studies of residential buildings they are often reported as m^2 and total house (Islam *et al.*, 2014). Furthermore, the lifespan of the building must be determined because it has a considerable impact on total operational energy use (Abd Rashid and Yusoff, 2015). A study period of 50 years is commonly applied by researchers for residential buildings (Abd Rashid and Yusoff, 2015), however RICS guidance suggests 60 years should be applied to domestic projects (RICS, 2017).

The second step, life cycle inventory (LCI), involves collecting data on any relevant inputs and outputs of a product life cycle, including data on materials, transportation, construction, operation, maintenance, and end-of-life (Abd Rashid and Yusoff, 2015). Environmental product declarations (EPDs) or building industry databases are the main source of building inventory data (Anand and Amor, 2017) and identifying the energy mix of the electricity supply is required to determine to operational energy use (Ortiz-Rodríguez, Castells and Sonnemann, 2010). Life cycle inventory analysis is highly complex because there are multiple materials and processes involved and the operation of a building is dynamic (Anand and Amor, 2017). Selecting the most suitable data is essential because the quality of data relates to the accuracy of results (Khasreen, Banfill and Menzies, 2009).

The third step, life cycle impact assessment (LCIA), uses data from the LCI to evaluate environmental impacts. The product system can be examined using a range of impact categories, such as global warming potential (GWP), acidification, eutrophication, and ozone depletion (which are commonly used for buildings), and category indicators linked to the LCI results, such as carbon dioxide, nitrogen dioxide, and methane for GWP and sulphur oxides and nitrogen oxides for acidification (Khasreen, Banfill and Menzies, 2009). Carbon dioxide equivalent (CO_2e) is used as a standardised metric to compare emissions from different greenhouse gas emissions based on their GWP by multiplying the quantity of the gas by the associated GWP (Eurostat, 2022).

The fourth step, interpretation, analyses the robustness and sensitivity of the results, validates them through comparison to other studies, and draws conclusions with reference to the LCA goals and objectives (Abd Rashid and Yusoff, 2015).

3.3.2 Limitations of LCA Methodology

There are significant limitations inherent to the LCA methodology. The results from LCA studies are largely incomparable, not only due to context specific differences such as building layout, climatic conditions, and local regulations (Buyle, Braet and Audenaert, 2013), but also because the methodologies applied are inconsistent across assessments (Säynäjoki *et al.*, 2017). In the first LCA step, this includes differences in functional unit, life span, and system boundary definitions (Nwodo and Anumba, 2019), which may be appropriate for the scope of an individual study but not for comparing across studies (Dixit, Culp and Fernández-Solís, 2013). In the second LCA step, the LCI databases used to perform LCAs are owned and managed by different companies, so without a reference database, gaps and overlaps between the databases exist, resulting in issues related to quality and comparability (Dossche, Boel and De Corte, 2017). In the third LCA step, the impact categories used for assessing environmental impacts vary across studies (Chau, Leung and Ng, 2015). Moreover, different studies have different levels of detail and are based on various assumptions that lead to comparison issues because of uncertainty (Buyle, Braet and Audenaert, 2013; Islam, Jollands and Setunge, 2015). The Royal Institute of Chartered Surveyors (RICS, 2017, p. 4) argue that the significant disparities between LCA results of similar projects have “undermined the reliability of carbon measurement, discouraging stakeholders from confidently adopting whole life carbon thinking in their projects” so to improve credibility and increase uptake, greater clarity and consistency in the implementation of LCA methodology is required.

A further substantial limitation of the LCA methodology is the availability of data related to, for example, building system components, building site operations, and specific products in LCI databases. The quality of the data determines the quality of the results (Feng *et al.*, 2022). However, the data required for assessment are often insufficiently comprehensive or not up to date, so assumptions must be made, which can lead to inaccuracies (Antón and Díaz, 2014). There is a distinct lack of data when it is most needed to reduce subsequent carbon emissions – during the early design stages of a project (Antón and Díaz, 2014). Paleari, Lavagna and Campioli (2016) argue that in-depth data collection is fundamental to LCA. They collected data after construction using site reports and invoices for purchasing materials and services, concluding that a detailed data collection process covering system components, product site locations, and building site activities to perform a comprehensive life cycle assessment provides a complete and accurate evaluation of life cycle carbon impacts from materials and processes but is both time-consuming and difficult (Paleari, Lavagna and Campioli, 2016).

Considering this point in relation to the subject of this research, it highlights an opportunity to use detailed design information (i.e. during or after construction) to provide the data inputs to conduct an LCA to create a baseline scenario for a prospective development. The baseline scenario could be used to develop, assess, and compare various design options that experiment with different materials and building services in order to optimise a future building in terms of carbon emission reductions. This approach could be utilised particularly effectively for housing developers seeking to standardise a sustainable model of construction, bearing in mind that specific constraints and/or conditions of a prospective site may differ from those of the original development.

3.3.3 LCA Tools

A number of LCA software tools have been developed in different regions using life cycle inventory (LCI) databases to evaluate environmental impacts (Islam, Jollands and Setunge, 2015). Examples of LCA tools include *Athena Impact Estimator* and *Tally* in North America, *GaBi* and *SimaPro* in Europe, and *One Click LCA* in North America, Europe, Middle East, Asia Pacific, and South America (Islam, Jollands and Setunge, 2015; Herrero-Garcia, 2020). LCA tools are linked to a variety of LCI databases, such as *Ecoinvent*, *U.S. Life Cycle Inventory (USLCI)*, and *Australian National Life Cycle Inventory Database (AusLCI)* (Islam, Jollands and Setunge, 2015), as well as *Athena* and *GaBi* containing their own LCI databases. In the UK, freely available Excel-based LCA tools have been developed, including the *Structural Carbon Tool* by the Institution of Structural Engineers (IStructE, 2022) and *Embodied Carbon Calculator* by Mesh Energy (Mesh Energy, 2022).

3.3.4 Application of LCA to Residential Buildings

LCA implementation has become increasingly commonplace in the building sector (Dong and Liu, 2022), including for residential buildings (Chastas *et al.*, 2018; Bahramian and Yetilmezsoy, 2020), but UK-based studies have been limited. At the time of publication, Cuéllar-Franca and Azapagic (2012) were only aware of four LCA studies conducted in the UK housing sector. According to Bahramian and Yetilmezsoy’s (2020) overview of the literature on the life cycle assessment of commercial and residential buildings between 1995 and 2018, there were no further studies identified.

Asif, Muneer and Kelley (2007) calculated the embodied energy and associated embodied carbon of eight building materials in a three-bedroom semi-detached house in Scotland. Hammond and Jones (2008) applied University of Bath’s inventory of carbon and energy database for construction materials to 14 case study dwellings to calculate embodied carbon impacts from ‘cradle-to-site’ (i.e. A1–A3 in the product stage and A4 of the construction process stage), each of which were found to be similar. Monahan and Powell (2011) assessed the embodied energy and associated embodied carbon of a house constructed using off-site panellised timber frame in comparison to an equivalent using traditional masonry construction, finding that the latter produced 51% more embodied carbon and concrete was the most significant contributor in both scenarios, responsible for 36% – though the authors acknowledge that a focus on embodied carbon can be counterproductive in the long-run, stating that concrete, for example, can reduce operational energy demand if used strategically.

These LCA studies of residential buildings in the UK were relatively limited in scope and did not consider the whole life cycle of the building from ‘cradle-to-grave’. Hacker *et al.* (2008) took a further step by evaluating the embodied and operational carbon of a two-bedroom semi-detached house in England over a study period of 100 years, testing lightweight to heavyweight building specifications and alternative cooling modes for the case study building, but did not include the end-of-life stage. On the other hand, Cuéllar-Franca and Azapagic (2012) conducted an LCA of a typical detached, semi-detached, and terraced house in the UK across every life cycle stage using a study period of 50 years. Over this lifetime, the detached house contributed 455 t CO_2e, 374 t CO_2e for the semi-detached house, and 309 t CO_2e for the terraced house, showing that a typical terraced house has the least impact (Cuéllar-Franca and Azapagic, 2012). Based on the typical specification at the time, each house type contributed 90% of its emissions from the use stage, 9% from the construction stage, 1% from the end-of-life stage, and a negligible contribution from transport (Cuéllar-Franca and Azapagic, 2012). This indicated that reducing operational carbon through energy efficiency measures to the building envelope was the key area to improve housing design.

However, the emphasis on operational carbon is reducing as new homes are built to higher energy efficiency standards to meet more demanding UK Building Regulations and heat and power are increasingly being supplied from renewable sources (MHCLG, 2019; National Grid ESO, 2021b). Studies have demonstrated that the design of highly energy efficient homes requires a greater focus on embodied carbon reductions. Chastas *et al.*

(2018) reviewed the range of embodied carbon emissions reported in 95 case studies of residential buildings and found that embodied carbon emissions constituted between 9% and 80% of total life cycle impacts. Conventional buildings clustered around 10% embodied carbon emissions whereas low energy buildings had mostly between 45–60% embodied carbon emissions, demonstrating the impact of energy efficiency on the balance of embodied and operational carbon emissions. Through a detailed analysis and presentation of each case study, it acknowledges the influence of building structure and energy mix, as well as the LCI database used, on the share of embodied carbon emissions (Chastas *et al.*, 2018).

Furthermore, it has been shown that bio-based building materials can significantly reduce embodied carbon emissions in residential buildings. Petrovic *et al.* (2019) conducted an LCA of the embodied carbon impacts of a single-family house in Sweden for a study period of 100 years using the software, One Click LCA. It compared the environmental impact of building materials in its construction, finding that concrete slab and thermo-treated wood contributed the most CO_2e/m^2, whereas untreated wood-based products, including cellulose insulation, contributed the least – demonstrating the importance of 'green' building materials (Petrovic *et al.*, 2019). However, understanding where to focus carbon reduction efforts across the whole life cycle is crucial to optimising the performance of the building and minimising overall emissions. Lavagna *et al.* (2018) undertook an LCA of 24 dwellings that were representative of EU housing stock in 2010 to evaluate the average environmental impacts and provide baseline scenarios from which redevelopment strategies could be simulated and the most effective solutions for reducing environmental impacts could be identified. Significantly, the study highlighted the relative impacts of different life cycle stages and, therefore, where carbon reduction efforts should be focused (Lavagna *et al.*, 2018).

Additionally, stakeholders are usually interested in economic, as well as environmental, factors. Islam, Jollands and Setunge (2015) contend that different floor, wall, and roof assemblage designs should be evaluated to understand the impact on optimal house design balanced against environmental and economic costs. Whilst the research in this dissertation acknowledges the need to assess economic costs (e.g. through life cycle costing) of energy efficient and low carbon design, particularly when considering the sustainability of the ESBC housing model, it is outside the scope of this research, and is therefore not reviewed in detail in the literature.

A review of the literature on LCAs conducted for residential buildings highlights that there are relatively few studies focused on the UK housing sector. Furthermore, most of the studies that do exist do not account for the whole life cycle of the building, which is needed to identify where to focus carbon reduction efforts. LCA studies that investigate the environmental impacts of homes with differing levels of energy efficiency demonstrate that designing to reduce embodied carbon emissions becomes increasingly important as the standard of energy efficiency improves and the proportion of renewable energy supply increases.

3.3.5 Integration of Building Information Modelling and Life Cycle Assessment Tools

Obtaining information about the quantities and characteristics of building materials is time-consuming (Paleari, Lavagna and Campioli, 2016) so Building Information Modelling (BIM) has emerged as a tool to simplify the LCA process by managing the building information required in the analysis (Nwodo and Anumba, 2019). BIM is “the process of development and use of a computer generated model to simulate the planning, design, construction and operation of a building facility” (Azhar, Brown and Farooqui, 2009). A BIM model provides a digital representation of the physical and functional characteristics of a building that can be shared amongst stakeholders to aid decision-making during its life cycle (US National Institute of Building Sciences, 2007). It contains interconnected parametric data attributed to assemblies and constructions, so any changes to the model automatically affect related objects (Wong and Fan, 2013).

The integration of BIM and LCA tools can reduce the efforts of performing an LCA study by importing information regarding the quantities of materials, either manually, semi-automatically, or automatically, from a BIM model into an LCA tool (Obrecht *et al.*, 2020). Importing the bill of materials is the most time-consuming step of an LCA but the amount of effort, time, and errors can be reduced by first exporting the data from computer-aided design (CAD) software (Herrero-Garcia, 2020) and simplified further through the automated data exchange from BIM to LCA tools (Obrecht *et al.*, 2020). Wastiels and Decuypere (2019) propose five strategies of workflows for the integration of BIM and LCA, as illustrated in Figure 3, including:

1. Bill of quantities (BoQ) export – the inventory of building materials is exported from the BIM model as a spreadsheet and imported into the LCA software. The LCA is performed in the LCA software.

2. Industry Foundation Classes (IFC) import of surfaces – geometric parameters that determine material quantities are automatically imported from the BIM model to LCA software and the building components are manually linked to LCA profiles in the LCA software database. The LCA is performed in the LCA software.
3. BIM viewer for linking LCA profiles – the BIM model is exported to a BIM viewer environment where LCA profiles are attributed to building geometry. The geometric data and associated LCA profiles are then imported to LCA software. The LCA is performed in the LCA software.
4. LCA plug-in for BIM software – specific LCA plug-ins are used in the BIM software to attribute LCA profiles to geometric data and the LCA is performed in the BIM environment, replacing the need for the LCA software.
5. LCA enriched BIM objects – geometric and material data inserted into the BIM environment is already attributed with LCA profiles. The LCA can be either performed with an LCA plug-in in BIM software or exported to and performed in LCA software.

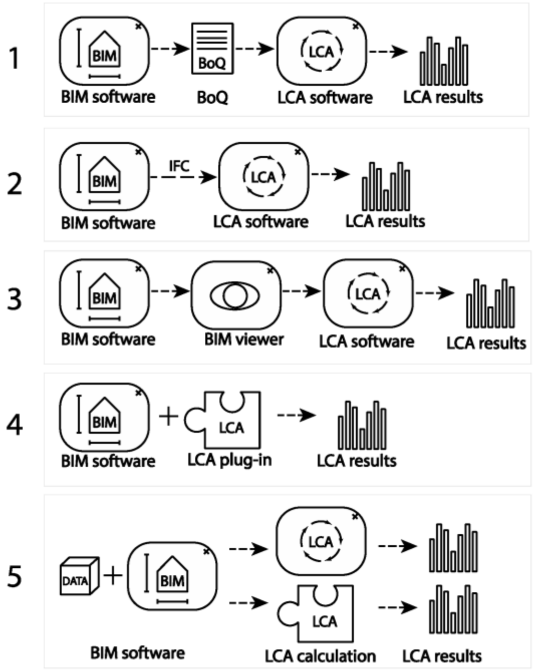


Figure 3. Types of BIM-LCA integration (Obrecht *et al.*, 2020)

Obrecht *et al.* (2020) reviewed 60 case studies of BIM-LCA integration across these workflow classifications and established that type 1 was the most adopted workflow, found in 36 studies, then type 4 in six studies, type 5 in three studies, and type 2 and 3 in one study each. In most cases of the most adopted workflow, type 1, data is imported into the

LCA tool manually, which can be time-consuming and risks errors (Obrecht *et al.*, 2020). One study integrated BIM and LCA tools, Revit and openLCA, and developed a functional database, including building assemblies, subassemblies, layers, and possible materials, to prepare Revit outputs for the LCA of a residential building in Québec, Canada (Rezaei, Bulle and Lesage, 2019). This process enabled different building design options to be assessed and the most sustainable building materials to be selected in order to reduce environmental impacts. The second most adopted workflow, type 4, enables fast results through the use of an LCA plug-in that automates data exchange, however it mostly uses generic data, which makes the procedure more suitable for assessing options in the early design stages (Obrecht *et al.*, 2020). For example, Bueno and Fabricio (2018) created design options for different wall typologies in Revit and linked these to the most relevant materials in the LCA plug-in's database. The limited availability of environmental data led to assumptions on the most similar types of building components to be correlated to construction systems in the Revit model (Bueno and Fabricio, 2018). Without accurate environmental life cycle data on specific building materials, it is unlikely the results will be representative of the true environmental life cycle impacts of the building, but ultimately, it can be argued that obtaining results easily and quickly is useful in comparing early design options to inform a more detailed, optimised design.

It is widely agreed that BIM and LCA tools should be integrated in the early design stages to make the most of their potential (Basbagill *et al.*, 2013; Antón and Díaz, 2014; Najjar *et al.*, 2017; Bueno, Pereira and Fabricio, 2018; Röck *et al.*, 2018). For example, Najjar *et al.* (2017) highlight the ability of BIM models to adjust design parameters such as material selection, building orientation, and ventilation and produce design alternatives that can be assessed by stakeholders during the early design stage of a project, which, integrated with the environmental impacts assessed by an LCA tool, can inform decision-making quickly and efficiently based on a range of sustainability criteria. This is echoed by Antón and Díaz (2014), who state that BIM-LCA integration provides a holistic approach that is able to analyse environmental, social, and economic criteria simultaneously during the early design stage whilst reducing design costs by improving information management and coordination. Furthermore, an early stage analysis provides the opportunity to compare between predicted performance and actual performance and gain insights from experience (Antón and Díaz, 2014). However, there is a crucial dilemma – the necessary data to undertake a precise and informative LCA are most scarce in the early design stage (Peng, 2016).

Several methodological challenges have been highlighted regarding BIM-LCA integration. Firstly, the precision of the LCA is significantly influenced by the BIM model's level of development (LOD), which represents the detail of the 3D geometry, assembly, and materials (ranging from LOD 100 to LOD 400), and the BIM software's capability to model and quantify that information (Soust-Verdaguer, Llatas and García-Martínez, 2017; Morsi *et al.*, 2022). Secondly, BIM has a limited database that may not include components, elements, or materials that a designer may want to analyse in the LCA (Peng, 2016; Najjar *et al.*, 2017). Thirdly, there are issues with interoperability and data exchange arising from BIM and LCA tools' different data formats leading to data loss, software incompatibility, and incompatibility of BIM data with the LCA database, which means that material data must be mapped manually (Safari and AzariJafari, 2021; Dauletbek and Zhou, 2022). As a result of this disconnect in the flow of information between BIM and LCA tools, whole-building LCAs are too time-consuming for most building industry actors so the process remains specialised and carried out largely by researchers and consultants (Peng, 2016). Therefore, seamless data exchange between BIM and LCA tools must be developed to improve integration and reduce uncertainty, whether this all occurs in the BIM environment or across tools (Obrecht *et al.*, 2020; Dauletbek and Zhou, 2022).

Finally, BIM-LCA integration presents a gap in the ability to analyse operational carbon impacts as part of the LCA. Most studies that integrate BIM and LCA tools focus on embodied carbon calculations using inputs from the BIM model regarding the quantity and quality of materials (Obrecht *et al.*, 2020). But to calculate operational carbon impacts, the energy demand of the building needs to be calculated. This can be simulated through building energy modelling (BEM) (also known as building performance analysis).

3.3.6 Integration of Building Energy Modelling and Life Cycle Assessment Tools

BEM is used to optimise energy efficiency in the design process by analysing the energy performance of various design options (Farid Mohajer and Aksamija, 2019; Gao, Koch and Wu, 2019). It is widely acknowledged that the application of BEM at the conceptual design stage can significantly benefit designers as it enables design options to be investigated in terms of energy consumption and thermal comfort (Gao, Koch and Wu, 2019). However, it is argued that from the perspective of architects and designers BEM tools are either not supportive as design tools or have complicated design requirements (Elnabawi, 2020).

In recent years, BIM-based BEM has emerged as an approach in which information is imported from the BIM model to the BEM tool, including building geometry, material properties, space types, HVAC systems, and space loads (Azhar and Brown, 2009; Bahar *et al.*, 2013). Figure 4 demonstrates the ideal workflow for BEM tools including the information that can be imported from BIM.

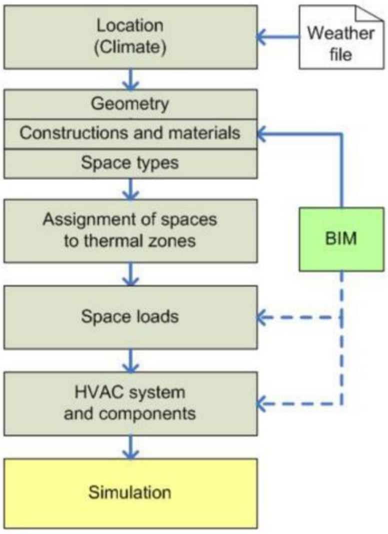


Figure 4. Ideal workflow of BEM tools with imports from BIM (Maile, Fischer and Bazjanac, 2007)

However, there are significant interoperability (i.e. the ability to exchange and interpret information correctly) issues between BIM and BEM tools whereby building information is misrepresented in BEM following the data exchange process (Guzmán Garcia and Zhu, 2015; Chen, Jin and Alam, 2018; Elnabawi, 2020). For example, Elnabawi (2020) investigated the interoperability of the BIM tool, Autodesk Revit, with the BEM tools, DesignBuilder and IES Virtual Environment. This highlighted discrepancies during the data exchange process that led to construction materials, thermal zones, HVAC, and occupant operation schedules being reassigned in the BEM tools (Elnabawi, 2020). Consequently, it has been argued that higher quality results can be achieved by remaking the model in BEM (Porsani *et al.*, 2021).

As such, BEM tools have been used independently from BIM tools to facilitate whole life cycle carbon assessments and compare the environmental impacts of different design options. Feehan *et al.* (2021) used the BEM tool, OpenStudio, to construct the reference office building and the BEM tool, EnergyPlus, to simulate energy consumption to calculate operational carbon emissions for three distinct building façade systems. The material properties and quantities associated with each design option were the basis for embodied carbon calculations using the corresponding material life cycle data in the Ecoinvent 3.6

database (i.e. the life cycle inventory database containing the relevant inputs and outputs of a product life cycle, including data on materials, transportation, construction, operation, maintenance, and end-of-life) (Feehan *et al.*, 2021). Cusenza *et al.* (2022) used the BEM tool, TRNSYS, to simulate the energy performance of two different thermal insulation scenarios either with or without a battery storage system for a residential building in order to calculate operational carbon emissions. Building design drawings were used to identify the material data and technical system components required for the embodied carbon calculations, again using the corresponding life cycle data in Ecoinvent 3.6 (Cusenza *et al.*, 2022). Hasik *et al.* (2019) input a physical model and component data to EnergyPlus, which was used to simulate the energy consumption of different building design scenarios for an office building. This was part of a whole life cycle assessment based on Python programming language to enable automation and parameters to be easily adjusted (Hasik *et al.*, 2019). Finally, Zaker Esteghamati *et al.* (2022) compared the life cycle environmental impacts of six design options for a hypothetical office building, They developed the design options in the 3D modelling software, SketchUp, and assigned space types, thermal zones, and construction materials in the OpenStudio plugin before simulating energy performance in EnergyPlus to calculate operational carbon emissions (Zaker Esteghamati *et al.*, 2022). The LCA tool, Athena Impact Estimator, was used to assess the embodied carbon emissions (Zaker Esteghamati *et al.*, 2022).

3.3.7 Conclusion

This section explained the LCA methodology and outlined its key limitations, highlighted the range of LCA tools available to conduct an assessment, demonstrated LCA studies for residential buildings in the UK and Europe, and described the integration of BIM and BEM tools in the LCA process to streamline the provision of material and energy data required for embodied and operational carbon calculations, which can be embedded in the design process.

The literature highlighted the importance of performing LCA in the early design stages to reduce overall carbon emissions but recognised it is impossible to attain accurate results given the limited data available. However, detailed design information can be obtained after construction to inform a more accurate LCA. Furthermore, there are few LCA studies of residential buildings in the UK, and only one of them assessed life cycle carbon emissions from cradle-to-grave. However, it is not clear how this study used energy consumption data to calculate operational carbon emissions over the 50-year life cycle and whether possible changes to the carbon intensity of the UK’s national grid was factored into the calculations. Therefore, there is an opportunity to calculate operational carbon emissions based on changes to the energy mix of the grid through the life cycle of the building.

Finally, the literature demonstrates that BIM-LCA tool integration is an effective approach to analyse embodied carbon emissions. Yet, BEM tools are required to perform the energy consumption simulations to calculate operational carbon emissions. BIM data can be automatically transferred to BEM to run these simulations. However, because of current issues with the data exchange process, building information is often misrepresented in BEM, which leads to unreliable results unless the building is remodelled in the BEM tool. Several studies demonstrate the ability of BEM tools, such as OpenStudio, EnergyPlus, and TRNSYS, to facilitate a whole life cycle assessment, sometimes using LCA tools, such as Athena Impact Estimator, for the embodied carbon assessment. However, no studies have been identified that integrate specific BEM and LCA tools and enable the automated exchange of material data to streamline a whole life cycle assessment. In other words, integrating specific tools to model the building information directly in the BEM tool without imports from a BIM tool, simulate energy consumption in the BEM tool to calculate operational carbon emissions, and automate the exchange of material data from the BEM tool to the LCA tool to calculate embodied carbon emissions.

In the context of this research, the LCA methodology is considered as a way of assessing environmental sustainability at the ‘building scale’. However, the case study, Water Lilies, should also be evaluated in its entirety – at the ‘neighbourhood scale’. The following section discusses neighbourhood sustainability assessment tools (NSATs) as a means of evaluating the multiple dimensions of sustainability in terms of design, delivery, and operation for a whole project.

3.4 Neighbourhood Sustainability Assessment Tools

Construction projects have typically been evaluated on their ability to deliver at the right time, cost, and quality, as well as returning sufficient profits and satisfying clients (Chan, Scott and Lam, 2002). However, these criteria are too limited when viewed from a sustainability perspective – planning for urban sustainability must balance environmental, economic, and social objectives (Lewin, 2012). Neighbourhood sustainability assessment tools (NSATs) emerged from the need to address the global environmental challenges set out in the Bruntland Report through sustainable development (Dawodu *et al.*, 2022). NSATs, which evolved from sustainable building assessments tools, are used to assess and rate the performance of developments at the neighbourhood scale against a range of sustainability criteria and demonstrate how successful they are regarding sustainability objectives (Sharifi and Murayama, 2013). NSATs provide guidance for developers to plan schemes that can be certified as sustainable through the use of themes, criteria, indicators, and allocation of sustainability credits (Dawodu *et al.*, 2022). Themes are “broad topics of concern to sustainability” (e.g. energy and resource use), criteria are “parameters used to evaluate the contribution of a project to meet the required objective” (e.g. carbon emissions reduction), and indicators are “variables that provide specific measurements” that are awarded credits if they are met (e.g. reduce carbon emissions by 10%) (Sharifi and Murayama, 2013; Sullivan, Rydin and Buchanan, 2014).

3.4.1 Types of Tools

Sharifi, Dawodu and Cheshmehzangi (2021) identified 40 NSATs studied in the literature originating from 18 countries with nine in the USA, five in Australia, and four in the UK. Sharifi and Murayama (2013) classify NSATs into two categories: ‘third-party assessment systems’ (i.e. developed from third-party building assessment systems) and ‘plan-embedded tools’ (i.e. NSATs embedded into neighbourhood-scale plans). Widely cited third-party assessment systems include Leadership in Energy and Environmental Design for Neighbourhood Development (LEED-ND), Building Research Establishment Environmental Assessment Method (BREEAM) Communities, Comprehensive Assessment System for Building Environmental Efficiency for Urban Development (CASBEE-UD), and Green Star Communities by Green Building Council in Australia and well-known plan-embedded tools include HQE^{2}R, Ecocity, One Planet Living Communities, Sustainable Community Rating (SCR), EcoDistricts Performance and Assessment Toolkit, and Sustainable Project Appraisal Routine (SPeAR) (Sharifi and Murayama, 2013; Sharifi, Dawodu and Cheshmehzangi, 2021). Table 3 highlights a selection of prominent third-party assessment systems and plan-embedded tools, including their country/region of origin and the number of studies that reference them in the literature. It is evident that third-party assessment systems have gained considerably more attention than plan-embedded tools in the literature.

Table 3. Prominent third-party rating systems and plan-embedded tools

Category	Tool name	Developer	Country/ region	No. of studies
	LEED-ND	US Green Building Council	USA	88

Third-party rating system	BREEAM Communities	Building Research Establishment	UK	40
	CASBEE-UD	The Institute for Building Environment and Energy Conservation	Japan	30
	Green Star Communities	Green Building Council	Australia	11
Plan-embedded tool	HQE^{2}R	Scientific and Technical Centre for Building	EU	8
	Ecocity	EU research project	EU	3
	One Planet Living Communities	Bioregional Development Group	UK	3
	SCR	Victorian State Government	Australia	2
	EcoDistricts Performance and Assessment Toolkit	EcoDistricts	USA	2
	SPeAR	Arup	UK	1

*Data from Sharifi and Murayama (2013) and Sharifi, Dawodu and Cheshmehzangi (2021)

Each NSAT applies different approaches to assessment in pursuit of the shared overarching goal of sustainability (Boyle, Michell and Viruly, 2018). However, there are common themes from the literature regarding the strengths and weaknesses of NSATs. To a certain extent, the strengths and weaknesses cannot be generalised to all tools: they mostly relate to third-party assessment systems, which are more widely discusses in the literature.

3.4.2 Strengths and Weaknesses of NSATs

This section discusses the strengths and weaknesses of NSATs related to feasibility of implementation, adaptability to local context, stakeholder participation, coverage of sustainability dimensions, interlinkages between indicators, quantitative and qualitative data, market influence, and value of results, referring to specific tools as examples where necessary.

Feasibility of Implementation

The main users of NSATs are construction and property development professionals (Sullivan, Rydin and Buchanan, 2014), so do not include a complete range of urban stakeholders in their development (Komeily and Srinivasan, 2015). Therefore, most NSATs require experts and high consultation fees for their implementation (Boyle, Michell and Viruly, 2018). There are further costs associated with application fees and accreditation (Boyle, Michell and Viruly, 2018) and large amounts of data collection needed to fulfil criteria (Sullivan, Rydin and Buchanan, 2014) that also limit uptake. With respect to LEED-ND, Garde (2009) also found the documentation required for certification to be burdensome. Consequently, users that do not have the financial resources to undertake demanding data collection and evaluation, skip the certification process, meaning that NSATs are not equally accessible and privilege those with greater resources (Boyle, Michell and Viruly, 2018). However, it is suggested that efforts to simplify procedures (Benson and Bereitschaft, 2019) and the provision of assessment guidelines and quantitative examples (Barnes and Parrish, 2016) increases opportunities for NSATs to be implemented by the user and without significant input from experts.

Adaptability to Local Context

An NSAT may not be able to contribute to local sustainability unless it is developed to be compatible with local conditions (Garde, 2009). Despite this, it has been argued that the structure of NSATs are insufficiently flexible to address context-specific issues (Deakin, 2011; Reith and Orova, 2015; Lin and Shih, 2016). Therefore, it should be possible to adapt evaluation indicators in response to the context of the site and local area (Berardi, 2012; Sharifi and Murayama, 2015). To address concerns related to adaptability, more recent versions of NSATs have taken steps to be less prescriptive (Pedro *et al.*, 2019). For example, BREEAM Communities made different regional weightings available to account for varying contexts (Berardi, 2013).

Stakeholder Participation

Stakeholder participation and partnership in the development and implementation of NSATs are perceived to accelerate the transition to sustainable development (Sharifi and Murayama, 2013). Turcu (2013) not only asserts that indicators should be embedded in the 'target context' (e.g. the development site and local area) to generate effective results, but the 'target audience' (e.g. the development stakeholders) should be involved in developing the indicators to use and appreciate the results. Berardi (2013) contends that NSAT methodologies should be developed to promote the local community engagement because the public's understanding local conditions can support the identification of local sustainability indicators. Moreover, Lin and Shih (2016) assert that public participation in the development of NSATs is required to facilitate local sustainable development and "avoid rigidity and professional arrogance". In terms of stakeholder participation in the actual assessment, an iterative process can improve its reliability and accuracy, stimulate group learning, and create shared understanding (Sharifi and Murayama, 2013; Boyle, Michell and Viruly, 2018).

Coverage of Sustainability Dimensions

Additionally, a common critique of NSATs is their overemphasis on the evaluation of environmental aspects of sustainability, whilst neglecting social and economic aspects, which should be considered of equal importance (Sharifi and Murayama, 2013; Komeily and Srinivasan, 2015; Sharifi, 2021; Sharifi, Dawodu and Cheshmehzangi, 2021). According to Sharifi and Murayama (2013), six out of the seven NSATs they reviewed were biased towards natural resources, environment, pattern, and design, whereas criteria such as transportation, social wellbeing, and economy were ascribed relatively less importance. Furthermore, Lin and Shih's (2016) analysis of five globally renowned NSATs found that the tools tended to ignore economic means of promoting sustainable urban development, suggesting that this could lead to a higher occurrence of social problems. Although there have been improvements (Boyle, Michell and Viruly, 2018) with examples of tools that have balanced sustainability dimensions including Green Township Index (Siew, 2018) and Assessment Standard for Green Eco-districts (ASGE) (Dang *et al.*, 2020), many tools require further attention on addressing social and economic dimensions (Sharifi, Dawodu and Cheshmehzangi, 2021).

Interlinkages Between Indicators

The selection of sustainability indicators are guided by the three pillars of sustainability (i.e. environmental, social, and economic dimensions), plus other proposed dimensions (e.g. institutional, technological, and cultural) (Cohen, 2017). However, criteria and indicators are grounded in a particular interpretation of sustainability (Lewin, 2012) and weights are assigned in a subjective manner because it is difficult to determine the relative contribution of each criterion to sustainable outcomes (Garde, 2009). It is argued that oversights in the individual definition and distribution of weighting can be mitigated by linking and integrating indicators (Lin and Shih, 2016). Although NSATs are expected to show how indicators are interlinked, this has generally not been addressed in practice (Sharifi, Dawodu and Cheshmehzangi, 2021). By clarifying interlinkages, NSATs should be able to establish the complex relationships between criteria but, instead, each criterion is more typically assessed in isolation (Kaur and Garg, 2019). However, Khan and Pinter (2016) propose 'scaling' indicators as a method to understand the relationships between spatial structure and environmental performance in complex urban systems, highlighting its potential to complement existing sustainability indicators in NSATs. Furthermore, Ali-Toudert *et al.* (2020) propose a Comprehensive Assessment Method for Sustainable Urban Development (CAMSUD), which considers the interactions between criteria. For example, in a positive interaction, an action on one criterion strengthens another criterion, and in a negative interaction, an action in relation to one criterion weakens another criterion (Ali-Toudert *et al.*, 2020). However, further research regarding interlinkages is needed (Ali-Toudert *et al.*, 2020).

Quantitative and Qualitative Data

Quantifiable indicators are useful because they enable neighbourhood sustainability performance to be clearly communicated to a range of stakeholders (Pedro *et al.*, 2019). Furthermore, quantification appeals to decision-makers because it allows progress to be scored, ranked, and monitored across different developments (Engle *et al.*, 2014). The adherence to consistent definitions and methodological standards in the implementation of quantitative indicators provides transparency for comparative analysis and encourage better practice (Engle *et al.*, 2014). Furthermore, Engle *et al.* (2014, p. 1301) assert that qualitative data "can help provide the process-related and context-specific information that indicators often miss". It is argued that qualitative data on impact and performance from the perspectives of users and beneficiaries are required to supplement quantitative assessment metrics (Hemphill, Berry and McGreal, 2016). Boyle, Michell and Viruly (2018) contend that the reverse is true – quantitative data should complement qualitative processes of collaborative inquiry and problem-solving to understand sustainability at the local level related to aspects such as sense of place, happiness, social cohesion, and well-being. However, for NSATs that are applied widely, and in some cases globally, such as LEED-ND, third-party assessors are not realistically able to study or visit each project to undertake a qualitative assessment. Therefore quantitative indicators may be the only feasible assessment approach (Lewin, 2012).

Market Influence

Due to high market demand for green-certified neighbourhoods, living in 'sustainable communities' comes at a premium (Boyle, Michell and Viruly, 2018). This creates enclaves of 'sustainable neighbourhoods' reserved for higher-income groups surrounded by neighbourhoods that are designed to a lower quality (Boyle, Michell and Viruly, 2018). Sharifi and Murayama (2014) highlight the regeneration project, MediaCityUK in Salford, as an example that was awarded a BREAM Communities 'Excellent' ranking but did not provide any affordable and social housing and limits inclusivity because the housing stock is not diverse. In addition, Benson and Bereitschaft's (2019) analysis of 246 LEED-ND sites suggested that these developments can catalyse neighbourhood gentrification and reduced inclusivity.

Value of Results

NSAT results can be used by a range of stakeholders, including planners, developers, local authorities, real estate actors, and residents, particularly to aid decision-making (Sharifi and Murayama, 2013). Furthermore, the results can stimulate dynamic and open dialogue and facilitate the communication of progress across sectors and actors – thus encouraging a greater understanding of sustainability in design and practice (Komeily and Srinivasan, 2015; Boyle, Michell and Viruly, 2018). NSATs that apply fixed point scoring for indicators (e.g. 20% of recycled material used qualifies for two points) are not able to adjust to uncertainties regarding data limitations (e.g. assumptions) and varying expert opinions, so overall scores or certification levels can be misleading (Haider *et al.*, 2018). Sharifi and Murayama (2013, p. 82) state that NSAT results should be straightforward and transparent "to avoid green washing and ill-based decisions". However, Liu, Wang and MacKillop (2020) argue that the mostly widely used NSATs, such as BREEAM Communities, do not reflect a transparent outcome because they aggregate the evaluation results into a single rate that can demonstrate a favourable score without balancing social, economic and environmental aspects. Additionally, Cohen (2017, p. 9) points to literature that suggests the three pillars model is a "reductionist approach to understanding complex problems that can lead to cherry-picking only convenient data". Garde (2009) found that LEED-ND overlooks projects that do not fit the NSATs criteria, even if they are more sustainable than a certified project, using the example of a scheme to redevelop a contaminated wetland that surpassed certification requirements for reducing energy, water usage, and contaminants but would not be certified because it did not meet the 'smart location' criterion.

3.4.3 Conclusion

This section discussed NSATs as frameworks to embed and assess sustainability in neighbourhood-scale developments. It outlined the range of tools available that are defined as either 'third-party assessment tools' or 'plan-embedded tools', highlighting that the third-party assessment tools have been more widely adopted and discussed in the literature. Drawing on the NSAT literature, the main strengths and weaknesses of the tools were discussed. Several factors, such as the need for experts, high costs, and large amounts of data collection, limit the uptake of NSATs. Furthermore, they have been criticised for being too prescriptive and unable to adapt to the local context, overemphasising the evaluation of environmental sustainability, assessing indicators in isolation, overlooking important qualitative information, creating developments with a price premium, and providing results that potentially cover up for deficiencies. These criticisms are largely aimed at third-party assessment tools, which are the focus of most studies.

Sharifi, Dawodu and Cheshmehzangi (2021) assert that it is vital to study other tools to address the issues highlighted. Moreover, Lewin (2012) argues that feedback is essential to update tools with improvements over time. Furthermore, simplified versions of NSATs could be implemented largely by self-assessment (i.e. by the user without significant input from experts) (Sharifi, Dawodu and Cheshmehzangi, 2021). This literature review highlights an opportunity to assess and compare plan-embedded tools, which are not widely discussed, against some of the themes discussed – providing critical feedback for tool improvement. Furthermore, plan-embedded tools that can be applied by self-assessment may be suitable for evaluating the sustainability performance of Water Lilies considering the substantial cost of using a third-party assessment system.

The following chapters 4, 5 and 6, address the gaps in the literature and respond to the research objectives set out in section 1.2.

Chapter 4 – Understanding the Market for Eco Self-Build Community Housing

The literature review highlighted that there is significant demand for self-build (NaCSBA and Building Societies Association, 2020) and community-led housing (Stevens, 2017) in the UK that is currently being unmet (Heywood, 2016; Lane *et al.*, 2020), partly because of common risk factors relating to land acquisition, gaining planning permission, establishing leadership, securing finance, changes to policy, and competition from speculative developers that make it difficult for community groups to start or complete projects (Tummers, 2016; Ward and Brewer, 2018; Gingell and Shahab, 2021). Similar to Water Lilies, examples of developer-led self-build and community housing projects have demonstrated they can take on these project risks to deliver sustainable homes and communities that are designed for the end-users (HomeMade Heartlands, 2020; Graven Hill, 2021a; Marmalade Lane, 2021). However, there is no data on the level and type of demand for ESBC housing specifically, and how this market might differ from the market for conventional self-build and custom-build homes. Hence, this chapter gains a broad understanding of the market for ESBC housing by analysing and comparing it with the market for conventional self-build and custom-build housing.

This chapter is adapted from the journal paper:

Newberry, P., Harper, P. and Morgan, T. (2021) ‘Understanding the Market for Eco Self-Build Community Housing’, *Sustainability*, 13(21), p. 11823.

I was the primary author and the contributions from the other named authors were purely in reviewing the paper and suggesting refinements to the content prior to submission.

The following modifications are made to this chapter to enhance the coherence of the thesis:

- The beginning section of the introduction has been moved to section ‘1.1 Background and Motivation’ and modified to contextualise the whole research project.

- The sections of the introduction related to speculative housing, self-build and custom build housing, community-led housing, demand for self-build and community-led housing, and developer-led self-build, custom-build and community housing have been moved to section '3.2 Housing Delivery Models'.
- The section of the introduction on the ESBC development process has been moved to section '2.8 Development Process'.
- The first research objective has been removed because it relates to aspects of introduction that have been moved to the sections highlighted in the bullet points above.

4.1 Introduction

This paper focuses on eco self-build community (ESBC) housing, embodied by the 33-home Water Lilies pilot scheme in Bristol, UK. ESBC housing proposes a potentially scalable approach to developing environmentally and socially sustainable community housing that enables residents to design their own homes and decide how their community functions.

The ESBC model of development is led by a specialised developer, Bright Green Futures, and aims to overcome the challenges usually faced in self-build and community-led schemes whilst offering the positive environmental and social benefits (Hughes, 2020). Prior to this paper, ESBC housing has only been discussed as a potential model of developer-led self-build community housing (Broer and Titheridge, 2010). This model has since been formalised through the work of Bright Green Futures. Using the pilot scheme, Water Lilies, as a case study, this is the first paper to discuss ESBCs as a functioning model of developer-led self-build community housing that can deliver social and environmental sustainability and contribute towards the UK's net-zero carbon transition. It can be argued that the model is scalable in theory, but for ESBC housing to scale up, the market needs to be understood. Drawing on recent data, this research addresses this gap in knowledge by analysing the current market for ESBC housing and, as a result, identifies the challenges and potential opportunities for growth. Consequently, the core aim of this paper is to address the research question: what are the main factors that influence people's purchasing decisions with respect to ESBC housing compared to conventional self-build and custom-build housing, and to what extent does the current ESBC development model satisfy the market, using Water Lilies as a case study? This has been broken down into the following more detailed objectives:

1. Gain an in-depth understanding of the market for ESBC housing by analysing data from potential consumers on the factors influencing their purchase decisions and comparing this to the market for conventional self-build and custom-build housing.
2. Evaluate the extent to which the ESBC development model satisfies the market and what further development of ESBC schemes is needed to facilitate their future expansion.

The ESBC development process, described in section 2.8, demonstrates a theoretically scalable model of housing. However, it must be proven through the successful delivery and profitability of a pilot scheme such as Bright Green Futures' 'Water Lilies' project. Moreover, there needs to be a market and it needs to be understood in relation to the market for conventional self-build and custom-build housing. This research analyses survey data of people who registered interest in an ESBC scheme (i.e. the market for ESBC housing) to understand the main factors that influence their purchasing decisions and explore how ESBC housing could be developed with this understanding. These data are compared with survey data of people interested in conventional self-build and custom-build housing (i.e. the market for self-build and custom-build housing) to understand how these markets differ. Ultimately, a robust, sustainable business model will be required to scale up ESBC housing, which could be supported by technological innovations and policy mechanisms to improve the cost-effectiveness and feasibility of developments.

4.2 Methods

To gain a comprehensive understanding of the market for ESBC housing, two surveys were used. Survey 1 was an online survey on Bright Green Futures' website targeted at people interested in buying a home in the ESBC development, Water Lilies, or a similar future project. This gave people the opportunity to register interest in a plot or home in an ESBC scheme by providing their contact details and responding to a series of questions that aimed to understand their needs and preferences related to this housing solution. Survey 2 was an online survey targeted at the market for conventional self-build and custom-build housing including people that want to design and/or build their own home or are in the process of doing so. By comparing results of the two surveys, factors that might influence buying decisions could be identified and differentiated between each market if they varied significantly, though it is possible that people could be interested in both forms of housing. Thus, the factors that attract consumers to ESBC housing and conventional self-build and custom-build housing would be highlighted.

4.2.1 Survey Samples

Data were collected in both studies using online surveys. Survey 1 was a website survey, embedded on the website of the ESBC developer, Bright Green Futures. As Sue and Ritter (2012) state, a key advantage of using a website survey is the “ability to collect data from individuals for whom you may not have a sampling frame.” Since previous research had not been undertaken into people interested in ESBC housing, a website survey was considered the most appropriate method to both identify and collect data on a population that was yet to be established. The survey employs non-probability convenience sampling as “a non-systematic approach to recruiting respondents that allows potential participants to self-select into the sample” (Sue and Ritter, 2012). The research is exploratory because it is trying to gain an understanding of a market that has not been investigated previously. Before submitting their survey responses, individuals were made aware of the Privacy Policy where it stated under the ‘Use of Data’ section that their data would be used to conduct research into sustainable housing and communities and that data used for this purpose would be anonymised with all identifiers removed. The faculty research ethics committee at the University of Bristol provided guidance on the exact wording required before the data were collected.

From the perspective of the ESBC housing developer, the priority of the survey was to collect information about potential customers that could be used to contact them regarding any relevant opportunities to purchase a home either in the Water Lilies development or in a future ESBC development. Furthermore, the primary concern of respondents is to express their initial interest and hear about potential opportunities, and thus they intend to complete the survey as quickly as possible. Therefore, the number of questions was kept to a minimum and only those of particular value were asked in order to reduce the risk of respondents ‘quitting midway’ through the survey. This meant that questions gathering personal data, such as those on gender, marital status, and qualifications, were excluded. Moreover, it was deemed that questions of this nature might suggest to potential respondents that the answers provided would be factored into the developer’s decision whether to contact them for sales or not. For example, a question asking for their highest qualification could be interpreted as a means of filtering out people without a university degree, whereas a question asking for their budget is clearly a practical limitation. It is understood that this may have been solved with a statement about the purpose of collecting demographic data, but it was ultimately judged to be a complication for respondents and the need to ensure people completed the survey and maximise the developer's contact database was prioritised.

Survey 2 was an online survey. This adopted non-probability purposive sampling with the aim of producing a sample that was representative of the population (Lavrakas, 2008). In this case, the population being sought was people that were looking to or were in the process of undertaking a self-build or custom-build project. It was not possible to obtain a list of people representative of this population through an organisation and directly contact them. Therefore, expert knowledge was applied instead to non-randomly select a sample of people that represented a cross-section of the population (Lavrakas, 2008). Two approaches were used to produce this sample. Firstly, organisations that held contact databases or had followers on social media interested in self-build and custom-build housing were approached to share the survey with their contacts or followers. These included The National Custom and Self-Build Association (NaCSBA), The National Self Build and Renovation Centre (NSBRC), Self Build Wales, Buildstore, Build It Magaizine, SelfBuild & Design Magazine, and Homebuilding and Renovating. Unfortunately, only NaCSBA and SelfBuild & Design shared the survey and the others were unable to share or did not respond to requests. Secondly, a list of groups on Facebook and LinkedIn were identified and the survey was shared on these platforms directly.

It is recognised that a much smaller number of responses was obtained in Survey 2 than Survey 1, and that a greater number of responses collected from a wider range of sources would have added confidence in the level of accuracy in the data shown. However, it is regarded that enough responses were gained to provide a valuable comparison of key differences between responses from the two surveys.

4.2.2 Survey Design

Survey 1 was developed on WordPress and presented on the Bright Green Futures website, whereas Survey 2 was created using Microsoft Forms and shared with a link. The key questions in Survey 1 were about 'number of bedrooms', 'build methods', 'importance of housing aspects', and 'budget'. Survey 2 largely mimicked these questions for direct comparison, although phrasing was adjusted where necessary to make them more relevant to a more generic target audience. There were also supplementary questions that sought to provide further understanding to some of these questions. Furthermore, Survey 2 aimed to identify reasons why living in a sustainable home is important to consumers and the additional costs they might be willing to pay for the average ESBC home than the average

UK new build and average UK existing home. These questions were included in Survey 2 to explore what the main drivers for living in a sustainable home are and to what extent they influence willingness to pay for a home that would typically be provided in an ESBC housing scheme. Table 4 shows the question topics selected for analysis in each survey.

Table 4. Question topics selected for analysis from Survey 1 and Survey 2

Question Topic	Survey 1	Survey 2
Number of Bedrooms	•	•
Build Methods	•	•
Importance of Housing Aspects	•	•
Budget	•	•
Importance of Sustainability		•
Willingness to Pay for a Sustainable Home		•

• The symbol is used to show that a question topic was selected for analysis in the survey.

In terms of 'number of bedrooms', both Survey 1 and Survey 2 gave respondents the option to say if they wanted a studio, 1 bedroom, 2 bedrooms, 3 bedrooms, or 4+ bedrooms.

For each survey, respondents could select one or more build method(s) that they were interested in. Survey 1 included:

1. Purchasing a plot for self-build;
2. Self-finishing the interior of the home;
3. Buying a completed sustainable home.

Survey 2, was similar with questions modified to cater for a more self-build audience, and included:

1. Purchasing a plot for self-build;
2. Self-finishing the interior of the home/custom-build interior choices;
3. Buying a completed home.

Survey 2 included custom-build with the self-finish option and omitted 'sustainable' from the completed home option because Survey 2 respondents may not be interested in sustainability, whereas Survey 1 intended to highlight sustainability as a key aspect of the homes provided by ESBC housing.

According to a 2016 survey by the Home Builders Federation (2016), price and location are the most important factors for people looking to buy a home by a considerable margin, with each chosen by 80% of respondents. Behind these two factors, 60% of respondents found off-street parking and a home with a garden to be important (Home Builders Federation, 2016). For each survey in this research, housing aspects were scored in importance on an interval scale from 1 (not important) to 5 (very important), thus showing what people who are interested in ESBC housing and conventional self-build and custom-build housing prioritise, respectively. It can also indicate the potential differences with the mainstream housing market. As ESBC housing offers a range of features not usually considered in mainstream housing development, Survey 1 included aspects specific to ESBC housing, as well as price and location. Survey 2 included aspects relevant to conventional self-build and custom-build housing, many of which were the same or similar as those in Survey 1. Table 5 shows the aspects chosen for each survey and the reasons for their inclusion/exclusion. It is worth bearing in mind that Survey 2 was designed after Survey 1. Therefore, some aspects were modified for Survey 2 to collect a wider body of evidence in some areas.

Table 5. Housing aspects and reasons for inclusion/exclusion from Survey 1 and Survey 2

Housing Aspect	**Reason for Inclusion/Exclusion**	**Included in**	
		Survey 1	**Survey 2**
Price	‘Price’ was included in both Survey 1 and Survey 2 because it dictates what consumers can and cannot buy and acts as a benchmark for size, quality, and location.	•	•
Value for money	‘Value for money’ was considered a worthwhile addition to Survey 2 beyond ‘price’ alone because it could indicate potential trade-offs consumers make between price and the value/quality of the product being offered.		•
Location	‘Location’ was included in both Survey 1 and Survey 2 because it is a central aspect of consumers’ purchasing decision. This may be driven by a number of factors that are important to them (e.g., proximity/access to family and friends, schools, health care and public transport).	•	•
Style and construction quality	‘Style and construction quality’ was included in Survey 1 because the style of a home and the quality of its build and finish, which have implications for energy efficiency, indoor temperatures, and durability, are important considerations in consumers’ purchasing decisions. This aspect was excluded from Survey 2 and divided into ‘construction quality’, ‘internal appearance/layout’, and ‘external appearance’ to understand the importance of individual aspects underlying ‘style and construction quality’ that figure in self-build and custom-build development. Further research could	•	

	investigate these aspects with respect to the ESBC housing market.		
Construction quality	‘Construction quality’ was included in Survey 2 because, as above, it has implications for energy efficiency, indoor temperatures, and durability, which are important considerations in consumers’ purchasing decisions.		•
Internal appearance/ layout	‘Internal appearance/layout’ was included in Survey 2 because internal appearance and layout decisions are essential considerations when designing a home through self-build and custom-build.		•
External appearance	‘External appearance’ was included in Survey 2 because it is a consideration when designing a home through self-build and custom-build. It is not always possible to have any or much control over this when the building envelope is being provided by a developer in a supported self-build or custom-build project.		•
Green lifestyle	Facilitating a ‘green lifestyle’ is a core aim for ESBC housing. A ‘green lifestyle’ is also commonly associated with conventional self-build housing (Heffernan and de Wilde, 2017). Therefore, it was included in both Survey 1 and Survey 2.	•	•
Community spirit	ESBC housing aims to engender ‘community spirit’ by creating shared experiences (workshops and build), shared facilities (community garden and community building), and shared responsibilities (managing and hiring out assets). ‘Community spirit’ may also be sought out in conventional neighbourhoods where people are looking to self-build or custom-build. Therefore, it was included in both Survey 1 and Survey 2.	•	•
Personal design and participation	‘Personal design and participation’ was included in Survey 1 because they are core elements of the design and build process in ESBC schemes. Consumers design their own homes and collectively design the community garden and community building. It was excluded from Survey 2 because it was addressed by ‘internal appearance/layout’ in a suitably generic way for this market.	•	
Advice and support for your build	‘Advice and support for your build’ in ESBC housing is provided through workshops, one-to-one mentoring, and design sessions with the project architects. Therefore, it was included in Survey 1. It was excluded from Survey 2 because it was not considered such a relevant factor for this market.	•	
Safe place for children	‘Safe place for children’ was included in Survey 1 because ESBC housing provides a traffic-free community garden for children to play and the homes surrounding it give natural surveillance. Familiarity between neighbours is likely to increase trust in the community and therefore the perceived	•	•

	safety of children. Before ESBC housing was developed into a functioning developer-led model of housing, ‘child friendly development’ was identified as the most important factor for attracting potential residents to eco self-build communities (Broer and Titheridge, 2010). ‘Safe place for children’ was also considered relevant to conventional self-build and custom-build development and housing in general. Therefore, it was included for Survey 2.		
Family-friendly	‘Family-friendly’ was considered a worthwhile addition to Survey 2 because wider housing aspects related to family, beyond a focus on children, could be considered important in consumers’ purchasing decisions.		•

• The symbol is used to show that a housing aspect was included in the survey.

Survey 2 sought to improve upon the shortcomings and limitations of Survey 1 by splitting aspects with overlapping considerations (i.e., ‘style and construction quality’ was split into ‘construction quality’, ‘internal appearance/layout’, and ‘external appearance’) and providing greater depth to the analysis of certain housing aspects (i.e., ‘price’ is also considered through the lens of ‘value for money’). It also omitted aspects only relevant to the ESBC housing market (i.e., ‘personal design and participation’ and ‘advice and support for your build’). Furthermore, descriptions of aspects were provided to eliminate potential ambiguity. For example, ‘green lifestyle’ was defined as *“low household energy use; sustainable travel choices; waste reduction; recycling”* and ‘community spirit’ was defined as *“sharing spaces and time with your neighbours; mutual support; local decision-making”*.

The way respondents were asked to give their budget differed between Survey 1 and Survey 2. Survey 1 sought to find out what budget range people were categorised by. A shortcoming of this was that there is overlap between the budget ranges (e.g., £200k–£300k and £300k–£400k). However, it can be understood that someone who considered their budget to be £300k, for example, would put themselves in the range of £200k–£300k if they could not possibly afford a home more than £300k and in the range of £300k–£400k if they were able to stretch to pay for a home slightly more expensive than £300k. As Survey 1 was primarily being used for the purpose of grouping large amounts of data and targeting mailouts to different market segments, this approach was deemed suitable. However, if the data were to be collected primarily from a research perspective, it would have taken the same approach as Survey 2. For Survey 2, people were asked to give their budget as a number. This provides more accurate results that could still be grouped subsequently for the purposes of comparison. However, grouping the data for comparison meant that the researcher, not the respondent, would need to decide where to place respondents who gave a budget that fell between two ranges. Therefore, the categories were adjusted to be "up to" a certain figure. In this instance, those who gave a budget of £300k were put in the category "up to £300k". This means that the data cannot be compared with complete confidence, but it provides an indication of how much people have to spend. Another small difference between the data collected for each survey was that in Survey 1, the lowest budget possible is £150k. This is because the developer does not provide homes for less than this, and therefore it is not in their interest to encourage people to register below the £150k–£200k category since it would give the impression that they can afford a home in an ESBC housing scheme. On the other hand, Survey 2 allowed people to respond with any number because it did not have this limitation.

Survey 2 explored whether living in a sustainable home is important to the market for conventional self-build and custom-build and, if so, for what reasons it is important to them. The reasons that respondents could choose from aimed to cover common aspects associated with housing and sustainability and were reviewed and refined through discussions with academics working in sustainability fields across disciplines. Respondents were asked to select up to three of the statements that were relevant to them. However, it was not possible to make this a restriction using Microsoft Forms, and therefore 7 of the 36 respondents selected more than three statements. These were included in the analysis because it was deemed fair that people may find more than three statements relevant to them.

Survey 2 aimed to explore willingness to pay for a sustainable home. It presented respondents with information about three homes: Home 1, Home 2, and Home 3, and asked them: as a percentage, how much more, if any, they would be willing to pay for Home 1 than Home 2, and Home 1 than Home 3. Home 1 was the "sustainable home" in this case and was based on an average ESBC home. Home 2 was based on an average new build in the UK and Home 3 was based on an average existing home in the UK. Information about the type of home each was based on was not given to respondents so their response would only be influenced by the SAP rating, energy sources, total energy cost, and operational CO_2 emissions (which was contextualised by the approximate equivalent number of flights between London and New York City). All the information on each home type is displayed in Table 6.

Table 6. Features of each home type given to respondents

Feature	Home 1	Home 2	Home 3

	Average ESBC Home	**Average New Build (UK)**	**Average Existing Home (UK)**
SAP rating	A [1]	B [2]	D [2]
Energy sources	Heating and electricity from clean and renewable sources on-site with battery storage [1]	Gas heating and electricity from the national grid [2]	Gas heating and electricity from the national grid [2]
Total energy cost (£/year)	165 [3]	915 [3]	1015 [3]
Operational CO_2 emissions (t CO_2/year)	0	1.47 [4] (approx. 3 flights between London and New York City) [5]	3.71 [4] (approx. 7.5 flights between London and New York City) [5]

[1] (Bright Green Futures, 2021e). [2] (Office for National Statistics, 2020). [3] See calculations and references in Table A.1 in Appendix A. [4] (MHCLG, 2020). [5] (Kommenda, 2019).

4.2.3 Data Analysis

Survey 1 responses through the website were stored in the WordPress database and exported to Microsoft Excel. Survey 2 responses were stored in Microsoft Forms and exported to Microsoft Excel for analysis. Duplicates and spam responses in both surveys were identified and removed in Excel before the data were analysed through descriptive statistics, predominantly by comparing percentage responses to different question topics.

4.3 Results

The results cover the core question topics highlighted in Section 2. For Survey 1, there were 1719 responses collected between 14 November 2018 and 17 February 2021. Of the 1719 respondents, 647 encountered Bright Green Futures through a search engine, 499 through social media, 360 through word of mouth, 60 through print media, 3 through the radio, and 150 did not specify. For Survey 2, there were 43 responses collected between 10 March 21 and 12 June 21. NaCSBA shared the survey through its Self Build Portal newsletter and Twitter, gaining 13 responses, and SelfBuild & Design Magazine shared it on Facebook and Twitter, gaining 9 responses. A total of 16 responses were gained by sharing the survey on the following Facebook groups: Self Build Home and Community, UK Self Builders, and Self Build and Home Alterations UK. There was one response through the Self Build & Custom Build Club group on LinkedIn and four responses from word of mouth.

Of the 43 respondents, 14 were looking to buy/develop a newly built home now (within the next 12 months), 13 were looking to buy/develop a newly built home in the future (12 months or more), and 16 were in the process of buying/developing a newly built home. For the purposes of the survey, a “newly built home” included self-build, self-finish, custom-build, and new build. There was a relatively even gender split, with 23 male and 20 female. In terms of marital status, 5 were single, 37 were married, in a civil partnership or co-habiting, and 1 preferred not to say. With respect to qualifications, 4 had a GCSE or equivalent, 7 had an A-level or equivalent, 4 had a foundation degree or equivalent, 11 had an undergraduate degree or equivalent, 15 had a Master’s degree or equivalent, 1 had a doctorate, and 1 preferred not to say.

Due to more data being available from Survey 1, respondents are also divided into sub-groups to understand their respective preferences and how they may differ. The response rate was considered too low in Survey 2 for any meaningful analysis of sub-group preferences.

4.3.1 Number of Bedrooms

Figure 5 shows that 39% of people interested in ESBC housing wanted 3 bedrooms, closely followed by 36% who wanted 2 bedrooms. A total of 15% of people wanted 4+ bedrooms, 9% wanted 1 bedroom and 1% wanted a studio bedroom. There was less of an even distribution across the number of bedrooms people wanted for the conventional market for self-build and custom-build. A total of 52% of people wanted 3 bedrooms, 33% wanted 4+ bedrooms and 15% wanted 2 bedrooms. None of the respondents wanted 1 bedroom or a studio bedroom. This suggests that the ESBC housing market tends to attract people looking for more of a variety of home sizes, which could include flats and houses. Whereas the market for more conventional self-build and custom-build housing are seeking larger 3-bedroom and 4+ bedroom homes. A further question in Survey 2 shows that 85% were looking for a house, 4% were looking for a flat, and 11% were looking for either a house or a flat. This reinforces the view that the conventional self-build and custom-build market is generally interested in larger houses.

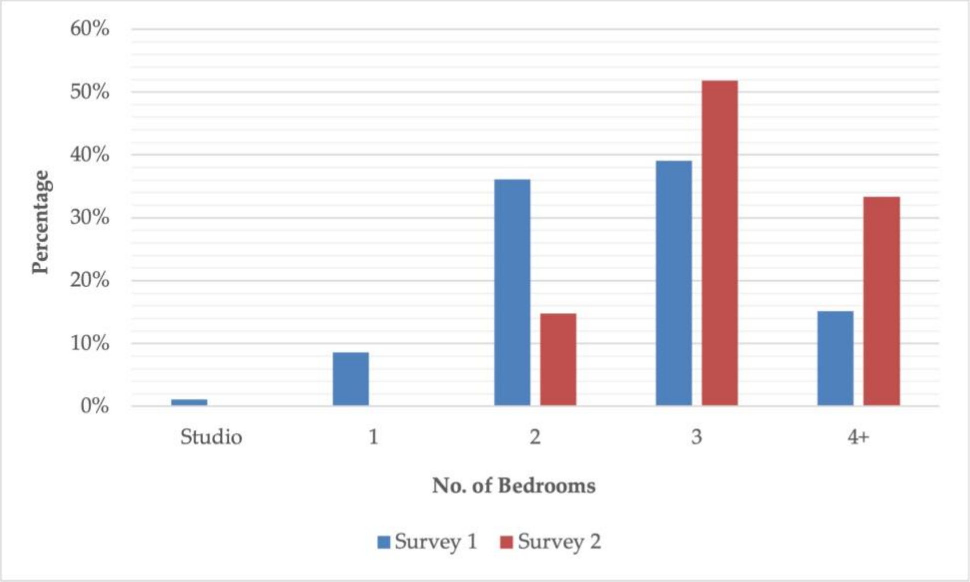


Figure 5. Percentage of respondents who wanted X number of bedrooms (Survey 1 and Survey 2)

4.3.2 Build Methods

Figure 6 shows the frequency of responses for interest in each build method as a percentage. The results varied significantly between each market surveyed. For Survey 1, the most selected build method was ‘completed home’ with 39%, even though it is not a build route that the ESBC housing developer undertakes but could be commissioned in special circumstances. This compares to ‘self-finish’, which was selected in 37% of responses, and ‘self-build’ selected in 24% of responses, as the least popular build method. In contrast, for Survey 2, ‘self-build’ was by far the most popular build method with 61%, followed by ‘self-finish/custom-build’ with 33% and ‘completed home’ with only 6%.

Figure 7 and Figure 8 show the distribution of specific responses to this question, revealing where people are willing to make compromise on their build method. Figure 7 shows that in Survey 1, 32% of respondents were interested in every build method and 26% in ‘self-finish or completed home’. ‘Completed home’ was the most selected individual response by 17% of respondents, followed by ‘self-finish’ with 9% and ‘self-build’ with 7%. In contrast, Figure 8 shows that in Survey 2, 56% of respondents selected ‘self-build’, followed by 22% for ‘self-finish/custom-build. A small proportion of respondents were willing to compromise between two build methods with 15% for ‘self-build or self-finish/custom-build’, and 4% for both ‘self-finish/custom-build or completed home’ and ‘self-build or completed home’.

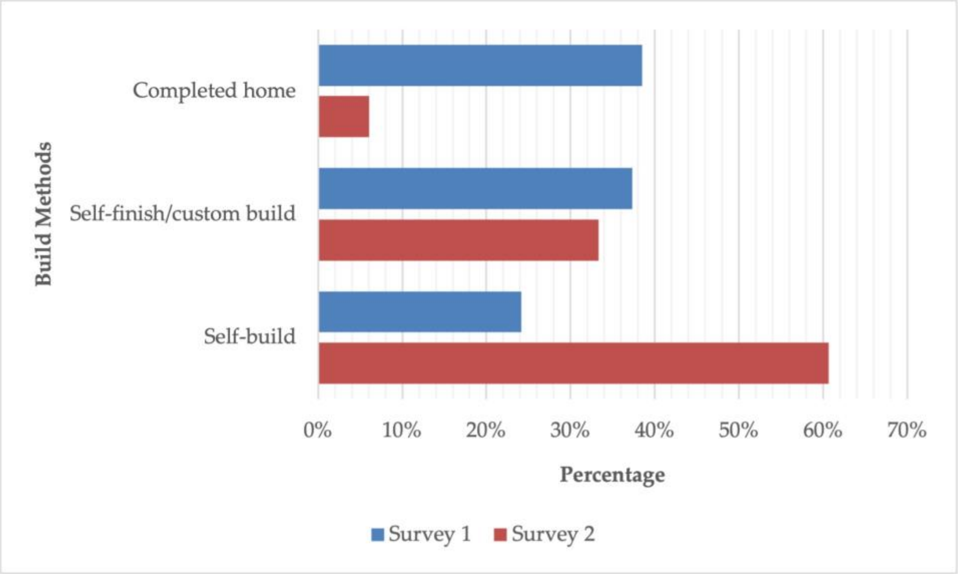


Figure 6. Frequency of responses for interest in each build method as a percentage (Survey 1 and Survey 2). N.B. Survey 1 only provided an option for 'self-finish', not 'self-finish/custom-build'

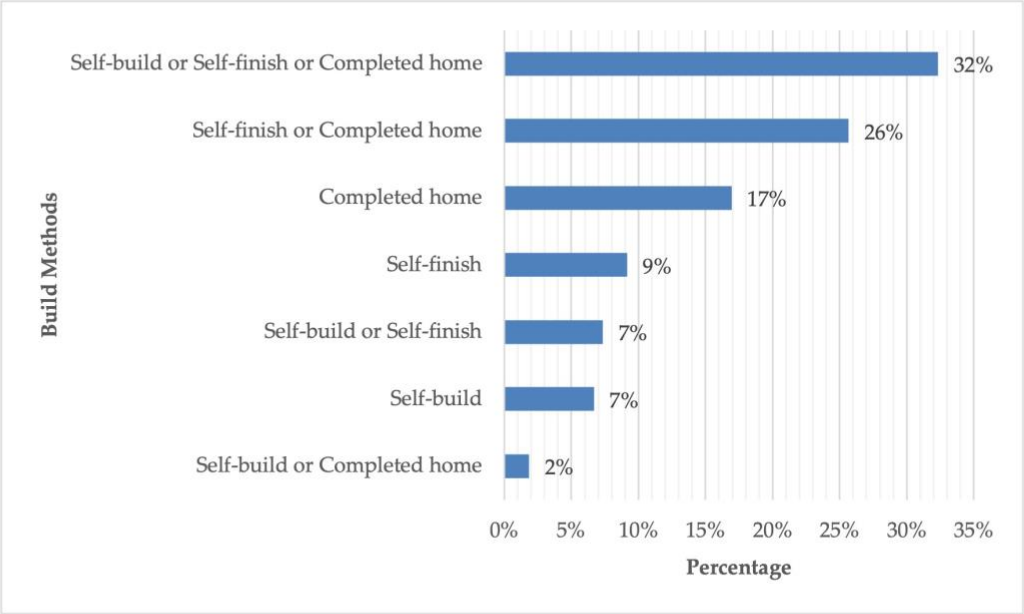


Figure 7. Percentage of respondents interested in one or more build method(s) (Survey 1)

The results for Survey 1 demonstrate that more than half of the market for ESBC housing is flexible about the build method. This suggests that aspects not related to the design and/or build of homes are appealing to consumers, such as aspects of community and environmental sustainability, which are integral to ESBC housing. Section 4.3.3 examines the importance of housing aspects to respondents in detail. In contrast, results from Survey 2 suggest that the conventional market for self-build and custom-build wants to be more involved in the build itself and are committed to a particular method.

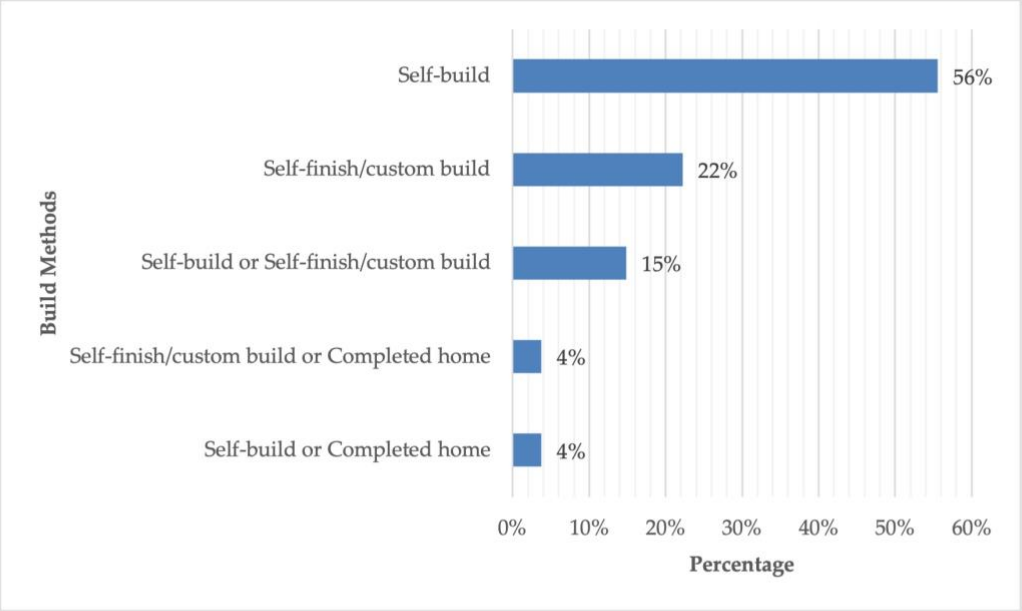


Figure 8. Percentage of respondents interested in one or more build method(s) (Survey 2)

4.3.3 Importance of Housing Aspects

Figure 9 and Figure 10 show the average importance of housing aspects to respondents of Survey 1 and Survey 2, respectively. Figure 9 shows that, for Survey 1, the most important aspect for respondents on average was ‘green lifestyle’, at 4.37. ‘Safe place for children’ was the lowest score on average, at 3.58. Whilst ‘location’ was still relatively important, with a score of 3.94 on average, ‘community spirit’, ‘style and construction quality’, and ‘green lifestyle’, all score above 4 on average. The most important aspects were not the same as those identified in the survey by the (Home Builders Federation, 2016), which found ‘price’ and ‘location’ to be the most important for people looking for a home. ‘Location’ may not be as important for those interested in ESBC housing because this type of housing is rare in the UK and therefore, people may be aware of the limited opportunities to buy a home in an ESBC development in their desired location. Furthermore, those who completed Survey 1 would have been assuming the location of ESBC homes would be in the Bristol area, whereas this would not necessarily be true for Survey 2. Unexpectedly, the results show that ‘personal design and participation’ was scored 3.71, the second to last priority, despite it being a core aspect of ESBC housing. This is relatively low compared to other core features of ESBC housing, including ‘green lifestyle’ and ‘community spirit’, which scored 4.37 and 4.15, respectively.

Figure 10 shows that, for Survey 2, ‘construction quality’ had the highest average score of 4.7. This was followed by ‘internal appearance/layout’ and ‘location’ with 4.47 each, and ‘price’ with 4.42. ‘Green lifestyle’ had a score of 4.33, which was not much lower than scored in Survey 1, but notably was the fourth priority in Survey 2, rather than the first. Considering 94% of respondents were interested in ‘self-build’ and ‘self-finish/custom-build’, it is logical that ‘internal appearance/layout’ was a priority. ‘Community spirit’ had the lowest average score of 3.49 in Survey 2, compared to 4.15 in Survey 1 where it was the third priority. In fact, when Survey 2 respondents were asked if they would like their newly built home to be part of a cohousing scheme, only 11% said ‘yes’, 37% said ‘no’, and 52% said ‘no preference’. ‘Community spirit’ is not only achieved through cohousing and can be present in conventional housing estates and neighbourhoods. However, because conventional self-build and custom-build is usually in the form of single dwelling builds, this may explain why community was not considered a priority by this market.

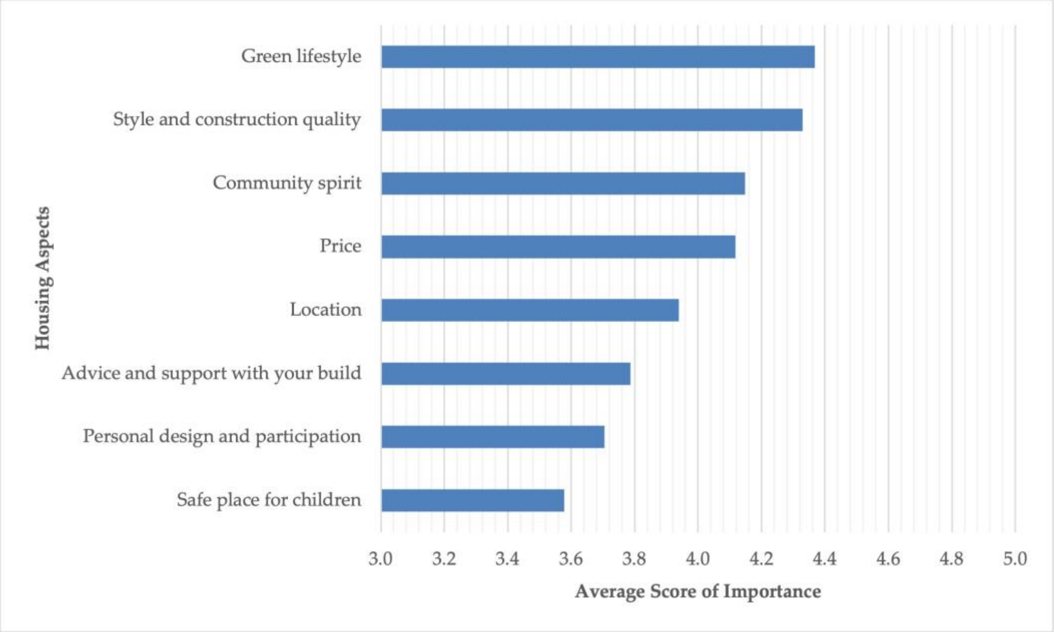


Figure 9. Average importance of housing aspects to respondents interested in buying/developing a home in an ESBC (Survey 1)

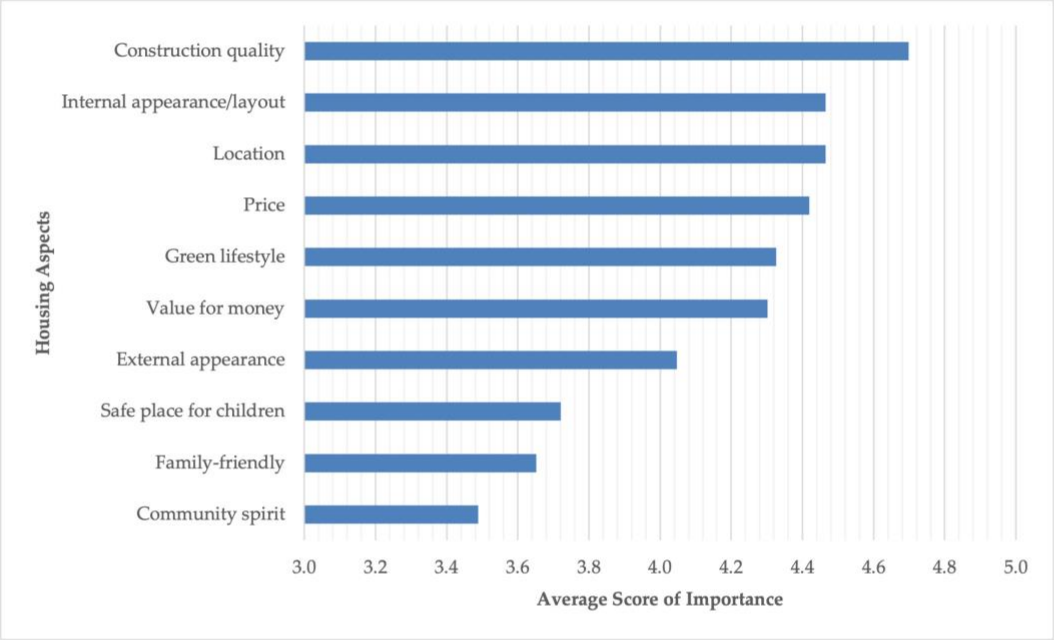


Figure 10. Average importance of housing aspects to respondents who are in the process of buying/developing or looking to buy/develop a newly built home (Survey 2)

Figure 11 organises the respondents in Survey 1 into sub-groups for those only interested in one build method including ‘self-build’ (108 respondents), ‘self-finish’ (148 respondents), and ‘completed home’ (274 respondents) to demonstrate what aspects are important to different segments of the ESBC housing market. It shows that the average score for ‘personal design and participation’ was much lower for those only interested in a ‘completed home’, who gave it an average score of 3.19, compared to 3.96 in the ‘self-finish’ sub-group, and 4.15 in the ‘self-build’ sub-group. The sub-group for ‘self-finish’ gave ‘advice and support with your build’ an average score of 4.04, whereas those interested in ‘self-build’ appear to be more content taking on greater responsibility themselves, giving it a score of 3.51, and it is a less relevant aspect for those who are interested in a ‘completed home’ who gave it a score of 3.45. The sub-group interested in ‘self-build’ was less interested in ‘community spirit’ than the average respondent, giving it a score of 3.97. This compares to 4.34 in the ‘self-finish’ sub-group and 4.08 in the ‘completed home’ sub-group.

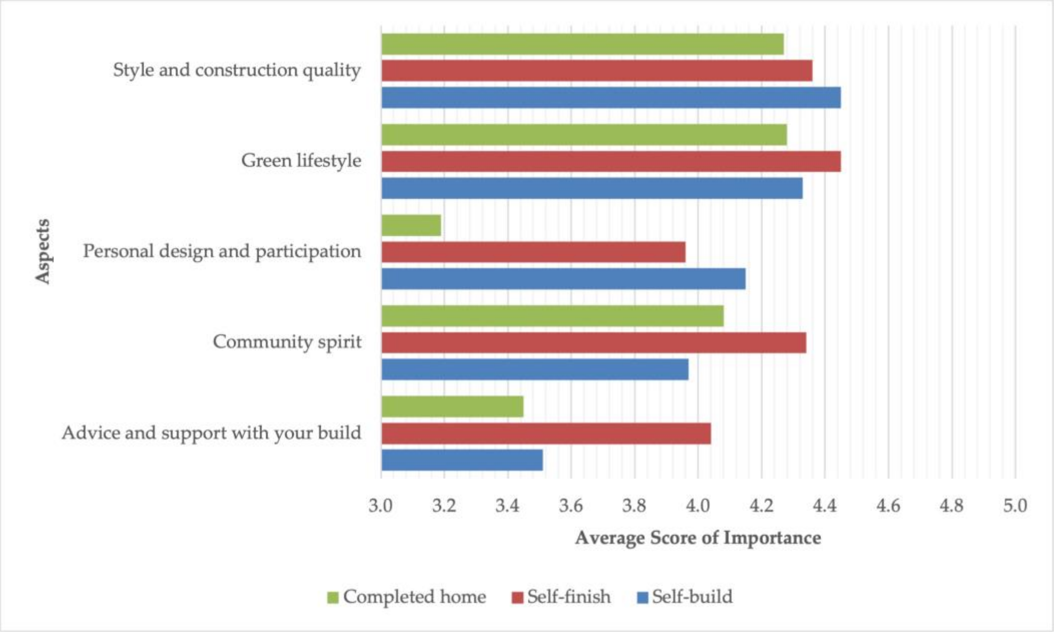


Figure 11. Average scores of importance for core ESBC housing aspects by respondents interested in one build method (Survey 1)

What is particularly striking about the results is that 'construction quality' is considered a top priority in both surveys. This suggests that those interested in ESBC schemes and conventional self-build and custom-build housing see these approaches as ways of acquiring a home built to a higher quality. In the case of Survey 1, this could be because the market sees that either high sustainability standards promised in ESBC schemes or participation in the design and/or build will result in high-quality construction. For Survey 2, this could be because of the quality control people have through self-build, self-finish, and custom-build.

4.3.4 Budget

Figure 12 shows the percentage of respondents in each budget range in Survey 1 and Survey 2. The percentage of respondents with budgets up to £300k is relatively similar in each survey: 54% in Survey 1 and 52% in Survey 2. However, there are significant differences between the two surveys for higher budget groups. Survey 1 has 29% in the £300k–£400k range and 11% in the £400k–£500k range, with only 6% of respondents in the £500k+ range. In comparison, Survey 2 has 7% in the "up to £400k" range and 15% in the "up to £500k" range, with 26% of respondents in the "more than £500k" range. This shows that the market for ESBC housing attracts people with a variety of budgets, but a relatively small percentage fall into the top two budget ranges. Whereas a relatively high percentage of the conventional market for self-build and custom-build in Survey 2 have the much higher budgets required for larger homes on larger parcels of land, which can be typical of one-off self-build developments. For Survey 2, most budgets in the "more than £500k" category far exceeded £500k, going as high as £1,100,000. In this budget range, the average percentage of their budget respondents could finance through their own resources was 78%, compared to 50% as an average across all respondents. This suggests that the conventional market for self-build and custom-build have significant capital to spend on their homes upfront, especially those in the higher budget ranges.

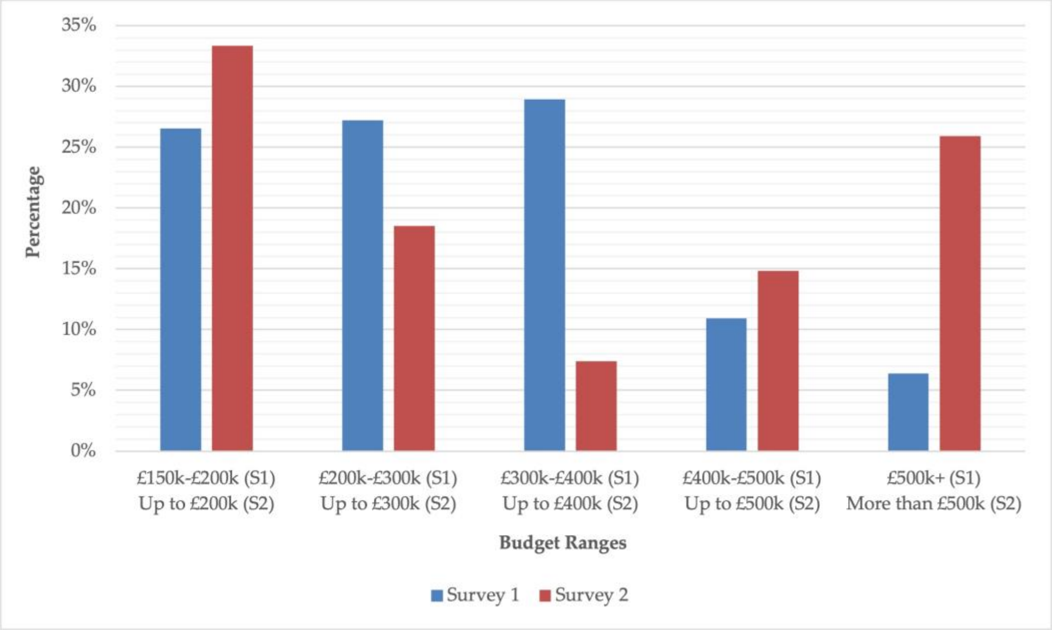


Figure 12. Percentage of respondents in each budget range (Survey 1 and Survey 2). N.B. The budget ranges slightly differ in Survey 1 (S1) and Survey 2 (S2)

4.3.5 Importance of Sustainability

A total of 84% of respondents to Survey 2 said that living in a sustainable home is important to them. As shown in Figure 13, from these 36 respondents, the statement 'I want to reduce my environmental impact' was selected 32 times. This was selected considerably more than any other reason. 'I want to save money on home running costs' was selected 22 times. This was followed by 'I think the home will have greater construction quality than most conventional housing', which was selected 15 times. This suggests that many people see that a well-constructed home is a sustainable home, and that conventional housing may not be able to deliver this quality. This argument is reinforced in section 4.3.3 where 'construction quality' was the most important housing aspect in Survey 2 and 'style and construction quality' was the second most important aspect in Survey 1, just behind 'green lifestyle'. Ultimately, both the market for ESBC housing and the market for more conventional self-build and custom-build housing may perceive their respective routes to housing as being able to deliver high-quality construction and sustainability in a way that conventional housing might not. ‘I want a lifestyle that aligns with my personal values and identity’ was selected 13 times, showing that over one-third of respondents are aware of how their housing choice and values and identity are interlinked. ‘I want to live in a home that is built with natural materials (e.g., timber, straw bale, rammed earth)’ and ‘I want to live in a home that utilises the latest lifestyle technologies (e.g., smart home systems)’ were both selected by one-quarter of respondents, which highlights that interest in sustainable materials and technologies—the actual features of a home—is a key reason why living in a sustainable home is important to some. ‘I think the home will be more aesthetically pleasing than most conventional housing’ was only selected 6 times, which indicates that sustainability is not necessarily seen by many as a driver of aesthetics in a home. However, results in section 4.3.3 show that ‘internal appearance/layout’ was the joint second most important housing aspect in Survey 2, and therefore respondents likely see aesthetic qualities being achieved through design choice offered in self-build and custom-build.

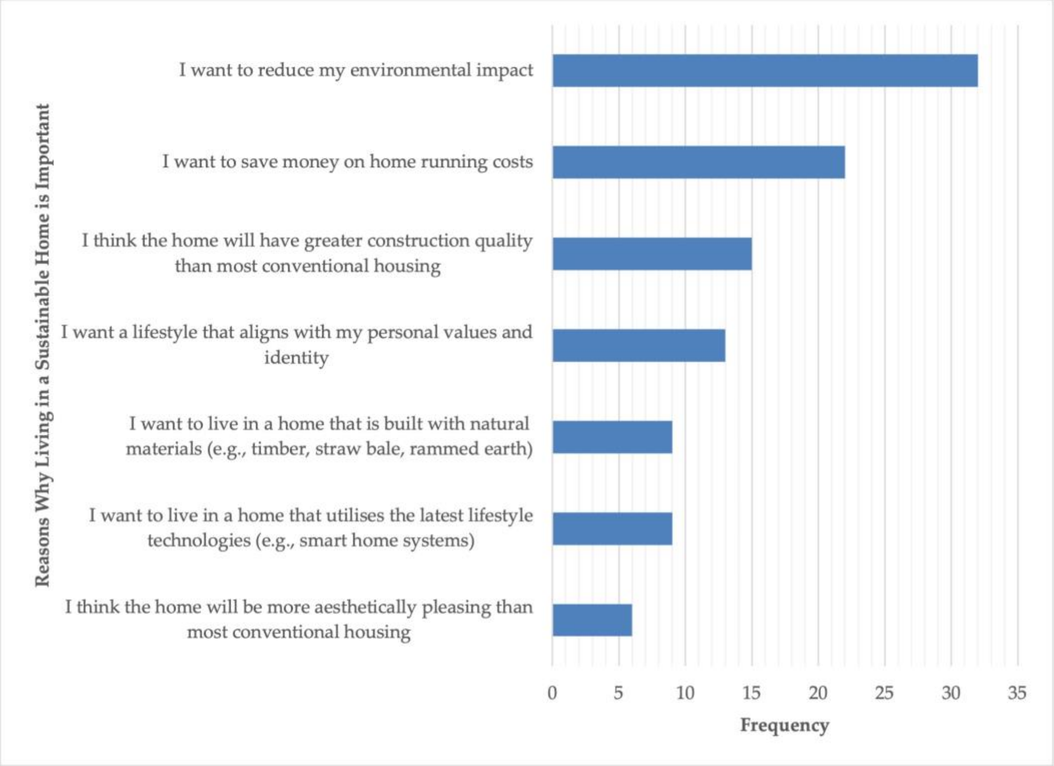


Figure 13. Frequency of responses for factors perceived as important for living in a sustainable home (Survey 2)

4.3.6 Willingness to Pay for a Sustainable Home

The data from Survey 2 show that on average, people would spend 27% more on Home 1 (average ESBC home) than Home 2 (average UK new build), and 37% more on Home 1 than Home 3 (average UK existing home). The characteristics of these homes are described in section 4.2.2, Table 6. Figure 14 and Figure 15 show the number of responses in each percentage value band, which represent how much more people would be willing to pay for Home 1 than Home 2 and Home 1 than Home 3. Figure 14 shows that 12 out of 36 respondents would be willing to spend 0–10% more for Home 1 than Home 2. This falls to 5 respondents in the 11–20% value band and rises sharply up to 11 respondents in the 21–30% value band. The number of respondents drops to 1 in the 31–40% value band and remains low up to the 91–100% value band. This seems to suggest that most people interested in self-build and custom-build would be willing to pay up to 30% more for a highly sustainable home than the current standard of the average new build home in the UK, and some would be willing to spend even more. In comparison, Figure 15 shows a more even distribution of respondents across the percentage value bands. There are 8 in the 0–10% value band, 6 in the 11–20% value band, 7 in the 21–30% value band, and then it falls to 4 in both the 31–40% value band and 41–50% value band. There are none in the 51–60% value band and a small number across the remaining value bands. This demonstrates that people concerned with living a sustainable home would be willing to pay a significant amount more for one than the typical homes on the market, and this rises when the environmental profile of the alternative worsens. As shown in section 4.3.5, the two most selected reasons why living in a sustainable home is important to respondents were ‘I want to reduce my environmental impact’ and ‘I want to save money on home running costs’. Hence, when presented with information on the operational CO_2 emissions and energy costs for each home type, respondents show they would be willing to pay more for the sustainable home. An analysis of Figure 14 and Figure 15 illustrates that people interested in self-build and custom-build put a considerable monetary value on the sustainability of a home and section 4.3.5 suggests the main drivers for this.

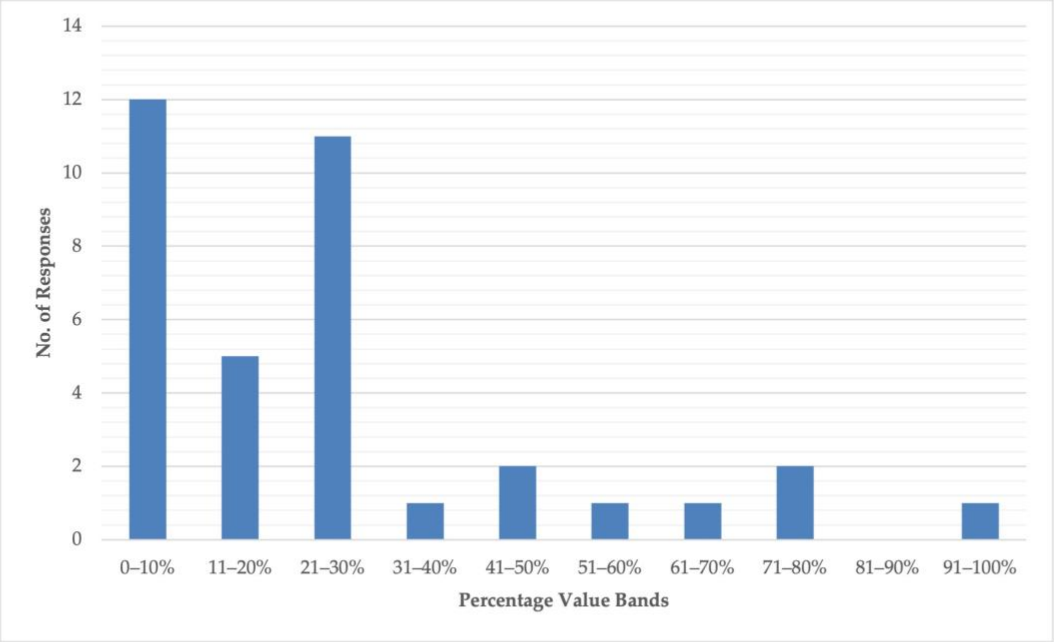


Figure 14. The number of responses in each value band, which represent the increased percentage people would be willing to spend for Home 1 than Home 2

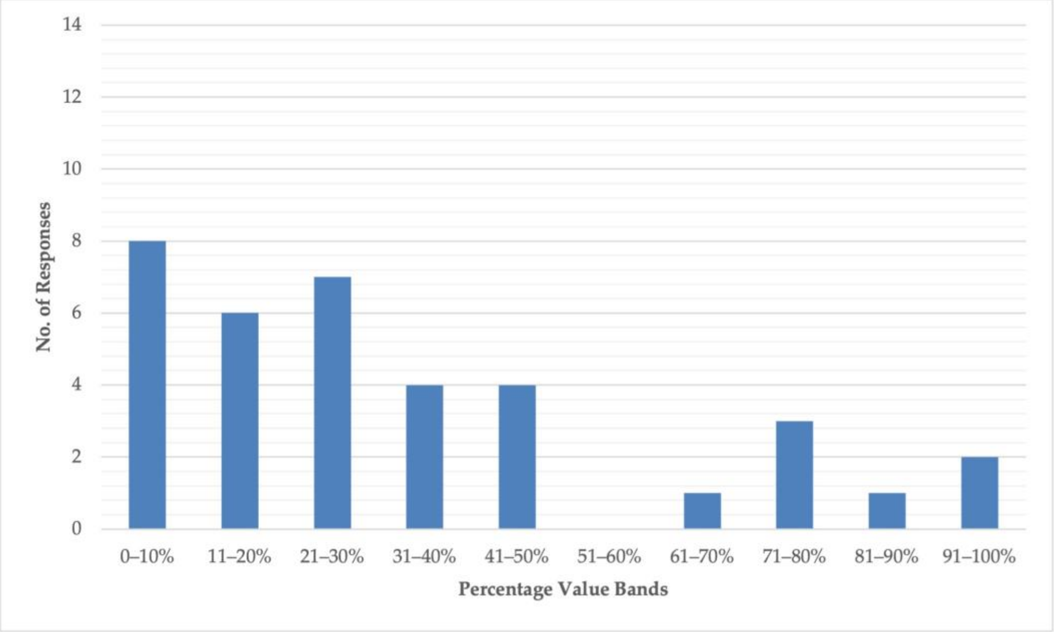


Figure 15. The number of responses in each value band, which represent the increased percentage people would be willing to spend for Home 1 than Home 3

4.4 Discussion

This section discusses the key findings and evaluates the extent to which ESBC housing satisfies the market, using Water Lilies as a case study, and what further development of ESBC schemes is needed to facilitate their future expansion.

As shown in section 4.3.1, ESBC housing attracts people looking for a range of dwelling sizes. Table 7 illustrates the dwelling types and number of bedrooms in the Water Lilies development. This shows that a variety of dwelling types and sizes are available. Furthermore, the houses enable users to decide the number of bedrooms they want through the self-finish approach. Since 39% were looking for a 3-bedroom home and 15% for a 4+ bedroom home, the scheme accommodates these segments of the market. However, the flats in Water Lilies do not necessarily reflect the potential demand because 9% of the market are looking for a 1-bedroom home, of which there are eight flats, and 36% of the market are looking for a 2-bedroom home, of which there are four flats. On this evidence, compared to the conventional market for self-build and custom-build, which can be seen to attract people seeking larger houses, ESBC housing should continue to offer a range of dwelling sizes and consider providing a greater proportion of 2-bedroom homes in future schemes.

Table 7. Dwelling types and number of bedrooms in the Water Lilies development

Dwelling Type	Build Method	No. of Bedrooms	No. of Dwellings
Flat	Custom-build	1	8
Flat	Custom-build	2	4
House	Self-finish	Up to 3	7
House	Self-finish	Up to 4	8
House	Self-finish	Up to 5	2
House	Self-finish	Up to 6	2
House	Self-finish	Up to 8	2

The results from section 4.3.2 show that the market for ESBC housing is largely open to more than one build method, but with a greater preference for purchasing a completed home and self-finish than self-build. In fact, those who selected a single build method: only 7% selected ‘self-build’ and 9% ‘self-finish’ compared to 17% that selected ‘completed home’. ESBC housing does not currently provide completed homes; however, the custom-build approach offered on flats only requires buyers to participate in two design sessions and the home is completed for them. In future schemes, this approach could be replicated for a proportion of houses so that people are still able to benefit from a home designed to their requirements, but without the responsibility of self-finishing. Based on the findings, there is an argument that ESBC housing should provide completed homes. However, this would conflict with the principles of the development model and the important role participating in the design and delivery of one’s home, including supportive workshops, has in creating a sense of community. There is anecdotal evidence to suggest that most of the self-finish buyers in Water Lilies would have preferred to take on less responsibility in the fit-out, which adds weight to the argument that a custom-build route could be provided for houses as well as flats. Therefore, future ESBC housing schemes could explore the provision of self-finish and custom-build houses to cater for different needs and desires.

A key finding from section 4.3.3 was that construction quality is significantly important to both the market for ESBC housing and the conventional market for self-build and custom-build. These findings are reinforced by self- and custom-build consumer survey research by NaCSBA and Building Societies Association, which found that 43% of people thought a benefit of building their own home was ‘the quality of the overall build could be higher than that of a pre-built home’ (NaCSBA and Building Societies Association, 2020). Once the Future Homes Standard comes into effect in 2025 (MHCLG, 2019), it will be interesting to see to what extent the requirements to build energy efficient and low-carbon homes will improve the construction quality and sustainability of new build homes and whether this will shift the perception of people who may be looking at ESBC housing as a means of buying a high quality, sustainable home.

However, construction quality and sustainability are not the only aspects attracting people to ESBC housing. The prospect of living in a community is also important to this market and is not widely offered in residential developments in the UK. A sense of community is fostered in ESBC housing by designing community spaces and facilities, delivering community workshops, and establishing an estate management company. This requires the ESBC developer to have skilled personnel to plan and facilitate workshops and it increases overheads for the associated time input. Whilst regulations may force speculative housing to catch up in terms of construction quality and sustainability, it can be argued that providing community-oriented housing to this extent would neither be necessary, given the lack of demand, nor possible to integrate into the standardised and efficient processes of speculative housebuilders (Payne and Barker, 2018). Therefore, the longer-term strategy for ESBC housing might be to sharpen the focus on social sustainability and develop a scalable approach to delivering aspects that build a sense of community.

Table 8 shows that there is demand for dwellings across every budget range offered in Water Lilies, but there is a potential mismatch in terms of demand for £400k–£500k homes and £500k+ homes with section 4.3.4 showing there was only 11% and 6% of respondents in these budget ranges, respectively. This was not necessarily a problem for Water Lilies because the houses sold out before the cut-off point where internal layouts would become fixed designs. Furthermore, as shown in Table 8, 14% of properties sold in Bristol between September 2020 and August 2021 cost £500k+, demonstrating a greater demand in the region for homes of this price than reflected by the ESBC housing market. It should also be noted that building highly energy efficient homes and integrating renewable energy technology increases build costs significantly and necessitates higher than average prices to ensure viability. However, if ESBC housing is to provide for a greater proportion of the market in the mid- to low-budget ranges, it would need to offer more homes that they can afford, and which meet their requirements. There is no straightforward solution to providing ESBC housing for a wider social mix because developing net-zero-carbon communities is an essential aim of the model (Bright Green Futures, 2021a), and this comes at a significant cost. Further research is required into the design and cost-effectiveness of the buildings to explore whether ESBC housing could provide for a greater proportion of the market, whilst balancing sustainability objectives. Additionally, further research could investigate how much people can finance through their own resources for the ESBC housing market. This may suggest ways potential buyers could be financially supported and incentivised to purchase a home.

Table 8. Number of dwellings in each budget range in the Water Lilies development

Budget Range	**No. of Dwellings in Budget Range[1]**	**Percentage of Dwellings in Budget Range**	**Percentage of Respondents in Budget Range**	**Percentage of Properties Sold in Bristol (September 2020–August 2021)[2]**
£0–£150k	0	0%	0%	5%
£150k–£200k	4	12%	27%	9%
£200k–£300k	4	12%	27%	36%
£300k–£400k	7	21%	29%	25%
£400k–£500k	12	36%	11%	12%
£500k+	6	18%	6%	14%

[1] The house prices in Water Lilies are based on the estimated total costs including the plot prices, shell prices, estimated fit-out costs (independently assessed based on typical new build specifications in the UK and the design of each house submitted in planning), and optional parking spaces. Some home prices were lower at sale due to discounts for purchasing pre-planning approval and the Help to Buy scheme available for flats. [2] (Plumplot, 2021).

Furthermore, the evidence from section 4.3.6 shows that people interested in self-build and custom-build are willing to pay more for a sustainable home. This suggests that ESBC housing may still attract potential buyers with homes that are more expensive than the average new build and therefore account for the increased build costs. As shown in section 4.3.5, the main drivers for people being willing to pay more for a sustainable home appear to be that they want to reduce their environmental impact and lowering home running costs. These qualities should be evidenced and promoted in ESBC housing schemes and compared to conventional speculatively built housing to highlight the carbon and monetary savings.

4.5 Conclusions

This paper answered the overarching research question: what are the main factors that influence people's purchasing decisions with respect to ESBC housing compared to conventional self-build and custom-build housing, and to what extent does the current ESBC development model satisfy the market, using Water Lilies as a case study? It did so by addressing the detailed objectives in the following ways:

1. It provided an extensive literature review to demonstrate the key characteristics of speculative housing and forms of self-build, custom-build, and community-led housing delivered by individuals, communities, and developers, with reference to case studies, and illustrates how ESBC housing differs in terms of its delivery model and output.
2. An in-depth understanding of the market for ESBC housing was gained by analysing data from potential consumers of ESBC housing and people interested in conventional self-build and custom-build housing on the factors influencing their purchasing decisions. The results indicated that there is a market for ESBC schemes where the priorities of prospective homeowners are distinctly different to those purely interested in self-build. For ESBC schemes, the provision of eco-housing with a low environmental impact and a sense of community are key priorities; this differs to the more general self-build market, where location and the need to tailor the house design to the owner's unique aesthetic and lifestyle preferences are the main priorities.
3. Based on this understanding, the extent to which the ESBC housing satisfies the market, using the Water Lilies development as a case study, was evaluated and recommendations were proposed for how future ESBC schemes could be developed to facilitate their future expansion. The key recommendations included:
    - Continue to offer a range of dwelling sizes and consider providing a greater proportion of 2-bedroom homes.
    - Explore the custom-build approach, not only for flats, but also for houses.

- As a longer-term strategy, consider sharpening the focus on social sustainability and develop a scalable approach to delivering aspects that build a sense of community.
- Investigate the design and cost-effectiveness of the buildings to explore whether ESBC housing could provide for a greater proportion of the market, whilst balancing sustainability objectives.
- Investigate how much people can finance through their own resources for the ESBC housing market to suggest ways potential buyers could be financially supported and incentivised to purchase a home.
- Highlight the carbon and monetary savings to consumers by evidencing and promoting how people can reduce their environmental impact and lower home running costs compared to conventional speculatively built housing.

Chapter 5 – Carbon Assessment of Building Shell Options for Eco Self-Build Community Housing Through the Integration of Building Energy Modelling and Life Cycle Analysis Tools

The literature review highlighted that there are relatively few life cycle assessment studies for residential buildings in the UK (Bahramian and Yetilmezsoy, 2020), and only one of those identified assessed life cycle carbon emissions from cradle-to-grave (Cuéllar-Franca and Azapagic, 2012). It was not clear from this study how the energy mix of the national grid impacted operational carbon emissions. This highlighted an opportunity to consider the sensitivity of operational carbon emissions to changes in the carbon intensity of the UK's energy supply. Furthermore, Chapter 4 concluded that the provision of eco-housing with a low environmental impact was a key priority for potential consumers of ESBC housing. However, life cycle carbon emissions associated with an ESBC home had not been calculated. As recommended in Chapter 4, this would demonstrate to potential consumers how ESBC housing can reduce their carbon emissions compared to conventional speculatively built housing. Considering the difficulty of attaining accurate life cycle assessment results from the limited data available in the early design stages (Antón and Díaz, 2014), this research recognised an opportunity to use technical design information from Water Lilies to analyse building-related carbon emissions and inform future schemes. Finally, the literature review highlighted that specific BEM and LCA tools could be integrated to facilitate a whole life cycle assessment. Therefore, this chapter integrates BEM and LCA tools, IES Virtual Environment and One Click LCA, to assess operational and embodied carbon emissions for a typical ESBC building shell. The results are based on the UK's Future Energy Scenarios, which provide best- and worst-case scenarios for the percentage of renewables in the energy mix of the national grid over time.

These are compared to an operationally net-zero carbon scenario, such as that demonstrated by Water Lilies, described in section 2.4.

This chapter is adapted from the journal paper:

Newberry, P., Harper, P. and Norman, J. (in press) 'Carbon assessment of building shell options for eco self-build community housing through the integration of building energy modelling and life cycle analysis tools', *Journal of Building Engineering*.

I was the primary author and the contributions from the other named authors were purely in reviewing the paper and suggesting refinements to the content prior to submission.

The following modifications are made to this chapter to enhance the coherence of the thesis:

- Examples of BEM-LCA integration have been moved from '5.1 Introduction' to section '3.3.6 Integration of Building Energy Modelling and Life Cycle Assessment Tools'.
- The section 'Water Lilies Eco Self-Build Community' in '5.2.1 Case Study' has been integrated into 'Chapter 2: Case Study Overview'.

5.1 Introduction

In a recent report, *Net Zero Strategy: Build Back Greener*, the UK Government sets out a roadmap to make a net-zero carbon transition by 2050 (BEIS, 2021). In terms of housing, new and existing homes currently emit 20% of greenhouse gas emissions in the UK (Committee on Climate Change, 2019). To address carbon emissions from new homes, the Government plans to introduce the Future Homes Standard in 2025. This will implement changes to Part L and F of the Building Regulations for new dwellings. As a result, new homes will no longer connect to the gas network from 2025. Furthermore, it is expected that the introduction of high building fabric standards and low carbon heating systems will reduce the carbon emissions of an average new-build home by 75-80% compared to one built to current energy efficiency standards (MHCLG, 2019).

In recent years, the standard of energy efficiency in new housing has significantly improved and guided by the UK's strategy, the national grid continues to decarbonise. Studies show that embodied carbon in energy efficient housing can account for as much as 40–60% of the total life cycle energy (Kovacic, Reisinger and Honic, 2018). Furthermore, the Future Energy Scenarios (FES) present credible ways of supplying and consuming energy that will reduce operational carbon from buildings and support the UK's net-zero carbon transition between 2020 and 2050 (National Grid ESO, 2021b). Consequently, given the increased share of embodied carbon relative to operational carbon in the life cycle of new buildings, focus on reducing embodied carbon has taken priority (Herrero-Garcia, 2020). Yet, operational energy use still accounts for approximately 23% of carbon emissions in medium-scale residential buildings (Gibbons and Orr, 2020) and, on average, 60% of residential energy demand comes from space heating (Sousa *et al.*, 2017). Following the introduction of the Future Homes Standard, from 2025, new homes will be heated using electricity from the national grid, unless connected to a localised energy grid. Since the national grid continues to rely on fossil fuels as part of its energy mix, the energy efficiency of the building shell remains an important consideration as it determines energy demand for space heating and, consequently, operational carbon emissions. Once the physical layout of a building is fixed, a principal design consideration for energy efficiency is the choice of insulation material in the building shell (Streimikiene *et al.*, 2020). Using efficient insulation reduces energy waste and creates comfortable indoor conditions whilst minimising maintenance costs (Aslani, Bakhtiar and Akbarzadeh, 2019).

Life cycle assessment (LCA) is a technique to assess the environmental impacts of a product from the raw material acquisition through production, use, end-of-life treatment, recycling and disposal (i.e. cradle-to-grave) (ISO, 2006). Considering the whole life cycle of a building, including embodied and operational carbon emissions, enables the optimal combined opportunities for reducing lifetime emissions to be identified (RICS, 2017). LCA implementation has become increasingly commonplace in the building sector (Dong and Liu, 2022) and there have been an increasing number of academic studies as attempts are made to analyse and reduce building-related environmental impacts (Anand and Amor, 2017), including for residential buildings (Chastas *et al.*, 2018; Bahramian and Yetilmezsoy, 2020). However, a review of papers between 2005 and 2015 by Zeng and Chini (2017) concluded that few studies attempted to measure the carbon emissions of buildings beyond the production stage (i.e. cradle-to-gate). Furthermore, Roberts *et al.* (2020) reviewed literature on implementation of LCAs in the building design process, highlighting barriers that hinder the widescale adoption of LCA at the early design phase, including access to detailed information, time constraints, and suitability of tools. Furthermore, small to medium-sized projects and small companies may lack resources to employ LCA expertise (Roberts, Allen and Coley, 2020). There are clear roadblocks to undertaking LCA in the early design phase, yet decisions made during this time have a significant impact on the environmental performance of the building as it underpins subsequent planning processes and detailed design (Hollberg *et al.*, 2018; Tabrizi and Brambilla, 2019).

Building information modelling (BIM) provides a digital representation of the physical and functional characteristics of a building that can be shared amongst stakeholders to aid decision-making during its life cycle (US National Institute of Building Sciences, 2007). BIM emerged as a tool to simplify the LCA process by managing the building information required in the analysis (Nwodo and Anumba, 2019). The integration of BIM and LCA tools can reduce the efforts of performing an LCA study by exchanging data regarding the types and quantities of materials from a BIM model into an LCA tool, either manually, semi-automatically, or automatically (Obrecht *et al.*, 2020). There is broad agreement in the literature that BIM and LCA tools should be integrated in the early design stages to take complete advantage of their potential and inform early decision-making (Basbagill *et al.*, 2013; Antón and Díaz, 2014; Najjar *et al.*, 2017; Bueno and Fabricio, 2018; Bueno, Pereira and Fabricio, 2018; Röck *et al.*, 2018; Rezaei, Bulle and Lesage, 2019). Most studies that integrate BIM and LCA tools focus on embodied carbon calculations using material inputs from the BIM model (Obrecht *et al.*, 2020). However, to undertake a whole life cycle assessment, the tools must also facilitate the analysis of operational carbon emissions, which involves calculating the energy demand of the building. This can be simulated through building energy modelling (BEM). BEM aims to analyse and quantify the energy performance of design alternatives to optimise energy efficiency in the design process (Farid Mohajer and Aksamija, 2019; Gao, Koch and Wu, 2019). Like BIM, it is widely acknowledged that the application of BEM in the early design stages can significantly benefit designers as it enables design options to be investigated in terms of energy consumption and thermal comfort (Gao, Koch and Wu, 2019).

Furthermore, BIM-based BEM has emerged as an approach in which information is imported from the BIM model to the BEM tool, including building geometry, material properties, space types, HVAC systems, and space loads (Azhar and Brown, 2009; Bahar *et al.*, 2013). However, there are currently major issues regarding interoperability between BIM and BEM tools (i.e. their ability to exchange and interpret information correctly). Studies have shown the data exchange process results in building information, including geometry, materials, and HVAC systems, to be misrepresented (Guzmán Garcia and Zhu, 2015; Chen, Jin and Alam, 2018; Elnabawi, 2020). Therefore, it has been suggested that better quality results can be guaranteed by recreating the model in the native BEM tool (Porsani *et al.*, 2021). As such, BEM tools have been used independently from BIM tools to facilitate whole life cycle carbon assessments and compare the environmental impacts of different design options. Several examples are provided in section 3.3.6.

However, there have not been any studies that integrate specific BEM and LCA tools, and enable the automated exchange of material data to streamline a whole life cycle assessment (i.e. modelling building information directly in the BEM tool without imports from a BIM tool, simulating energy consumption in the BEM tool to calculate operational carbon emissions, and automating the exchange of material data from the BEM tool to the LCA tool to calculate embodied carbon emissions). Therefore, developing a clear methodological approach that integrates specific BEM and LCA tools and implementing it for a case study would provide insights regarding their interoperability and highlight how effective the integration is in performing a whole life cycle assessment. A method that integrates BEM and LCA tools, without the need for BIM imports, may offer a more efficient and less time-consuming process for conducting a whole life cycle assessment, particularly for assessing options in the early design phase.

This research proposes and implements a method of undertaking a 60-year life cycle assessment from cradle to grave by integrating BEM and LCA tools. The reference study period was defined as 60 years as per the RICS guidance for domestic projects (RICS, 2017). BEM software, IES Virtual Environment (IES VE), creates a digital model and transfers building data into the LCA tool, One Click LCA, to calculate embodied carbon emissions. IES VE further simulates space heating demand, which is used to calculate operational carbon emissions. IES VE and One Click LCA were selected as the BEM and LCA tools because of their integration capabilities. Material data (and energy consumption data if needed) can be transferred from the IES VE model to One Click LCA for embodied carbon analysis (IES Virtual Environment, 2023; One Click LCA, 2023). The case study housing project used for this research is Water Lilies, a 33-home eco self-build community (ESBC) in Bristol, UK that is operationally net-zero carbon. The scheme utilises renewable energy connected to a localised microgrid and occupants fit-out their building shell through ‘self-finish’. The case study building shell is adapted for level ground, rather than a steep sloping site, and replicated to form a row of three almost identical terraced homes, creating a generic housing typology for a future project. The methodology is applied to the terraced building shells to calculate and compare the life cycle carbon impacts of an average terraced building shell pre-fit-out for six design options that use different insulation materials in the external walls and roof. The operational carbon calculations over the 60-year period are based on the most optimistic and most pessimistic Future Energy Scenarios (FES) for connection to the national grid and compared to the operationally net-zero carbon Water Lilies Community Energy (WLCE) scenario for connection to a localised microgrid powered by renewable energy. The research seeks LCA results from a technical building design and provide data to inform future designs. In turn, it establishes a method that could be used to undertake a more proactive assessment in the early design phase of a project.

Consequently, this research is guided by the following aims:

1. Develop a method that integrates BEM and LCA tools to conduct a life cycle assessment of the operational and embodied carbon impacts of a typical terraced building shell in an eco self-build community (ESBC) housing project, using Water Lilies as a case study.

2. Evaluate and compare the 60-year life cycle carbon impacts, based on Future Energy Scenarios (FES) and Water Lilies Community Energy (WLCE) scenario, of six design options that apply different insulation materials to the building shell of a typical terraced house in an ESBC.

This paper makes a novel contribution to the literature in two ways: by demonstrating a method that integrates specific BEM and LCA tools, IES Virtual Environment and One Click LCA, to perform a whole life cycle carbon assessment; and by applying Future Energy Scenarios to analyse how changes to the carbon intensity of the UK's national grid affects carbon emissions over time. In the following sections, the case study is described, the system boundary of the analysis is outlined, and the methodology is explained through its implementation. Then, the LCA results are discussed and compared based on different energy scenarios over a 60-year period. Lastly, the methodology is evaluated, conclusions are made on general trends and specific differences between design options, the limitations of the study, and potential areas for future research.

5.2 Material and Methods

The methodology integrates BEM and LCA tools, IES VE and One Click LCA, to conduct a 60-year life cycle assessment of a typical terraced building shell in an ESBC with capacity for up to four bedrooms. The study is based on adapted design-stage plans and specifications.

5.2.1 Case Study

This section specifies the structure and materials used in the baseline building shell. This research focuses on the design of the self-finish building shell and the integration of IES VE and One Click LCA to analyse different options from technical designs. Water Lilies provides specifications for a typical ESBC terraced house to use as a baseline design and analyse alternative options.

Baseline Building Shell Design

This study uses plans and specifications for a representative building shell as the basis of design and analysis, making several alterations for the purposes of this research. The building shell has a gross internal area (GIA) of 121m^2 and has capacity for up to four bedrooms, depending on the design of the occupant. Like the other terraced houses in the scheme, it is in the style of a three-storey townhouse with a roof terrace. Figure 16 and Figure 17 show the elevations and floor plans for the building shell respectively.

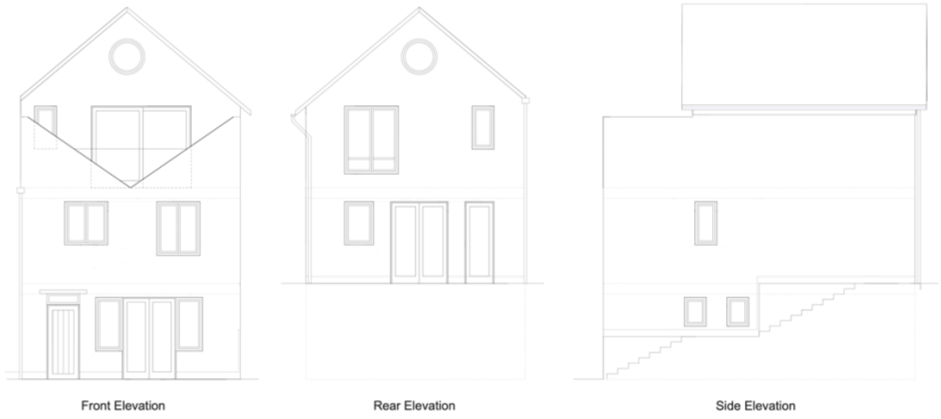


Figure 16. Case study building shell elevations (Marshall and Kendon Architects, 2020)

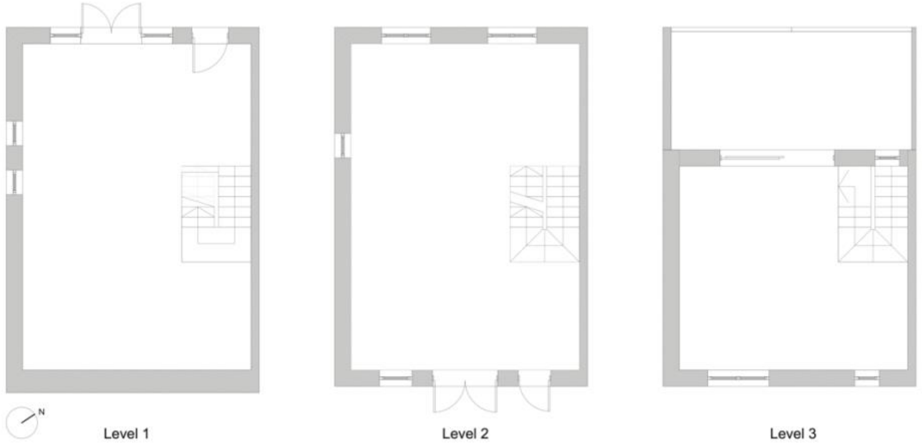


Figure 17. Case study building shell floor plan (Marshall and Kendon Architects, 2020)

For this research, the case study building shell has been converted into a row of three terraced houses with a total GIA of 363m^2. The building structure is adapted to create a terraced housing typology designed for level ground, rather than a steep sloping site. The external concrete wall on the ground floor, which is needed to stabilise the building on the existing sloped site, has been replaced with a continuation of timber frame. To account for this adjustment, the first-floor rear elevation has been moved to the ground floor, and the first-floor front elevation has been reflected on the first-floor rear elevation. Figure 18 shows the timber frame construction for the external walls. The same construction principles are applied to the roof.

BCIS Standard Form of Cost Analysis (SFCA) categorises building elements that can be used as a framework for defining elements in carbon analysis (Gibbons and Orr, 2020). Table 9 describes the building elements in the baseline building shell. These include building element group “1 Substructure” and “2 Superstructure”, which are the minimum building elements required for a life cycle assessment (Gibbons and Orr, 2020). The only building element that is changed in alternative design options is the insulation in the external walls and roof.

Table 9. Building elements of baseline building shell aligned with BCIS SFCA element categories

Building element group	**Building element**	**Description**
1 Substructure	1.1 Substructure	In-situ concrete ground-bearing slab.
2 Superstructure	2.1 Frame	Timber frame comprising 140mm studs. It is graded at an average moisture content not exceeding 20% with no reading being more than 24%.

	2.2 Upper floors	Upper floors: Metal web joists and oriented strand board (OSB) (but not ceilings) with a stair void. Roof terrace[1]: Timber studs have OSB sheathing with an airtight membrane fixed to the outer face. The inner face of the structure is lined with two layers of plasterboard providing fire and sound proofing. A single layer of PIR insulation (120mm) sits above the deck and the structure is completed with tiles on pedestals laid on top of the single ply waterproofing system.
	2.3 Roof	Roof: rafters have external structural sarking board with an airtight membrane fixed to the outer face. The inner face of the structure is lined with two layers of plasterboard providing fire and sound proofing. Two layers of PIR insulation (total thickness 135 mm) and a breather membrane are held down with counter battens, battens and finished with a profiled galvanised steel sheet roof covering.
	2.4 Stairs and ramps	Stairs are not included in the shell design because they are built by self-builders in their fit-out stage.
	2.5 External walls	Timber studs have OSB sheathing with an airtight membrane fixed to the outer face. The inner face of the structure is lined with two layers of plasterboard providing fire and sound proofing. Two layers of PIR insulation (total thickness 120 mm) and a breather membrane are held down with counter battens, battens and finished with render on carrier board.
	2.6 Windows and external doors	A mixture of highly energy efficient double and triple glazed windows and external doors cladded with a combination of timber and aluminium. There are also external wooden doors.
	2.7 Internal walls and partitions	Party walls: from either side of the centre line of the party wall there is a ventilated batten cavity with an airtight membrane fixed to OSB sheathing. This sits on the timber frame where mineral fibre slabs lie between the studs. Two layers of plasterboard providing fire and sound proofing complete the structure.

[1] Some data not available therefore assumptions about the OSB sheathing, airtight membrane and plasterboard are based on guidance in Pitts and Lancashire (2011).

Building Shell Design Options

Categories for conventional insulation materials include blanket insulation and foam boards. Blanket insulation is based on flexible fibres and examples include fibreglass, mineral wool, plastic, or natural fibres, and types of foam board include polystyrene and polyurethane (Streimikiene *et al.*, 2020). For each design option, all the building element materials were fixed apart from the insulation in the external walls and roof, which were switched. Table 10 summarises the specification of each design option. There were two typologies of timber frame construction. Foam board insulation materials, including types of polyisocyanurate (PIR) and polyurethane (PUR) were located on the outside of the timber frame (as shown in Figure 18), and blanket insulation materials, including types of hemp fibre, rock wool, and glass wool, were located between the timber frame (as shown in Figure 19). The same principles of construction are applied to the external wall and roof.

Table 10. Building shell design options

Design option	Insulation material type	Insulation manufacturer and product	Location in frame	Ext. wall insulation thickness (mm)[1]	Roof insulation thickness (mm)	Conductivity (W/mK)
PIR 1	Polyisocyanurate (PIR)	Kingspan Kooltherm K112 and K107	Outside frame	120 (60+60)	135 (60+75)	0.018
HF	Hemp fibre	Ekolution Hemp Fibre Insulation	Between frame	140	140	0.04
RW	Rock wool	Rockwool Flexibatts 37	Between frame	140	140	0.037
GW	Glass wool	Knauf Glass Wool Mineral Insulation	Between frame	140	140	0.031
PUR	Polyurethane (PUR)	Soprema Efigreen Alu+	Outside frame	120 (60+60)	120 (60+60)	0.022
PIR 2	Polyisocyanurate (PIR)	EcoTherm Eco-Protect Plus	Outside frame	132 (66+66)	132 (66+66)	0.022

[1] Numbers in brackets denote the thickness of each layer of insulation making up the total.

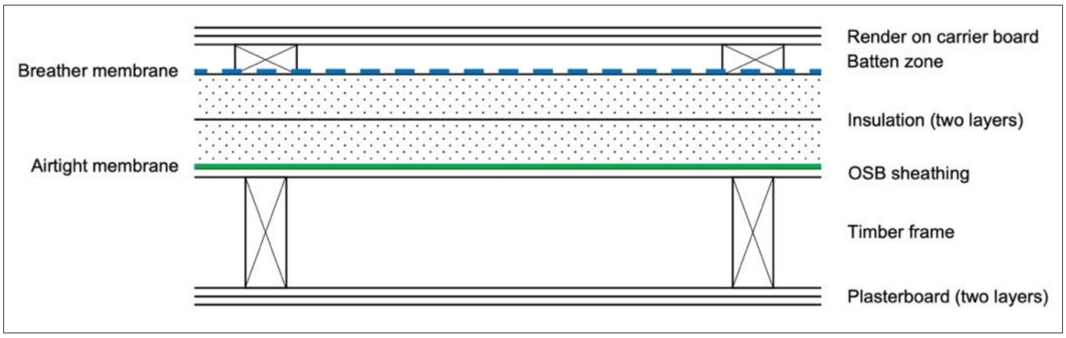


Figure 18. Timber frame construction with insulation located outside of the frame (PIR 1, PUR and PIR 2)

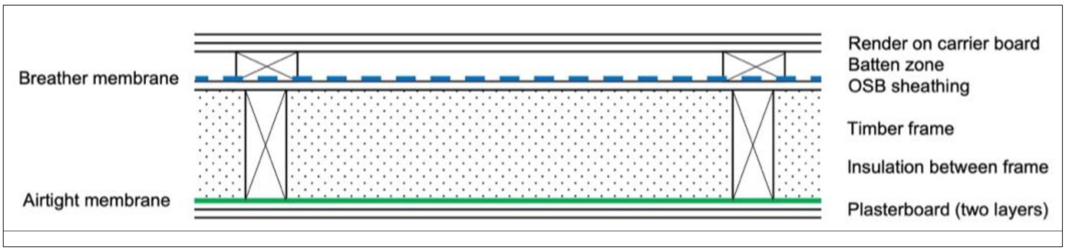


Figure 19. Timber frame construction with insultation located between the frame (HF, RW and GW)

The following list briefly describes the insulation materials used in each design option:

1. Polyisocyanurate rigid foam (PIR 1) – the products applied are Kingspan Kooltherm K112 for the external wall and K107 for the roof, aligning with the case study shell specification. PIR is one of the most efficient thermal insulation materials (Makaveckas, Bliūdžius and Burlingis, 2020). It has been widely used in construction because of its superior mechanical properties and low thermal conductivity (Jin *et al.*, 2014).

2. Hemp fibre (HF) – the product applied is Ekolution Hemp Fibre Insulation, which consists of soft, woody fibres from the hemp stems that have a high tensile strength and provide very good thermal and acoustic insulating capacity (Ekolution AB, 2020). Hemp fibre is a natural material obtained from renewable resources using a manufacturing process that minimises its impact on the environment (Santoni *et al.*, 2019) through lower pollutant emissions, lower greenhouse gas emissions, and end-of-life biodegradability (Joshi *et al.*, 2004).

3. Rock wool (RW) – the product applied is Rockwool Flexibatts 37, which is a firesafe material for insulation against heat, cold, fire, vibrations and noise (Rockwool, 2019). Rock wool is a form of mineral wool, and the light and soft variety of products are used in structures with cavities, such as timber frame houses (Jelle, 2011)

4. Glass wool (GW) – the product applied is Knauf Glass Mineral Wool Insulation. This product is approximately 95% glass comprising recycled glass (up to 80%) and other mineral raw materials, and the remaining 5% is bio-based resin binder and additives that aid performance (Knauf Insulation, 2020).

5. Polyurethane foam (PUR) – the product applied is Soprema Efigreen Alu+. Polymeric foams, such as this, are highly efficient thermal insulation materials

because blowing agent gas with low thermal conductivity traps in the closed porous structures of the material (Zhang *et al.*, 2017).

6. Polyisocyanurate rigid foam (PIR 2) – the product applied is EcoTherm Eco-Protect Plus, an alternative PIR insulation from the baseline, PIR 1. This enables a comparison of life cycle carbon impacts between different products with different manufacturing processes.

5.2.2 System Boundary

The importance of defining a system boundary in a life cycle assessment has been emphasised in the literature (Dixit, Culp and Fernández-Solís, 2013). The following sub-sections detail the system boundary of this study, including the building elements in the scope of analysis, the Future Homes Standard as a benchmark for building element fabric performance, the embodied and operational carbon life cycle stages covered by this study, and the different energy scenarios used to calculate operational carbon emissions from energy demand.

Building Elements in Scope of Analysis

As described in section 2.6, ESBC housing provides a building shell to plot holders to complete their fit-out through self-finish. Therefore, this study focuses on the life cycle carbon impacts of the building shell at handover to plot holders, including the superstructure and the concrete slab of the substructure (Bright Green Futures, 2021b). The ground floor construction above the concrete slab is completed with insulation and screed by plot holders. Consequently, the insulation and screed were omitted from One Click LCA's analysis because the type and quantity of these materials are chosen by plot holders and are not part of the building shell provided to them. However, suitable assumptions of these materials were included in the IES VE model to enable a more realistic in-use thermal analysis. Table 11 shows the breakdown of building elements required for analysis in IES VE and One Click LCA, which is based on the BCIS SFCA building element categorisations relating to structural elements (Gibbons and Orr, 2020).

Table 11. Building elements included in scope of analysis for IES VE and One Click LCA

Building element group	Building elements	Scope of analysis	
		IES VE	One Click LCA
1 Substructure	1.1 Substructure [1]	•	•
2 Superstructure	2.1 Frame		•

	2.2 Upper floors incl. balconies	•	•
	2.3 Roof	•	•
	2.4 Stairs and ramps		
	2.5 External walls	•	•
	2.6 Windows and external doors	•	•
	2.7 Internal walls and partitions	•	•
	2.8 Internal doors		

[1] The complete ground floor construction is not provided to plot holders; however, a suitable insulation material is modelled in IES VE to enable in-use thermal analysis.

Building Fabric Standards

The building elements in the study, including the alternative external wall and roof constructions for each design option, achieve the U-values proposed by the Future Homes Standard to be fully adopted in Building Regulations: Part L by 2025 (MHCLG, 2019), apart from the roof construction for HF, RW and GW. This was to ensure high levels of energy efficiency and future-proof potential alternative designs. Table 12 shows the minimum standards for fabric performance of new dwellings proposed in the Future Homes Standard Consultation and the U-values that will be achieved in a typical ESBC building shell based on the Water Lilies project.

Table 12. Future Homes Standard's minimum U-value requirements for building elements compared to those predicted for a typical ESBC building shell

Building element	**Proposed minimum U-values for fabric performance of new dwellings [1] (W/m^2K)**	**Predicted U-values of a typical ESBC building shell [2] (W/m^2K)**
External walls	0.26	0.13
Party walls	0.20	Not defined
Floor	0.18	Not defined
Roof	0.16	0.13
Windows	1.6	1.1
Roof-lights	2.2	Not defined
Door	1.6	≤1.1

[1] As set out in the Future Homes Standard Consultation (MHCLG, 2019), which is yet to be adopted in Building Regulations.

[2] As set out in the Water Lilies Build Contract Shell Specification (Bright Green Futures, 2021b).

Life Cycle Stages

Figure 20 illustrates the life cycle stages from cradle to grave with the modules included for analysis in this study circled. The life cycle stages encompassed by the study were product (A1-A3), construction processes (A4-A5), use (B4), operational use (B6 and B7), and end-of-life (C1-C4). This study does not report on the flow of biogenic carbon, i.e. the uptake of CO_2 during biomass growth, which is transferred to the building system and reported as a negative emission in the product stage (A1-A3), before it is released at the end-of-life stage (C1-C4) (Hoxha *et al.*, 2020). There are two main approaches used to assess the impact of biogenic carbon uptake and release as part of the LCA process for buildings. The first approach, the '0/0 approach', assumes that the release of CO_2 from bio-based products at the end-of-life stage is balanced by the equivalent uptake of CO_2 during biomass growth (Hoxha *et al.*, 2020). The second approach, the '-1/+1 approach', assumes that the uptake of CO_2 during biomass growth is transferred to the building system and reported as a negative emission in the product stage before it is released at the end-of-life stage (Hoxha *et al.*, 2020). Both approaches should provide the same overall results (Andersen *et al.*, 2021). Yet, the procedure for accounting for biogenic carbon in life cycle assessments is neither standardised nor universally agreed (Brandão *et al.*, 2013). This paper applies the generic method provided by One Click LCA where neither the negative emissions of storing the CO_2 from the atmosphere nor the release of CO_2 are included in the results (i.e. the '0/0 approach'). The '0/0 approach' was selected because any material assumptions would result in uncertainties in biogenic flows. Furthermore, this approach provides results that can be compared with a greater number of residential case studies, including those that only consider the product stage (these cannot use the '-1/+1 approach' because it would provide misleading results (Andersen *et al.*, 2021)). However, to acknowledge the impact of materials on the flow of biogenic carbon, particularly given the high use of timber in the case study building and hemp fibre as a bio-based insulation option, separate results taking the '+1/-1 approach' are presented in Appendix B.

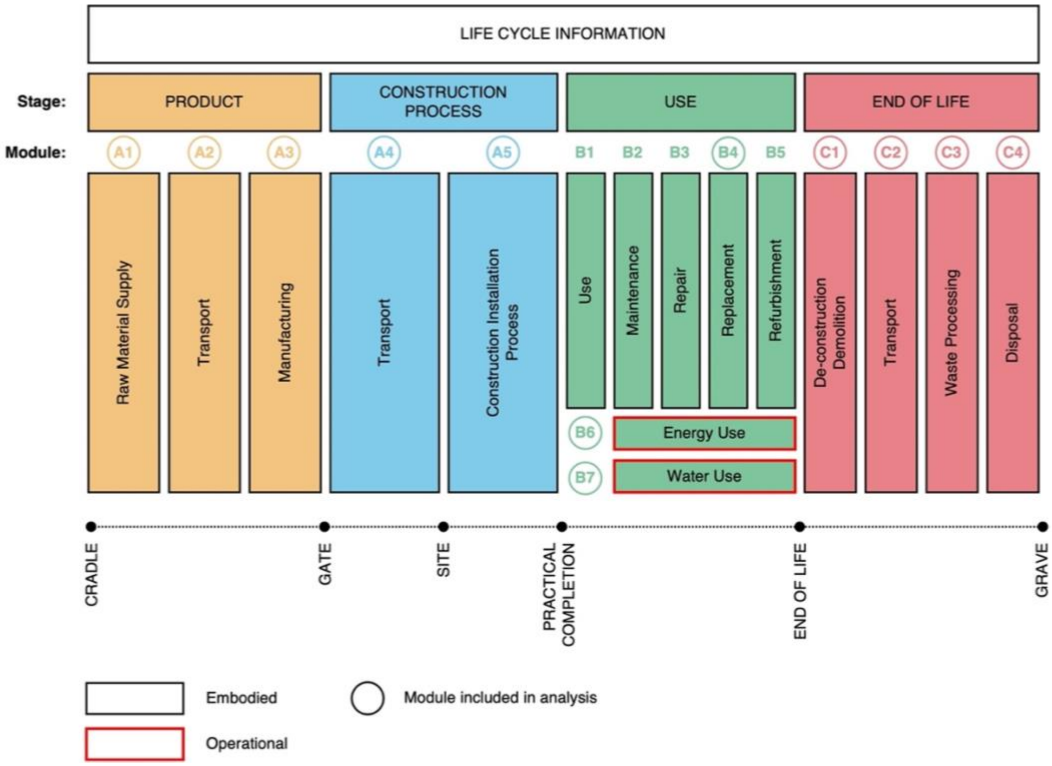


Figure 20. Building life cycle stages adapted from Gibbons and Orr (2020)

Energy Scenarios

The Future Energy Scenarios (FES) outline four different pathways for the future of energy from 2020 to 2050. FES were used to make predictions on the carbon intensity of the national grid, extending beyond 2050 to cover the 60-year period of life cycle assessment, and calculate the operational carbon of design options based on different energy scenarios. This method is explained in the section ‘Operational Carbon Calculation in MS Excel’.

FES aim to inform network operations, investment decisions, and energy policy, and support the UK to meet its 2050 net-zero carbon target (National Grid ESO, 2021b). Consumer Transformation and System Transformation represent two ways to reach net-zero carbon by 2050 – either by changing the way it is used or by changing how it is generated and supplied. Leading the Way offers the fastest credible decarbonisation route, combining high consumer engagement and leading-edge technology to reach net-zero carbon by 2047. Steady Progression only reduces emissions by 73% of 1990 levels by 2050. Some sectors can only achieve net-zero carbon by 2050 through the use of greenhouse gas removal technology in other sectors to offset any residual emissions (National Grid ESO, 2021b).

As the case study building uses electricity for both power and heating, this study is concerned with FES in respect to electricity supply. It focuses on the most optimistic and most pessimistic FES. Leading the Way has the fastest growth in renewable technologies with high levels of offshore and onshore wind growth and rapid phasing out of natural gas generation. Steady Progression sees gradual decarbonisation of the power sector as offshore wind continues to grow but there is limited growth of onshore wind and solar. The Water Lilies Community Energy (WLCE) scenario presents a net-zero operational carbon scenario based on the microgrid plans for Water Lilies, as described in section 2.4. This is used to compare national grid-connected scenarios to the case study microgrid-connected scenario where only embodied carbon emissions are factored in.

It is worth emphasising that this research only factors in the changing carbon intensity for each FES during the 60-year study period. It should be acknowledged that changing weather patterns could have an impact on results (e.g. changes in temperature and cloud cover affecting heating and lighting demands). Due to the 60-year study period, one would expect average weather patterns to apply (e.g. any extreme years would have a negligible impact on results). Accounting for any changes in these averages due to global warming effects was considered outside the scope of the study but should be considered in future research.

5.2.3 Life Cycle Assessment Through BEM-LCA Tool Integration

The BEM tool, IES VE, is used for modelling building geometry, defining energy profiles, and building component properties, and simulating and analysing data (Oleiwi *et al.*, 2019), which provides information to make more sustainable decisions (IES Virtual Environment, 2022). The LCA tool, One Click LCA, is an automated life cycle assessment software that calculates the environmental impacts of a building or infrastructure project by using Environmental Product Declarations (EPDs), which provide verified data on the environmental performance of a product or building material (Petrovic *et al.*, 2019; One Click LCA, 2022).

Figure 21 illustrates the methodology for conducting a life cycle assessment by integrating IES VE and One Click LCA, using MS Excel to store data, forecast Future Energy Scenarios, and calculate operational carbon emissions. It highlights the interfaces between different workspaces and the key data used to produce results for the six design options described in the section ‘Building Shell Design Options’. The following sub-sections describe the life cycle assessment methodology through its application to the case study building shell and alternative design options.

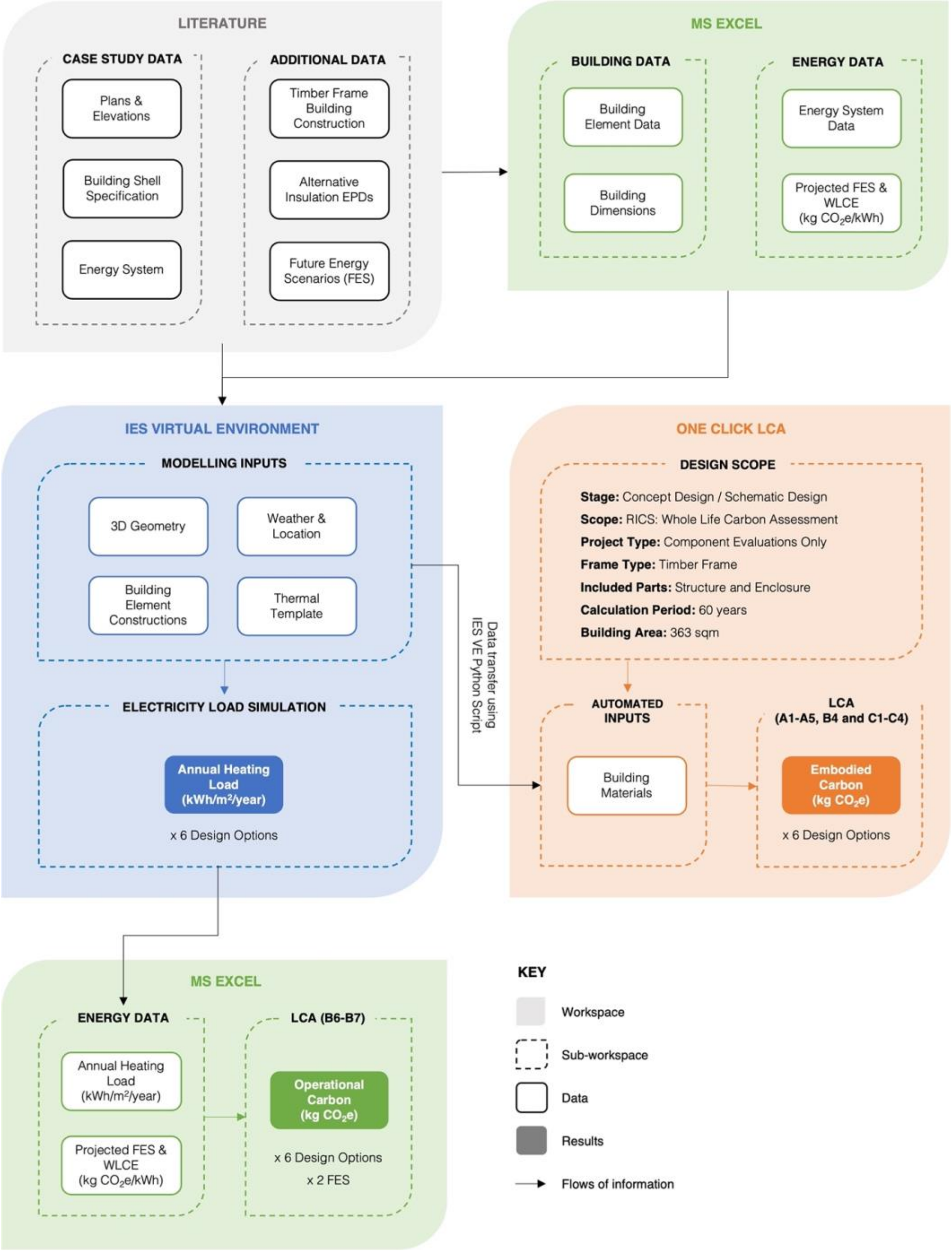


Figure 21. Diagram of LCA methodology integrating BEM and LCA tools

Data Collection Through Literature

The first step in the life cycle assessment process was to gather data on the case study building shell, including: plans and elevations; the building shell specification comprising construction material information and air tightness; and the energy system comprising the technologies used and predicted energy use data that was available. The case study building shell data is provided in the section ‘Baseline Building Shell Design’. Additional data from literature on timber frame building construction (Lancashire and Taylor, 2011; Pitts and Lancashire, 2011) was used to address any gaps in the case study documentation, Environmental Product Declarations (EPDs) provided data on alternative insulation materials for the design options, and Future Energy Scenarios (National Grid ESO, 2021b) provided data on the carbon intensity of the power sector from 2020-2050 for potential energy scenarios.

Case Study Database in MS Excel

The building element data, building dimensions, and energy system data were entered into Excel. The building element data contained the materials and their thickness (mm) and conductivity (W/mK), which are the properties required for performing thermal analysis in IES VE. Where exact building products were specified, namely the insulation materials for design options, the manufacturers’ product data was entered into the spreadsheet. Most building products were yet to be specified in the case study design documentation, only the generic materials. Therefore, system material data in IES VE was used to identify the typical conductivity of these materials. Where building materials were not specified at all in the design documentation, for example materials in the roof terrace, assumptions were made based on construction principles in the external walls and roof cross-referenced with relevant literature on timber frame buildings.

Modelling and Space Heating Demand Simulation in IES VE

The plans and elevations, building element data, and energy system data were used to model the 3D geometry of the case study building shell and run an energy demand simulation in IES VE to calculate the annual space-heating demand (kWh/m^2/year). The plans and elevations for the building shell were used to model the 3D geometry of the case study building, adapted, and replicated as a row of three terraced homes. The building element data was used to create building element constructions in the model, applying materials with the specified thickness (mm) and conductivity (W/mK) to generate U-values (W/m^{2}K).

Table 13 shows the building element constructions input to IES VE for the design options, including each material and its respective thickness and conductivity. IES VE automatically calculates a U-value for the building element based on these inputs. In this case, the EN-ISO method was used to calculate the U-value. A 140mm cavity was input for PIR 1, PUR and PIR 2 on the external wall and roof because the insulation sits on the outer face of the timber frame and leaves a cavity between the gypsum plasterboard and plywood sheathing. Whereas, for HF, RW and GW, the insulation sits between the timber studs, so there is no cavity. It should be noted that building materials including breather membranes and vapour control layers were not available in IES VE and, regardless, have a negligible impact on the resulting U-values. However, these material quantities, along with that of the timber frame, were added manually in One Click LCA for the embodied carbon analysis. Furthermore, plywood sheathing was used as a suitable replacement for OSB sheathing in terms of thermal properties as it was not available in the IES VE database. The quantities of plywood sheathing were later substituted for OSB sheathing in One Click LCA to measure embodied carbon.

Table 13. IES VE building element constructions and key inputs (materials ordered outside to inside)

Building element	Design option	Building materials	Thickness (mm)	Conductivity (W/mK)	U-value (W/m^{2}K)
External Wall	PIR 1	External Rendering Cement Bonded Particle Board Cavity PIR Insulation Plywood Sheathing Cavity [2] Gypsum Plasterboard	10 12 38 120 10 140 25	0.5 0.23 - 0.018 [1] 0.14 - 0.16	0.13
	HF	External Rendering Cement Bonded Particle Board Cavity Plywood Sheathing Hemp Fibre Gypsum Plasterboard	10 12 38 10 140 25	0.5 0.23 - 0.14 0.04 [1] 0.16	0.24
	RW	External Rendering Cement Bonded Particle Board Cavity Plywood Sheathing Rock Wool Gypsum Plasterboard	10 12 38 10 140 25	0.5 0.23 - 0.14 0.037 [1] 0.16	0.23
	GW	External Rendering Cement Bonded Particle Board	10 12	0.5 0.23	0.19

		Cavity	38	-	
		Plywood Sheathing	10	0.14	
		Glass Wool	140	0.031 [1]	
		Gypsum Plasterboard	25	0.16	
	PUR	External Rendering	10	0.5	0.16
		Cement Bonded Particle Board	12	0.23	
		Cavity	38	-	
		PUR Insulation	120	0.022 [1]	
		Plywood Sheathing	10	0.14	
		Cavity [2]	140	-	
		Gypsum Plasterboard	25	0.16	
	PIR 2	External Rendering	10	0.5	0.15
		Cement Bonded Particle Board	12	0.23	
		Cavity	38	-	
		PIR Insulation (Alternative)	132	0.022 [1]	
		Plywood Sheathing	10	0.14	
		Cavity [2]	140	-	
		Gypsum Plasterboard	25	0.16	
Roof	PIR 1	Steel	0.7	50	0.12
		Cavity	38	-	
		PIR Insulation	135	0.018 [1]	
		Plywood Sheathing	10	0.14	
		Cavity [2]	140	-	
		Gypsum Plasterboard	25	0.16	
	HF	Steel	0.7	50	0.25
		Cavity	38	-	
		Plywood Sheathing	10	0.14	
		Hemp Fibre	140	0.04 [1]	
		Gypsum Plasterboard	25	0.16	
	RW	Steel	0.7	50	0.24
		Cavity	38	-	
		Plywood Sheathing	10	0.14	
		Rock Wool	140	0.037 [1]	
		Gypsum Plasterboard	25	0.16	
	GW	Steel	0.7	50	0.20
		Cavity	38	-	
		Plywood Sheathing	10	0.14	
		Glass Wool	140	0.031 [1]	
		Gypsum Plasterboard	25	0.16	
	PUR	Steel	0.7	50	0.16
		Cavity	38	-	
		PUR Insulation	120	0.022 [1]	
		Plywood Sheathing	10	0.14	
		Cavity [2]	140	-	
		Gypsum Plasterboard	25	0.16	
	PIR 2	Steel	0.7	50	0.15
		Cavity	38	-	
		PIR Insulation (Alternative)	132	0.022 [1]	
		Plywood Sheathing	10	0.14	
		Cavity [2]	140	-	
		Gypsum Plasterboard	25	0.16	
Roof Terrace	All	Single Ply Membrane	2	1	0.18
		PIR Flat Roof Insulation	120	0.024 [1]	
		Plywood Sheathing	18	0.14	
		Cavity [2]	140	-	
		Gypsum Plasterboard	25	0.16	

Internal Wall	All	Gypsum Plasterboard Mineral Fibre Slab Cavity Mineral Fibre Slab Gypsum Plasterboard	25 90 60 90 25	0.16 0.035 - 0.035 0.16	0.17
Ground Floor [3]	All	Concrete Slab PIR Insulation Screed	200 120 80	1.6 0.018 0.41	0.14
Upper Floor	All	Plywood (Lightweight)	18	0.15	3.13

[1] Conductivity figures for insulation materials have been taken from the manufacturer’s data.

[2] Cavity, in this case, represents the gap between the timber studs or rafters.

[3] The ground floor is completed by plot holders who install insulation and screed (Bright Green Futures, 2021b). Therefore, these material properties have been assumed based on achieving the intended U-value as finished and a typical construction. This complete building element is required for thermal analysis but only the concrete slab was analysed in the LCA.

Figure 22 illustrates the Water Lilies case study row of three terraced houses modelled in the IES VE and the U-values that were generated based on the building element constructions for the design options.

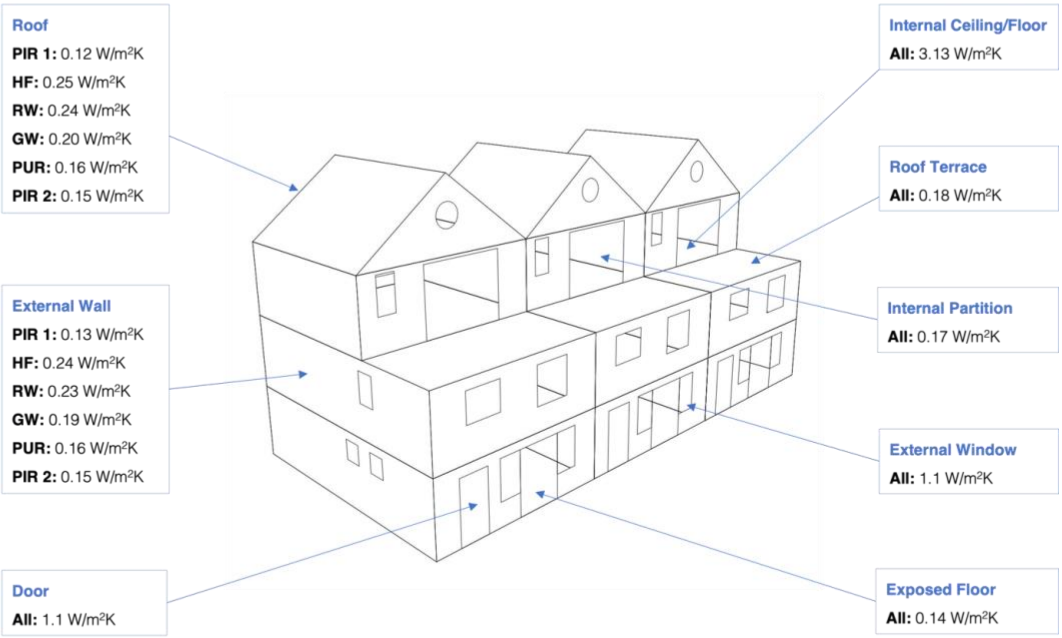


Figure 22. IES VE model demonstrating building elements and U-values for the design options

The energy system data was used to inform the thermal template of the building. Therefore, a central heating system using radiators and an air source heat pump with a seasonal efficiency of 2 was applied. A domestic heating profile with a constant setpoint of 19°C was assigned as the space conditions. For internal gains, it was assumed that three people occupied each building at 40m^2/person with a maximum sensible gain of 90 W/person and a maximum latent gain of 60 W/person. Air exchanges provided losses from infiltration, measured at 2ACH, as specified in the building shell specification (Bright Green Futures, 2021b). Weather and location data, which in this case was Bristol, U.K., was also applied to the model to be able to simulate weather conditions throughout the year. Room volume data, building element U-values, the thermal template, and weather and location data provided the basis for automated calculations to simulate the annual space-heating demand (kWh/m^2/year). The simulation was run for design options and the results are presented in section 5.3.1.

Building Data Transfer from IES VE to One Click LCA

Once the thermal simulations had been run, the next step was to transfer building data of PIR 1 automatically from IES VE to LCA. This involved running the LCA in IES VE with ‘No Energy Results’ to automatically submit material data only to One Click LCA. An IES

VE Python Script was provided to extract and process the data, which is highlighted in Figure 21 (One Click LCA, 2023). Table 14 highlights the steps carried out via One Click LCA to complete the import. The IES VE and One Click LCA material databases do not align, so the materials transferred from IES VE that One Click LCA can identify are mapped against suitable material products in the One Click LCA database. Changes to the data could be made during the 'mapping' stage and subsequently, once materials were imported to the One Click LCA project.

Table 14. Key actions at each import stage of data from IES VE to One Click LCA

Import stage	Key actions
Settings	• Chose the One Click LCA project to import to, which had been set up as 'Water Lilies IES VE Integration'. • Chose the assessment tool, 'Whole life carbon assessment, GLA / RICS'. • Selected 'All data' as the filter settings.
Classify	• Reviewed the new standardised Industry Foundation Classes (IFC) assigned to building elements which provide a target location for the building materials in One Click LCA (e.g. Class: INTERNAL CEILING/FLOOR > New class: HORIZONTAL FINISH > Target Location: Horizontal structures: beams, floors, and roofs).
Filter	• Filtered any classifications not required in the One Click LCA analysis. No class was filtered out at this stage but the insulation and screed in the SLAB class would be deleted at the 'review' stage because they were not required for the analysis, as discussed in section 3.1.
Combine	• Any data points that were grouped, for example layers of plasterboard, were ungrouped for clarity.
Review	• Reviewed the materials and their RICS categories and quantities. Roof terrace materials were changed from RICS category '2.3 Roofs' to '2.3.2 Roof Coverings'. • There was a warning for the 'implausible thickness' of the external rendering but it was not amended as the quantity aligned with building shell specification.
Mapping	• Building materials from IES VE were mapped to building material products in the One Click LCA database. These included 'identified data', where a suitable material assumption could be made, and 'unidentified and problematic data', where no material assumption could be made. • Most materials under 'identified data' were considered suitable for the analysis, but some were amended, for example Plywood from IES VE was changed to an OSB product in One Click LCA. • 'Unidentified or problematic data' included the windows and doors and the PIR insulation and single ply membrane in the roof terrace, which were all input manually based on specifications.

Table 15 shows the areas (m^2) of materials transferred from IES VE to One Click LCA and the difference with actual measurements from floor plans. There are mainly small discrepancies due to margins for error when drawing the model in IES VE. There was a large discrepancy for the upper floor building element, which was because of an issue with the tool that IES VE referred to One Click LCA to investigate. This issue was simply resolved once in One Click LCA by adjusting the quantities of materials within that building element to align with the specifications. However, this demonstrates the need to cross-check the areas transferred with those shown in the IES VE model before undertaking the life cycle assessment.

Table 15. Comparison between automated building element areas transferred from IES VE to One Click LCA and actual building element areas

Building element	**Area (m^2)**		**Difference (%)**	**Reason for % difference**	**Adjust in One Click LCA?**
	Automated value	**Actual**			
External Wall	324	321	+0.9%	Small margin for error when drawing windows in IES VE model without locking guides.	No
Roof	135	136	-0.7%		No
Roof Terrace	55	55	0%		No
Internal Walls	113	113	0%		No
Upper Floors	188	245	-23.3%	Discrepancy raised with IES VE, and query referred to One Click LCA for investigation.	Yes
Windows and Doors	94	97	-2.8%	Small margin for error when drawing windows in IES VE model without locking guides.	No
Ground Floor	162	162	0%		No

Embodied Carbon Assessment in One Click LCA

Before building data could be transferred from IES VE to One Click LCA and the life cycle assessment could be undertaken, the One Click LCA project required parameters to be entered and each design required the stage of construction process, the LCA calculation tool, and scope and type of analysis to be selected. At this point, data inputs, including building materials transferred from IES VE, could be entered into the design option.

The parameters (i.e. default values for material calculations) chosen in the One Click LCA project included the service life values for materials, transportation distance default values for materials, and the end-of-life calculation method. The service life of materials was set to ‘technical service life’, which assumes that the same types of materials have the same service life setting and represents how long a type of material lasts in good condition (One Click LCA, 2021). This was considered more suitable than ‘product-specific service life’, which might produce misleading results because most of the manufacturers and products were yet to be selected at this stage of the design process. In terms of transportation distance values, the UK was chosen as the most appropriate region. The end-of-life calculation method used was ‘material-locked’, which applies the end-of-life scenario that is most typical for the material in that market. This method was chosen instead of the ‘EPD end-of-life scenario’ due to the lack of data supplied by manufacturers with respect to life cycle stages C1-C4. This is a limitation of the study and LCAs in general. However, it was deemed an appropriate method for exploring early design options when specific materials were yet to be selected.

Each design option was set up with the following inputs:

- Stage of construction process (RIBA): ‘2 – Concept Design’.
- Calculation tool: ‘Whole life carbon assessment, GLA / RICS’.
- Pre-defined scope: ‘RICS: Whole life carbon assessment’.
- Project type: ‘Component evaluations only’
- Frame type: ‘Timber frame’
- Included parts: ‘Foundations and substructure’ and ‘Structure and enclosure’.

The mandatory data inputs for each design option included building materials, energy consumption, construction site operations, calculation period, and building area. The energy consumption was set to zero because this was provided by the IES VE simulation of space-heating energy demand and predicted energy demand data provided by CEPRO on domestic hot water and lighting and appliances. The impact of construction site operations was also set to zero because project specific information was not yet available. As per RICS guidance for domestic projects, the reference study period was defined as 60 years (RICS, 2017). The building area was set with a gross internal floor area of 363m^2 (three buildings of 121m^2). As discussed in the section ‘Building Data Transfer from IES VE to One Click LCA’, the building material data inputs were transferred from IES VE, providing accurate quantities of building materials (apart from materials in the upper floor, which needed manual adjustment due to a technical issue with the software, as shown in Table 15).

Operational Carbon Calculation in MS Excel

The equation to calculate operational carbon for a year is:

$$Annual\ operational\ carbon\ (kg\ CO_2e/year) = \\ annual\ energy\ demand\ (kWh/year) \times carbon\ intensity\ (kg\ CO_2e\ /\ kWh)$$

(Eqn. 1)

This study sought to calculate operational carbon emissions for a 60-year life cycle. 'FES 2021 Data Workbook' provides a projection of the carbon intensity of the power sector for each FES for each year from 2020 to 2050 (National Grid ESO, 2021a). So, this data was used to forecast the estimated change in carbon intensity of each FES from 2022 to 2081 to cover the study life cycle.

Using the 'FES 2021 Data Workbook', the carbon intensity figures for each year for each FES were copied into an MS Excel table, then a line graph was generated from the data, starting in 2022. For each FES line on the graph, an exponential trendline was added to the graph and the equation was displayed. For example, for Consumer Transformation, the equation was:

$$y = 102.93e^{-0.115x}$$

(Eqn. 2)

The carbon intensity is y, the constant is e, and the year in which the carbon intensity is being calculated is x. The years were expressed as numbers in Excel. The equation was converted into the Excel formula:

$$= 102.93 * EXP(-0.115 * 31)$$

(Eqn. 3)

In this case, 31 stands for the year 2051 because a numeric value was required for the formula. This formula was repeated for each year to 2081 (i.e. 61 as a numeric value). Figure 23 shows the resulting carbon intensity of each FES projected over a 60-year life cycle. For each FES, the potential for bioenergy with carbon capture and storage (BECCS) was excluded from the analysis. BECCS would otherwise lead to negative carbon intensity for Consumer Transformation, System Transformation, and Leading the Way.

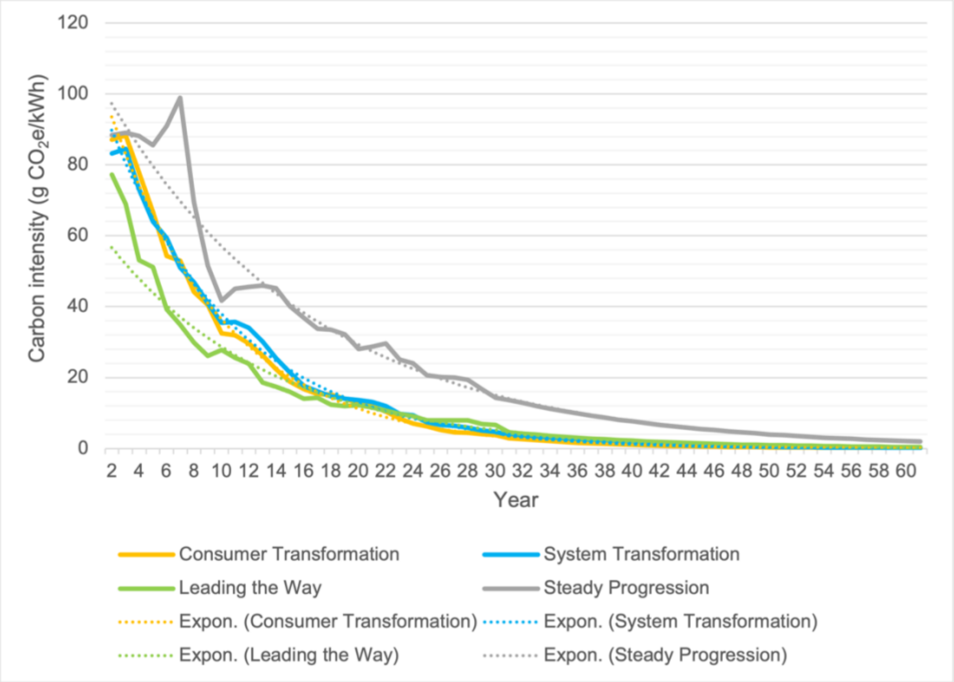


Figure 23. Power sector carbon intensity excluding negative emissions from BECCS projected for a 60-year life cycle (2022-2081) for Future Energy Scenarios and Water Lilies Community Energy scenario

With the carbon intensity (kg CO_2e/kWh) forecast for each year of the 60-year life cycle for each design option, only the annual energy demand (kWh/year) was required to calculate the operational carbon per year (kg CO_2e/year). The annual energy demand was calculated by adding the estimated figures for annual energy demand for lighting and appliances and annual domestic hot water (DHW) demand, provided for the case study building shell by CEPRO, to the annual space-heating demand simulated is IES VE, as described in the section ‘Modelling and Space Heating Demand Simulation in IES VE’. As a result, the annual energy demand (kWh/year) was multiplied by the carbon intensity (kg CO_2e/kWh) (see Eqn. 1) for each year from 2022 to 2081 and added up to calculate the operational carbon (kg CO_2e) for a 60-year life cycle.

5.3 Results

This section presents results on space heating demand and life cycle carbon emissions. This will enable an evaluation of the relative impacts of different design options over the whole building life cycle, with respect to both embodied and operational carbon. The results are given for a typical single terraced building in an ESBC housing project based on an average of the three terraces analysed. Space heating demands are presented first because these are essential in explaining the trends seen in the life cycle carbon emissions between the different design options.

5.3.1 Space Heating Demand

Figure 24 shows the monthly space heating demand per metre squared (kWh/m^2) for each design option throughout a typical year in Bristol, UK. This graph demonstrates the fluctuation in energy demand during colder and warmer months. None of the design options require energy to heat the home to 19°C in the spring and summer months from May to September. The energy requirements rise rapidly from October to a peak of between 5.2 kWh/m^2 and 5.9 kWh/m^2 for the different design options in January before declining again until May when they return to zero.

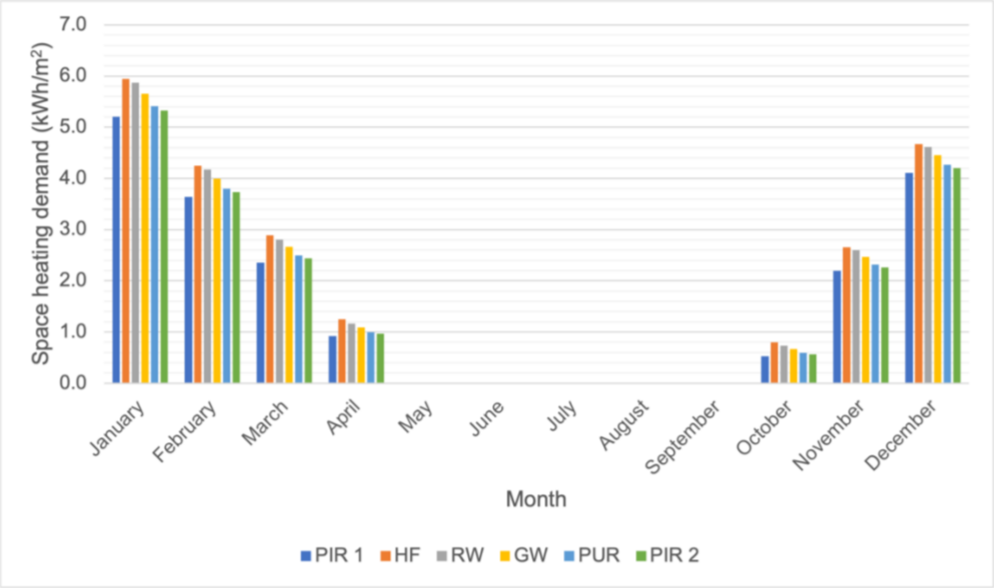


Figure 24. Monthly space heating demand for design options modelled on an average terraced ESBC house

Although the relative difference in space heating between the different options is small (the maximum difference is 0.7 kWh/m^2 between PIR 1 and HF, 12% of the maximum 5.9 kWh/m^2 required for HF in January), it can still have a significant impact on the relative life cycle carbon emissions for the different options depending on the carbon intensity of the grid. Figure 25 demonstrates the annual space heating demand, annual demand for lighting and appliances, and annual DHW demand for each design option.

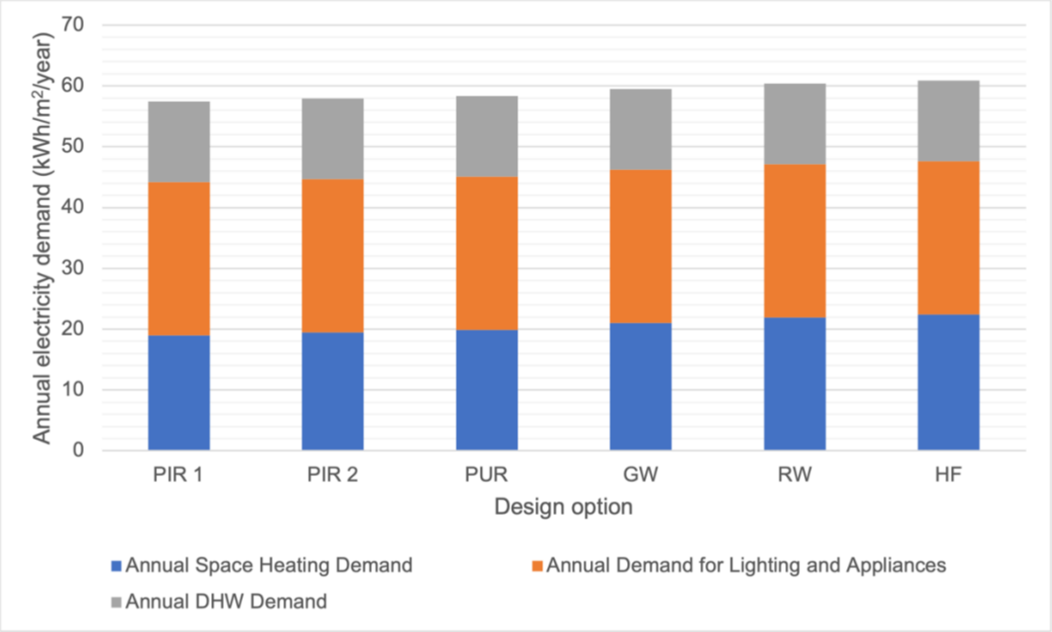


Figure 25. Annual space heating demand, annual demand for lighting and appliances, and annual DHW demand for design options modelled on an average terraced ESBC house

The annual demand for electricity and appliances is 25 kWh/m^2/year and annual DHW demand is 13 kWh/m^2/year for all design options because these forms of energy demand are not influenced by changes to the building shell. In terms of annual space heating demand, PIR 1 uses 19 kWh/m^2/year for space heating and HF uses 22.5 kWh/m^2/year. Therefore, there is an 18% difference in annual space heating demand between the most and least energy efficient design options. By comparison, Passivhaus buildings reduce space heating demand to below 15 kWh/m^2/year (Passivhaus Trust, 2011), whereas the space heating demand for an average UK home is approximately 145 kWh/m^2/year and a new build is approximately 50 kWh/m^2/year (Mitchell and Natarajan, 2020). The annual space heating demand of PIR 1 and HF account for 33% and 37%, respectively, of the total annual demand of the building. The space heating demand for PIR 1 is validated by separate data provided by CEPRO (Clean Energy Prospector) for the case study building shell (i.e. the same specification as PIR 1), which also predicted a space heating demand of 19 kWh/m^2/year.

5.3.2 Operational Carbon Emissions

Figure 26 demonstrates the operational carbon emissions of each design option in the most optimistic FES, Leading the Way, and the most pessimistic FES, Steady Progression. From left to right, the results are displayed for design options in order of the least operational carbon emissions to most operational carbon emissions. In Leading the Way, both PIR 1 and PIR 2 produce 41 kg CO_2e/m^2, whereas HF produces 44 kg CO_2e/m^2. In Steady Progression, PIR 1 produces 86 kg CO_2e/m^2, whereas HF produces 91 kg CO_2e/m^2. There is only a 6% difference between the least and the most operational carbon emissions in each FES. In terms of the difference in operational carbon emissions between each FES, there is a 110% increase from Leading the Way to Steady Progression for every design option.

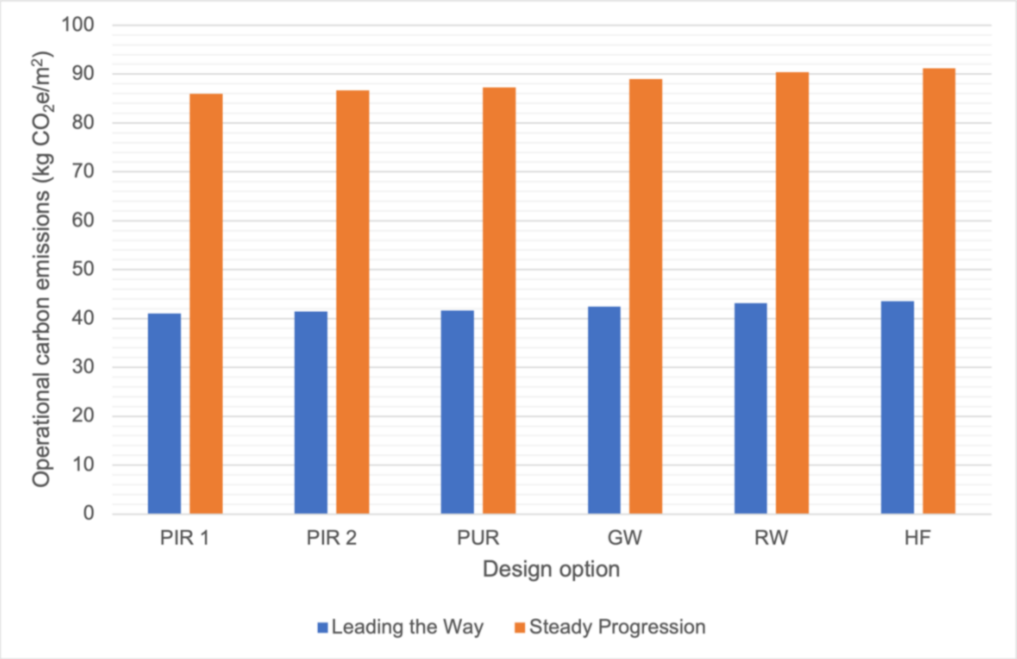


Figure 26. Operational carbon emissions of design options in the Leading the Way and Steady Progression FES

5.3.3 Embodied Carbon Emissions

Figure 27 breaks down the embodied carbon emissions of each design option into each life cycle stage addressed by this study. The results are shown for the whole building and the denominator is gross internal floor area. These are independent of the energy scenarios. HF has the least embodied carbon emissions, producing 134 kg CO_2e/m^2. PUR has the most, producing 166 kg CO_2e/m^2, an increase of 24%. Whilst the same material types, PIR 1 and PIR 2, produce similar operational carbon emissions, as shown in Figure 26, PIR 1 performs significantly better in terms of embodied carbon emissions. PIR 1 produces 139 kg CO_2e/m^2, whereas PIR 2 produces 154 kg CO_2e/m^2, an increase of 11%. The product (A1-A3) stage causes a significant difference in embodied carbon emissions between design options, where HF produces 93 kg CO_2e/m^2, 70% of its embodied carbon emissions, and PUR produces 124 kg CO_2e/m^2, 75% of its embodied carbon emissions. Results that factor in the flow of biogenic carbon are presented in Figure B.1 of Appendix B.

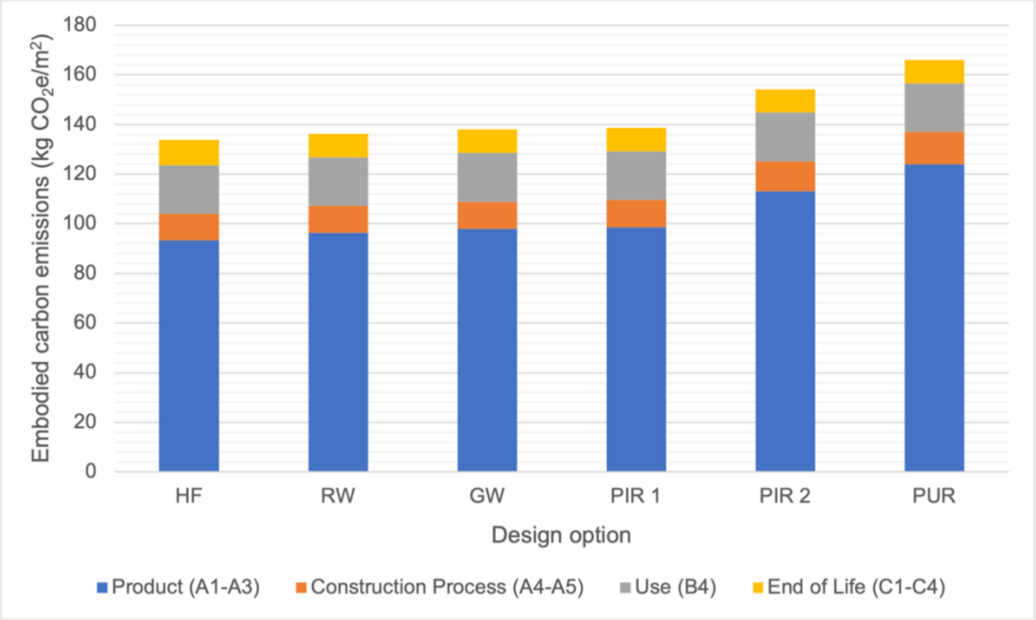


Figure 27. Embodied carbon emissions of design options (accounting for the whole building)

5.3.4 Whole Life Cycle Carbon Emissions

This section combines the operational carbon and embodied carbon to present the results of the whole life cycle assessment. Table 16 compares the results for each design option, including the percentage difference to the baseline, PIR 1, in the WLCE energy scenario (i.e. embodied carbon only), the most optimistic FES, Leading the Way, and the most pessimistic FES, Steady Progression.

Table 16. Life cycle carbon emissions of each design option and percentage difference from the baseline, PIR 1

Design option	WLCE (renewable microgrid)		Leading the Way (main grid best-case FES)		Steady Progression (main grid worst-case FES)	
	kg CO_2e/m^2	% diff. from PIR 1	kg CO_2e/m^2	% diff. from PIR 1	kg CO_2e/m^2	% diff. from PIR 1
PIR 1	139	0%	180	0%	225	0%
HF	134	-3.5%	177	-1.3%	225	+0.2%
RW	136	-1.7%	179	-0.1%	227	+0.9%
GW	138	-0.5%	180	+0.5%	227	+1.1%
PUR	166	+19.7%	208	+15.6%	253	+12.8%
PIR 2	154	+11.3%	196	+8.9%	241	+7.3%

N.B. Green indicates better performance and red indicates worse performance than PIR 1 (baseline).

As previously discussed, the WLCE scenario assumes operational carbon to be non-existent, so only embodied carbon is considered. On the other hand, Leading the Way and Steady Progression factor in the carbon intensity of the national grid for 60 years.

Consequently, operational carbon has a significant impact and can be greatly influenced by the space heating demand of each design option.

In WLCE, HF produces the least life cycle carbon emissions (134 kg CO_2e/m^2), 3.5% less than PIR 1. RW and GW also produce marginally less than PIR 1. PUR produces the most carbon emissions (166 kg CO_2e/m^2), significantly more than PIR 1 (+19.7%). In Leading the Way, HF produces the least life cycle carbon emissions (177 kg CO_2e/m^2), 1.3% less than PIR 1. RW also produces marginally less than PIR 1. PUR produces the most carbon emissions (208 kg CO_2e/m^2), 15.6% more than PIR 1. In Steady Progression, PIR 1 produces the least life cycle carbon emissions (225 kg CO_2e/m^2), only performing marginally better than HF, RW and GW. PUR produces the most carbon emissions (253 kg CO_2e/m^2), 12.8% more than PIR 1.

Table 17 demonstrates the relative impact of the embodied and operational carbon phases on total carbon emissions in each energy scenario. It can act as a guide of where to focus carbon reductions depending on the future energy mix of the grid. Embodied carbon has greater impact than operational carbon in every energy scenario. However, operational carbon becomes increasingly important as the carbon intensity of the grid increases, contributing around a quarter of total emissions over a 60-year life cycle in Leading the Way, and over a third in Steady Progression.

Table 17. Percentage of total carbon emissions from embodied and operational phases for each energy scenario

	WLCE (renewable microgrid)	**Leading the Way (main grid best-case FES)**	**Steady Progression (main grid worst-case FES)**
Embodied carbon (% of total emissions across design options)	100%	75-80%	59-66%
Operational carbon (% of total emissions across design options)	0%	20-25%	34-41%

Finally, across all design options, there was a 25-33% increase in whole life cycle carbon emissions between WLCE and Leading the Way, and a 53-68% increase between WLCE and Steady Progression (in both cases, PUR is the lowest increase and HF is the highest increase).

5.4 Discussion

The results from LCA studies are largely incomparable, not only due to context specific differences such as building layout, climatic conditions, and local regulations (Buyle, Braet and Audenaert, 2013), but also because the methodologies applied are inconsistent across assessments (Säynäjoki *et al.,* 2017). There are often differences in functional unit, lifespan, and system boundary definitions (Nwodo and Anumba, 2019), which are unique to each individual LCA but make comparing studies difficult (Dixit, Culp and Fernández-Solís, 2013). Moreover, different studies have different levels of detail and are based on various assumptions that lead to comparison issues because of uncertainty (Buyle, Braet and Audenaert, 2013; Islam, Jollands and Setunge, 2015).

However, Chastas *et al.* (2018) analysed case studies of 95 residential buildings, providing a range of embodied and operational carbon emissions, normalised in kg CO_2e/m^2 and for a 50-year lifespan. A second normalisation step that excluded case studies not accounting for the construction process stage and the end-of-life stage of the life cycle, and the energy for domestic hot water and electricity for lighting and appliances reduced the sample to 31 (Chastas *et al.,* 2018). The range of embodied carbon emissions for the 31 case studies was between 179 kg CO_2e/m^2 and 1,050 kg CO_2e/m^2 for the 50-year lifespan. For the residential buildings using wood structures, like the case study presented in this research, the range was between 179 kg CO_2e/m^2 and 495 kg CO_2e/m^2. In comparison, the baseline design option, PIR 1, produced 139 kg CO_2e/m^2 of embodied carbon emissions for a 60-year lifespan. This suggests that the baseline design option performs well in terms of embodied carbon emissions compared to other residential buildings, including those categorised as “low energy” (i.e. operating primary energy below 120 kWh/m^2/year) and “passive” (i.e. operating primary energy ≤120 kWh/m^2/year, heating demand ≤15 kWh/m^2/year, cooling demand ≤15 kWh/m^2/year, and pressurisation test value ≤0.6 1/hour). However, the significance of this is caveated by the factors previously highlighted that make LCA studies difficult to compare.

As the primary operating energy of the design options in this research are below 120 kWh/m^2/year (as shown in Figure 25), the results are compared with other low energy case studies. In Chastas *et al.* (2018), the share of embodied carbon emissions in low energy buildings ranged between 21% and 80%, compared to 59% and 66% in the Steady Progression FES. The extreme value of 80% reflected the case study’s Swiss energy mix comprising renewable (32.9%) and nuclear power (52.6%) “which do not directly release CO_2” (Chastas *et al.*, 2018). This can be compared to the share ranging from 75% to 80%

in the Leading the Way FES, which represents a potentially comparable energy mix scenario characterised by fast growth in renewable technologies and phasing out natural gas generation.

In terms of operational carbon, no comparisons are made with other studies because of variability in the energy mix of the grid. The baseline option, PIR 1, produced 41 kg CO_2e/m^2 (23% of total emissions) and 86 kg CO_2e/m^2 (38% of total emissions) of operational carbon in Leading the Way and Steady Progression, respectively. From Leading the Way to Steady Progression, there was a 110% increase in operational carbon emissions for every design option. As such, operational carbon can have a significant impact on life cycle carbon emissions over a 60-year period, but this is highly dependent on the carbon intensity of the grid. In the most optimistic FES, Leading the Way, operational carbon accounts for 20-25% of life cycle emissions across the design options. This compares to 34-41% of life cycle emissions in the most pessimistic FES, Steady Progression. These findings reinforce conclusions from Moradibistouni, Vale and Isaacs (2021) that the percentage of renewables in the national energy profile's energy mix is critical to life cycle carbon emissions.

Consequently, it can be argued – if thinking purely in terms of minimising carbon emissions – the lower the carbon intensity of the grid, the more building design should prioritise reducing embodied carbon emissions over optimising energy efficiency because of the lesser impact of operational carbon emissions as a percentage of overall life cycle carbon emissions. Following this logic, focusing on embodied carbon emissions becomes increasingly important the further in the future that a scheme will be constructed because, as shown in Figure 23, the carbon intensity of the grid is predicted to decrease rapidly over the next 10 years in each scenario. Therefore, the anticipated construction start date should be factored into design decisions early on because the percentage of renewables in the national grid's energy mix will have changed.

The Future Homes Standard's proposed changes to Part L of Building Regulations was used to guide the thermal performance of building elements in the study, with only the roof of HF, RW and GW having higher U-values than the benchmark. Ultimately, all design options were highly energy efficient. This meant there was only an 18% difference in annual space heating demand between the most and least energy efficient design options, PIR 1 and HF. However, using a bio-based insulation material, HF had the least embodied carbon emissions. Only in the most pessimistic FES, Steady Progression, did HF's higher annual space heating demand influence operational carbon emissions sufficiently to make it a slightly worse option in terms of life cycle carbon emissions than PIR 1.

It is not possible to accurately predict the carbon intensity of the national grid. However, the results show that, if external wall and roof building elements achieve or are even slightly above the U-values proposed in the Future Homes Standard and a relatively pessimistic energy scenario plays out, they may still provide a suitable design option when considering whole life cycle carbon emissions, provided their embodied carbon is low. This suggests that building elements designed to the Future Homes Standard should prioritise the use of materials with low embodied carbon over marginal gains in energy efficiency because this is likely where they will have the greatest impact on life cycle carbon emissions.

Furthermore, PIR 2 presented an alternative PIR insulation material to PIR 1 with similar energy efficiency. Regardless of the FES applied, the impact of operational carbon emissions was negligible. Yet, embodied carbon emissions increased by 11.3%. This highlights the need to investigate and compare specific products, even at an early design stage, because their influence on embodied carbon can vary significantly, whereas broad material types may provide misleading results.

To summarise the key findings, HF produced the least life cycle carbon emissions in WLCE and Leading the Way, whereas PIR 1 produced the least in Steady Progression. HF, RW, and GW have no more or less than 1.3% difference to PIR 1 in both Leading the Way and Steady Progression. PUR produced the most carbon emissions in every scenario, from 12% more than PIR 1 in Steady Progression to 20% more in WLCE – its relative impact reduced as the carbon intensity of the grid increased.

5.5 Conclusions

This study aimed to integrate BEM and LCA tools to conduct a life cycle assessment from cradle-to-grave. This paper addressed the core research aims by (1) developing a method that integrated BEM and LCA tools to conduct a life cycle assessment of the operational and embodied carbon impacts of a typical terraced building shell in an ESBC housing project, using Water Lilies as a case study and (2) evaluating and comparing the 60-year life cycle carbon impacts, based on Future Energy Scenarios (FES) and Water Lilies Community Energy (WLCE) scenario, of six design options that applied different insulation materials to the building shell of a typical terraced house in an ESBC.

The integration of IES VE and One Click LCA was successful in streamlining the assessment of operational and embodied carbon emissions allowing an evaluation of life cycle data to inform future design decision-making. IES VE was a valuable tool to model the basic 3D geometry and create and test different building element constructions to analyse their impact on energy demand and resulting operational carbon emissions. A key advantage of the tool integration was the ability to automatically transfer quantities and types of building materials from IES VE to One Click LCA, streamlining the LCA process. The IES VE and One Click LCA material databases do not exactly align. However, One Click LCA made relatively accurate assumptions of products based on the types of materials assigned to building element constructions in IES VE. Furthermore, One Click LCA's extensive material database provided the opportunity to investigate a wide range of products that may not have been previously considered, which could be fed back into the IES VE model.

The research has produced life cycle assessment results from a technical building design, which has provided data to inform future ESBC housing designs. Moreover, it has established a method to conduct a more proactive assessment in the early design phase of a future ESBC housing project, including baseline data inputs for a typical terraced building shell. The implementation of the method and results provided the following key insights to inform future studies and practitioners, including those involved in ESBC housing development, to help inform design options:

- The integration of BEM and LCA tools, IES VE and One Click LCA, provides a more streamlined whole life cycle assessment where building information is modelled directly in the BEM environment without needing imports from BIM; energy consumption is simulated in BEM to calculate operational carbon emissions; and material data from the model is automatically exchanged from BEM to the LCA tool to calculate embodied carbon emissions. However, expertise may be required to manage the complexity of the process, use the tools, and interpret the data.

- In Leading the Way, embodied carbon accounted for 75-80% of total emissions compared to 20-25% from operational carbon across design options. In Steady Progression, embodied carbon accounted for 59-66% of total emissions compared to 34-41% from operational carbon across design options. This shows that operational carbon results are highly sensitive to the percentage of renewables in the energy mix of the grid, which is difficult to predict, and can significantly influence the design choice.

- The further in the future a scheme is planned, the more embodied carbon should be prioritised over operational carbon because, regardless of the FES, the carbon intensity of the grid is predicted to decrease rapidly over the next 10 years. Consequently, assessing design options should consider potential changes to the energy mix of the grid by the time construction is due to commence as the life cycle calculation period will shift.

5.5.1 Limitations and Areas for Future Work

There are several limitations and uncertainties that should be highlighted. A key challenge was the inability to automate the transfer of timber frame from IES VE to One Click LCA. This was because IES VE interprets layers of materials in the walls, floors, and roof to be continuous masses of material, whereas timber frame has studs, joists, and rafters filled with insulation or cavities, depending on the construction type. Therefore, the layer where timber frame exists was assigned as either an insulation material or a cavity to enable appropriate thermal analysis in IES VE. As this research was able to make use of data from a more advanced design stage, timber quantities for the case study building shell were specified by the supplier and could be entered manually into One Click LCA for the embodied carbon analysis. However, this data may not be available in the early design phase, and other projects would benefit from the ability to automatically transfer the structural frame from IES VE to One Click LCA.

Moreover, where material-specific data was unavailable, assumptions were made based on the material type. This enabled a good initial prediction of life cycle carbon emissions, but greater accuracy may be possible once material-specific data becomes available. Furthermore, EPDs do not necessarily report every life cycle stage, which results in gaps in the data on life cycle processes specific to that product. For all materials, there is variability in the range of values possible for embodied carbon related to transport, depending on where the materials are produced in relation to the building location. Again, greater accuracy would be possible with material-specific data to reduce the number of assumptions made.

The use of predicted Future Energy Scenarios enabled operational carbon emissions and their sensitivity to varying grid carbon intensities to be calculated over the 60-year life cycle. However, the complexity of the process and the expertise required to use the tools and interpret the data were considered potential barriers to adoption in practice. In addition, there is uncertainty of future trends in terms of the percentage of renewables in the energy mix of the national grid. These uncertainties reduce the reliability of the results and a margin for error should be considered when comparing them. Nonetheless, with a robust and transparent process, the results provide a valuable comparison to inform design decision-making.

This study focused on the life cycle carbon emissions associated with the insulation materials for each design option. To inform design decision-making for future ESBC housing projects, the results should be considered alongside a range of other factors, such as cost, availability/viability at different scales of development, suitability of use with other building materials, and impact of wall thickness on floor space. With respect to ESBC housing, further research could explore the trade-offs between life cycle carbon emissions and build costs for different design options, and an assessment of how different building shell typologies could provide for different budgets groups identified in previous research (Newberry, Harper and Morgan, 2021). In addition, future research could investigate the impact of different structural materials (e.g. steel frame), types of foundation, and changing weather patterns.

Chapter 6 – Selecting and Applying a Neighbourhood Sustainability Assessment System to Evaluate an Eco Self-Build Community Housing Project

Chapter 5 analysed the life cycle carbon emissions associated with a typical ESBC housing building shell and compared the results with alternative designs using different insulation materials. The results will inform future sustainable building design and demonstrate environmental impact to potential consumers, which was a key recommendation from Chapter 4, as it supports their decision-making. Whilst Chapter 5 investigates environmental sustainability at the building-scale, Chapter 6 explores how the multiple dimensions of sustainability are addressed in ESBC housing at the neighbourhood-scale. The literature review discussed neighbourhood sustainability assessment tools (NSATs) for evaluating the sustainability performance of neighbourhood developments. Furthermore, it highlighted that NSATs classified as 'plan-embedded tools' have not been widely discussed in the literature (Sharifi, Dawodu and Cheshmehzangi, 2021). Plan-embedded tools have the potential to be applied largely by self-assessment and avoid barriers to NSAT adoption that are mostly associated with 'third-party assessment tools', such as a requirement for experts, high consultation and application costs, intensive data collection activities, and the inability to adapt the framework to the local context (Deakin, 2011; Sullivan, Rydin and Buchanan, 2014; Reith and Orova, 2015; Lin and Shih, 2016; Boyle, Michell and Viruly, 2018). Hence, this chapter provides a comprehensive evaluation of plan-embedded tools and selects the most suitable for application to Water Lilies. It specifies implementation measures to successfully evaluate the case study using the selected tool. Consequently, this provides a framework to guide future improvements in the design and delivery of ESBC housing schemes.

This chapter is adapted from the journal paper:

Newberry, P. and Harper, P. ‘Selecting and applying a Neighbourhood Sustainability Assessment system to evaluate an eco self-build community housing project’, *Journal of Cleaner Production*. Manuscript in preperation.

I was the primary author and the contributions from the other named authors were purely in reviewing the paper and suggesting refinements to the content prior to submission.

The following modifications are made to this chapter to enhance the coherence of the thesis:

- Part of the case study section has been moved to ‘6.1 Introduction’ and the rest has been integrated in ‘Chapter 2: Case Study Overview’.

6.1 Introduction

The performance of a construction project has traditionally been evaluated through the narrow lens of time, price, and quality, whilst aiming to provide the client with a high level of satisfaction (Chan, Scott and Lam, 2002). These are essential evaluation criteria. However, they are not geared toward assessing the multi-dimensional sustainability of a project. Since the World Commission on Environment and Development’s (1987) report, *Our Common Future*, the terms ‘sustainability’ and ‘sustainable development’ have been embraced by private and public sector bodies but much debated (Gibson, 2006). Yet, the definition is significant given its influence on indicators of sustainability and, in turn, how a project is developed and evaluated (Komeily and Srinivasan, 2015). Most sustainability frameworks are guided by ‘environmental’, ‘social’, and ‘economic’ dimensions of sustainability (Dawodu *et al.*, 2022), known as the three pillars (Elkington, 1999), although further ‘political’ and ‘cultural’ pillars have been conceived and considered in evaluating sustainability (Gibson, 2006).

It is widely acknowledged that the sustainable development of urban communities requires urgent attention among developers, municipalities, and academia (Haider *et al.*, 2018). Furthermore, the built environment, public transportation, and services need to be considered simultaneously because of the rapid increase of urbanisation (Haapio, 2012). 4.4 billion people (56% of the global population) live in cities, increasing to 6 billion by 2045 (The World Bank, 2022). Since the turn of the 21st century, a range of urban sustainability assessment systems have emerged and developed across the world to create and monitor sustainable urban development at different spatial scales including the building, neighbourhood, and entire city level (Kaur and Garg, 2019).

The neighbourhood is a specific area of a city that has distinct architectural, cultural and economic systems and the inhabitants share a common consciousness (Reith and Orova, 2015). It is considered a suitable scale for developing innovative sustainability solutions and accelerating the transition to sustainable development through the mobilisation of various stakeholders (Dawodu, Cheshmehzangi and Sharifi, 2020). The neighbourhood scale can be defined as an urban system of interrelating components including buildings, public transport, and services (Pedro *et al.*, 2019). Therefore, evaluating these interrelating components and the interactions between them makes the process more complex than at the building scale and can involve a great number of stakeholders (Berardi, 2015; Pedro *et al.*, 2019). The perceived complexity of sustainability and assessment systems can limit uptake of sustainability practices by building stakeholders (Berardi, 2012). This means that an effective and efficient sustainability assessment system needs to overcome the challenge of "striking a balance between completeness in the coverage and simplicity of use" (Ding, 2008). However, a recent review of the literature on urban sustainability assessments highlights that not a single assessment tool has managed to capture the complex relationships between criteria, with each criterion assessed in isolation regardless of its influence on other criteria (Kaur and Garg, 2019).

Neighbourhood sustainability assessment tools (NSATs) can be used to evaluate and rate the performance of a neighbourhood-scale development against a set of criteria and themes to assess its progress towards sustainability and specify the extent of its success in approaching sustainability goals (Sharifi and Murayama, 2013). Sharifi and Murayama (2013) provide two classifications of NSATs: (i) "third-party assessment systems", which have developed as spin-off tools from third-party building assessment systems to assess sustainability at the neighbourhood-scale, and; (ii) "plan-embedded tools", which are embedded in neighbourhood-scale plans to assess sustainability. Examples of widely cited third-party assessment systems include Building Research Establishment Environmental Assessment Method (BREEAM) Communities originating in the UK, Leadership in Energy and Environmental Design for Neighbourhood Development (LEED-ND) in the USA, Comprehensive Assessment System for Building Environmental Efficiency for Urban Development (CASBEE-UD) in Japan, and Green Star Communities in Australia (Sharifi, Dawodu and Cheshmehzangi, 2021). Examples of plan-embedded tools include HQE^{2}R and Ecocity originating in the EU, Sustainable Community Rating (SCR) in

Australia, EcoDistricts Performance and Assessment Toolkit in the USA, and One Planet Living Communities, Sustainable Project Appraisal Routine (SPeAR), and the recently emerging Value Toolkit in the UK (Sharifi, Dawodu and Cheshmehzangi, 2021). The characteristics of NSATs are strongly linked to the region in which they are developed so assessing the sustainability of a community in another context can be problematic and adaptation to the local context is indispensable (Berardi, 2012; Haapio, 2012; Sharifi and Murayama, 2015).

NSATs utilise sustainability indicators to assess performance quantitatively through a points-based system, thus providing a development with an overall sustainability rating and enabling its comparison with other developments (Dawodu, Cheshmehzangi and Sharifi, 2020). Additionally, NSATs ensure sustainability is considered in the early planning phase of development, highlight sustainability issues that otherwise risk being overlooked, and provide a common language for communication and collaboration amongst project stakeholder groups leading to a shared understanding of intended project outcomes (Wangel *et al.*, 2016). Furthermore, NSATs contribute to promoting sustainable development (Wangel *et al.*, 2016) and can act as a marketing tool for developments (Lewin, 2012; Ali-Toudert *et al.*, 2020). However, NSATs commonly suffer from a number of shortcomings, such as: insufficiently addressing the complexity of projects and context-specific issues due to their prescriptive structure (Deakin, 2011; Reith and Orova, 2015; Lin and Shih, 2016); prohibitively high costs associated with application fees, intensive data collection, expert consultation, and accreditation (Boyle, Michell and Viruly, 2018); burdensome documentation required for certification (Garde, 2009); greater importance ascribed to assessment criteria related to environmental sustainability than social and economic sustainability (Komeily and Srinivasan, 2015; Sharifi, 2021); the price premium associated with green-certified neighbourhoods (Boyle, Michell and Viruly, 2018), and; catalysing gentrification and reducing inclusivity (Benson and Bereitschaft, 2019). These factors play a role in limiting the widespread adoption of NSATs.

A recent systematic literature review of NSATs contends that it is critical to further study other tools that could help address these problems (Sharifi, Dawodu and Cheshmehzangi, 2021). It is argued that simplified versions of NSATs could be applied by self-assessment (i.e. the developers undertake the evaluation mostly themselves) and promote the sustainability agenda at the neighbourhood scale (Sharifi, Dawodu and Cheshmehzangi, 2021). It is evident that some plan-embedded tools can be applied by self-assessment and implemented without the considerable financial costs associated with using third-party assessment systems. However, a significantly larger volume of studies has focused on third-party assessment systems than plan-embedded tools. For example, LEED-ND, the most cited third-party assessment system, has featured in 88 studies, whereas HQE^{2}R, the most cited plan-embedded tool, has featured in 8 studies (Dawodu *et al.*, 2022). Therefore, further exploration of plan-embedded tools is required, and there is an opportunity to consider those that can be applied by self-assessment.

This research focuses on evaluating plan-embedded tools that were developed for the UK context and selecting the most suitable for a specific type of neighbourhood housing project. It draws on the wider NSAT literature to inform the criteria used to evaluate plan-embedded tools as part of the selection process. The case study used is ‘Water Lilies’, a 33-home eco self-build community (ESBC) housing project in Bristol, UK, by the developer, Bright Green Futures. The scheme is considered to be at the ‘neighbourhood scale’ because it is a system of interrelating components wherein the homes and their inhabitants are connected through shared spaces (e.g. a community garden and community hub), services (e.g. solar energy supplying a community micro-grid), facilities (e.g. communal waste and recycling facilities), ownership and management (e.g. individual and collective responsibilities guided by the residents’ estate management company’s constitution), and initiatives/activities (e.g. car-share scheme and co-working) as part of an architecturally distinct site. Previous research suggests that ESBC housing has the potential to be a scalable and sustainable housing model (Broer and Titheridge, 2010; Hughes, 2020; Newberry, Harper and Morgan, 2021). To deliver a scheme that offers self-finish and custom-build homes and engages the community in decision-making throughout design and construction requires a developer to expand its typical role and gives residents greater responsibility. Bright Green Futures provided individual design and mentoring sessions, as well as a wide range of community workshops to assist residents as the project progressed (Newberry, Harper and Morgan, 2021). Contractors working on the project were employed to engage with residents on technical design, construction, and project management matters outside of the developer’s understanding. As a result, a variety of stakeholders, including the homeowners, are essential to the success of the project, so any evaluation would require significant consideration of their experiences and/or contributions.

In order to robustly evaluate NSATs best suited to a specific project, this paper uses a multi-criteria decision analysis (MCDA) method. MCDA methods can support decision-making where multiple factors need to be taken into account (De Montis *et al.*, 2000), such as the characteristics of different NSATs. As described by De Montis *et al.* (2000), MCDA methods vary in regards to “the way of assessing criteria, the application and computation of weights, the mathematical algorithm utilised, the model to describe the system of preferences of the agent facing decision-making, the level of uncertainty embedded in the data set and the ability for stakeholders to participate in the process”. The analytical hierarch process (AHP), originally conceived by Saaty (1980), is an MCDA method that is adept at handling independent criteria, local scale problems, and quantitative and qualitative data, whilst involving stakeholders (i.e. the client) in the problem-solving process (De Montis *et al.*, 2000). Consequently, it was determined to be an appropriate method to facilitate a systematic and logical decision-making process with respect to selecting a suitable NSAT. In this paper, the AHP methodology proposed, guided by a procedure defined by Department for Communities and Local Government (2009a), provides a robust approach to investigate the different characteristics of NSATs and systematically weigh these up against the needs of the case study project and the priorities of the client. AHP has been applied in similar fields, such as urban sustainability assessment framework development (Ameen and Mourshed, 2019), sustainable development (Dos Santos *et al.*, 2019), construction management (Darko *et al.*, 2018), smart city development (Myeong, Jung and Lee, 2018), and urban renewal proposals (Lee and Chan, 2007).

The overall research project consists of three phases: ‘Phase 1’ is the NSAT selection process using an MCDA approach, ‘Phase 2’ is the specification of implementation measures for the chosen NSAT, and ‘Phase 3’ is the evaluation of Water Lilies using the NSAT. This paper addresses Phase 1 and Phase 2 through the following objectives:

RO1. Using an MCDA approach, provide a comprehensive evaluation of NSATs that could be applied to Water Lilies and select the most suitable.

RO2. For the chosen NSAT, define the specific implementation measures necessary to provide a successful evaluation of the Water Lilies project.

This paper makes a novel contribution to the literature by providing a comprehensive evaluation of plan-embedded tools using an original framework that can support decision-makers to select an NSAT that is suitable for their neighbourhood scheme and demonstrates the application of a plan-embedded tool, the Value Toolkit, in relation to the Water Lilies case study. The paper describes the methodology, in relation to the case study, for the research objectives set out for Phase 1 and Phase 2 above. Then, it discusses the key findings and limitations of the study with respect to both Phase 1 and Phase 2.

6.2 Methodology

The overarching methodology for the research project consists of three phases as set out in the introduction and illustrated in Figure 28. The methodology for this paper addresses the research objectives, labelled RO1 and RO2 in the swimlane diagram. These relate to the process of selecting the most suitable NSAT using an MCDA approach in Phase 1 and how the chosen tool has been implemented to the specific needs of the Water Lilies project in Phase 2.

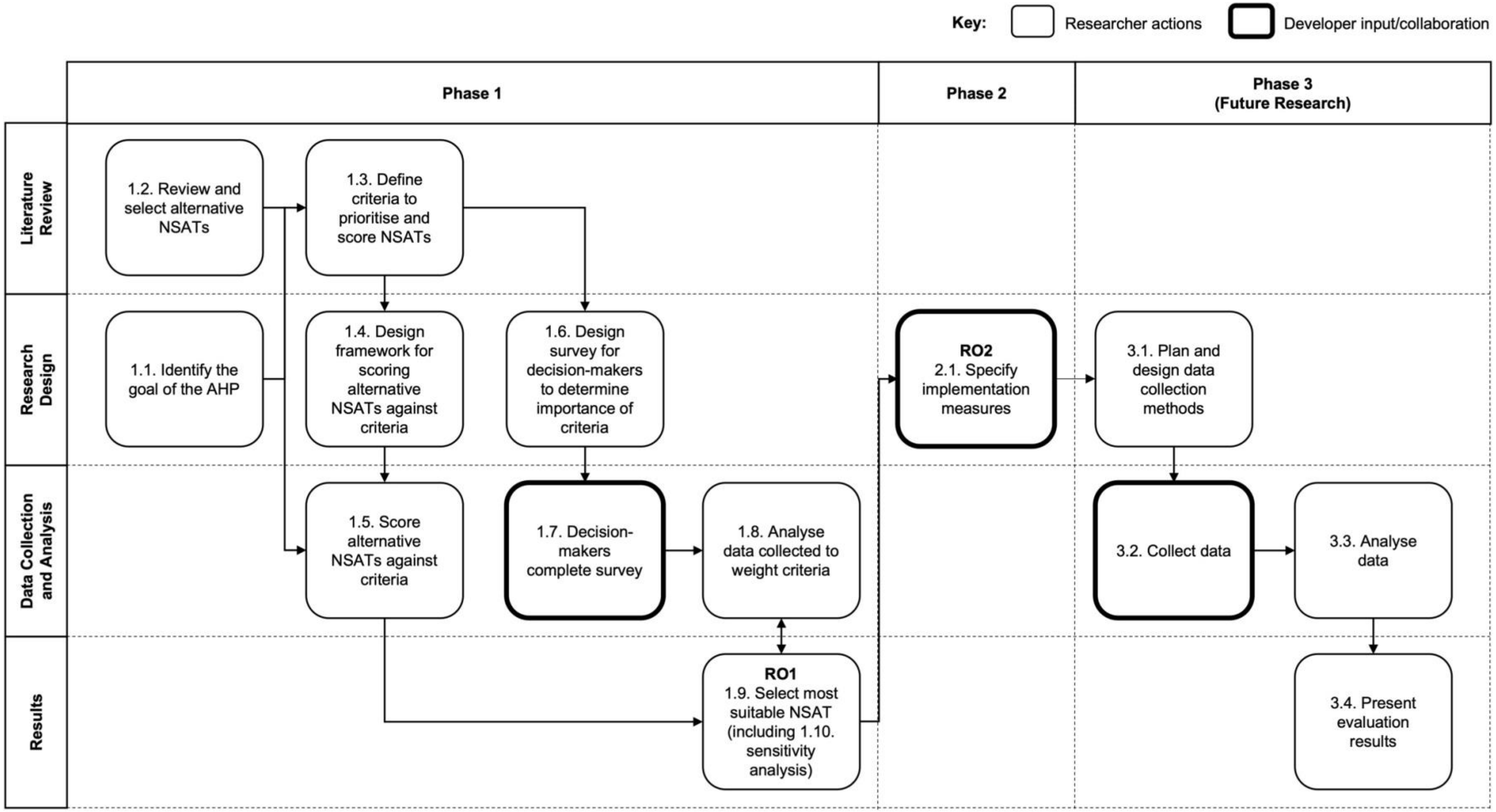


Figure 28. Swimlane diagram of methodology

6.2.1 Phase 1: NSAT Selection Using Multi-Criteria Decision Analysis

The decision-making process of selecting a suitable NSAT required the tools to be evaluated against a set of criteria, justified through the literature, that would be relevant to any client and project. This research considered NSATs for selection that are defined as plan-embedded tools. However, given the limited literature on this classification of NSAT, it drew on the wider literature regarding the strengths and weaknesses of NSATs to inform the evaluation criteria. As explained in section 6.1, the analytical hierarchy process (AHP) was judged to be a robust method to facilitate the decision-making process of selecting a suitable NSAT for evaluating Water Lilies (De Montis *et al.*, 2000).

AHP was originally devised by Saaty (1980). The method arranges a selection of factors into a "hierarchic structure descending from an overall goal to criteria, sub-criteria, and alternatives in successive levels" (Saaty, 1990). The factors at each level are weighted based on their impact on the level above, providing a measure for the factors at the lowest level with respect to those in the upper levels and the top (Saaty and Alexander, 1989). The mathematical algorithms demanded from Saaty's (1980) method are complicated and require AHP software to run them. Consequently, this research followed a methodological procedure by Department for Communities and Local Government (DCLG, 2009a), which is aimed at practitioners (and government officials) that can be undertaken using simplified calculations. Further, the method was adapted for the purposes of this research. Factors on the lowest level of the hierarchy (i.e. the alternatives) were weighted using the proposed scoring system and multiplied by the relative weights of criteria determined using the procedure set out by DCLG (2009a). In this study there was only one level of criteria. Figure 29 shows the hierarchy structure formed for the decision problem consisting of three levels: the goal, the criteria, and the alternative NSATs.

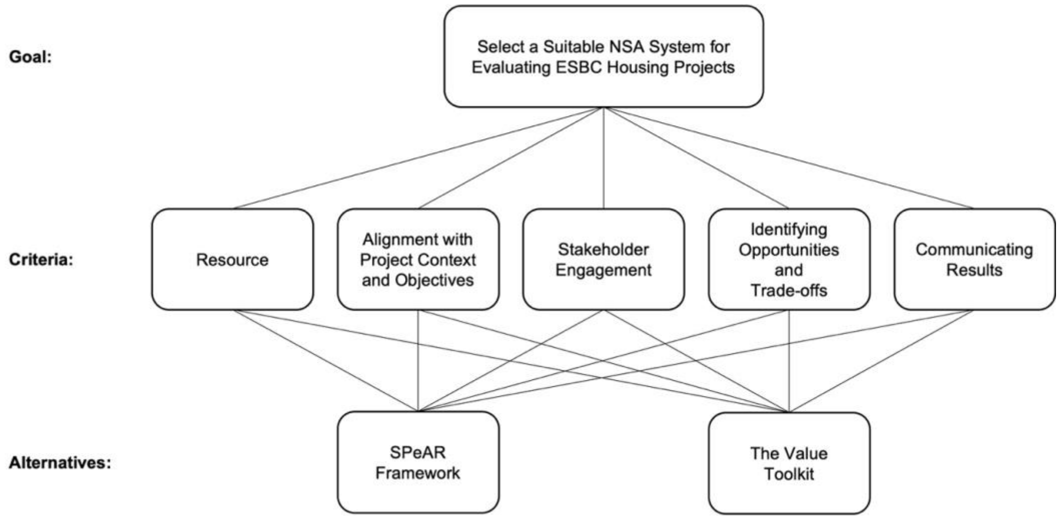


Figure 29. AHP hierarchy structure for the decision problem

The AHP process involved the following steps, which are referred to by number in the swimlane diagram in Figure 28.

Step 1.1. **Identify the *goal* of the AHP.** The *goal* of the AHP was to “select a suitable NSAT for evaluating Water Lilies”.

Step 1.2. **Review and select *alternative* NSATs for detailed evaluation.** The *alternatives* were plan-embedded tools that could be applied to evaluate the case study project, Water Lilies. As explained in the literature, NSATs are strongly linked to the region in which they are developed, so the shortlist of tools originated in the UK. These included One Planet Living Communities, Sustainable Project Appraisal Routine (SPeAR), and the Value Toolkit. One Planet Living Communities was ruled out because at the time of this research, Water Lilies was under construction, while this tool needs to be embedded in decision-making from the start of the project and could not be used to retrospectively evaluate the scheme. Therefore, this research focused on comparing SPeAR, a well-established tool developed by Arup’s software and sustainability experts (Arup, 2022), and the Value Toolkit, a tool developed by Construction Innovation Hub in partnership with industry and Government experts (Construction Innovation Hub, 2022). The Value Toolkit has not previously been defined as an NSAT in the literature, but it has the core characteristics of an NSAT, evaluating performance quantitatively across multiple dimensions of sustainability.

Step 1.3. **Define *criteria* to prioritise and score NSATs.** Each *criterion* was given a description to clarify its meaning, and the inclusion of *criteria* was justified based on a review of the relevant literature on NSATs. The list of criteria, their descriptions, justification for inclusion in the AHP based on the literature, and the relevance to the project context, are shown in Table 18.

Table 18. Criteria for AHP, justification for their inclusion based on a review of relevant literature, and their relevance to the case study project context

Criteria	Description	Justification based on literature	Relevance to case study project context
Resource	The NSAT should be able to be used effectively without exceeding staff hours available to the client.	• Adoption of NSATs is limited by consultation fees and large amounts of data collection (Boyle, Michell and Viruly, 2018). • Assessment guidelines and quantitative examples increases application of NSATs through self-assessment (Barnes and Parrish, 2016). • Relative success of NSATs partly attributed to efforts to enhance procedural simplicity (Benson and Bereitschaft, 2019).	• As the NSAT is being applied by self-assessment, it should be sufficiently simple and have clear guidelines for the client to undertake without exceeding resources, including any training that may be required.
Alignment with Project Context and Objectives	The NSAT should encompass the social, economic, and environmental objectives of the project, as prioritised by the client, and be adaptable to the project context and capture both the objectives and indicators of success.	• NSATs should not have fixed rules, but be sufficiently flexible to accommodate unique characteristics (Deakin, 2011; Reith and Orova, 2015; Lin and Shih, 2016). • Accordingly, NSATs are becoming decreasingly prescriptive (Pedro *et al.*, 2019). • NSATs have been criticised for emphasising the environmental dimension of sustainability at the expense of others, when the socio-economic dimension requires further attention (Sharifi and Murayama, 2013; Komeily and	• Water Lilies aims to address sustainability across social, economic, and environmental dimensions through a unique model that engages the co-builders in design and build and provides workshops and support alongside. Therefore, it requires an NSAT that can accommodate these distinct differences from a typical development model and involve the client to ensure it meets site-specific objectives and indicators.

		Srinivasan, 2015; Sharifi, 2021; Sharifi, Dawodu and Cheshmehzangi, 2021). • Indicators should be embedded in the target context and the target audience (i.e. the developer) should be able to participate in the development of these indicators (Turcu, 2013). • Adaptation of indicators to the local context/site is essential (Berardi, 2012; Sharifi and Murayama, 2015).	
Stakeholder Engagement	The NSAT should enable key project stakeholders to engage productively so as to understand their perspectives. It should not be too much of a burden on stakeholders or overly reliant on their participation.	• Stakeholder participation and partnership can accelerate the transition to sustainable development (Sharifi and Murayama, 2013). • An iterative participation process can enhance the reliability and accuracy of the NSA, build mutual understanding, and enable group learning (Sharifi and Murayama, 2013; Boyle, Michell and Viruly, 2018).	• It is essential that the client learns from key project stakeholders, such as homeowners and contractors, to inform the delivery of future ESBC housing projects. However, the client needs to be mindful of the time and effort that key project stakeholders have committed to the project and to minimise the amount of participation required for aspects of the evaluation.
Identifying Opportunities and Trade-offs	The NSAT should be able to identify opportunities for improvement and potential trade-offs between evaluation criteria to aid decision-making throughout the project and inform future projects.	• NSATs have the ability to realise co-benefits related to health, resilience, and climate change adaptation and mitigation (Sharifi, Dawodu and Cheshmehzangi, 2021). • Indicators must be linked and integrated to prevent oversights in the individual definition and distribution of weighting (Lin and Shih, 2016).	• Particularly as Water Lilies is a flagship project, innovating with a new development model, it is crucial that the NSAT can highlight opportunities for improvement. It is also recognised that there are likely to be trade-offs between criteria. For example, increased build costs will improve construction quality but will result in higher house prices for the consumer. Therefore, for future projects, it

		• NSATs can demonstrate how indicators are linked to each other, yet this has largely not been addressed (Sharifi, Dawodu and Cheshmehzangi, 2021). • NSATs have not succeeded in establishing the complex relationships between criteria. Instead, each criterion is assessed in isolation (Kaur and Garg, 2019). • 'Scaling' indicators, considering the hierarchical and multi-dimensional structure of complex and dynamic systems, such as neighbourhood-scale developments, have been proposed (Khan and Pinter, 2016). • Interlinkages between indicators requires further research (Ali-Toudert *et al.*, 2020).	is important to consider that opportunities have potential trade-offs as the success of one assessment criterion may come at the expense of one or more others.
Communicating Results	The NSAT should be able to communicate the results, including the benefits and challenges of the project, effectively and credibly to a wide range of stakeholders, including contractors, architects, customers, and investors. The results should have the potential to attract funders, appeal to landowners, and influence policy.	• Quantifiable indicators enhance the communication of neighbourhood sustainability performance to stakeholders (Pedro *et al.*, 2019). • NSA results can be used by a range of stakeholders, including planners, developers, local authorities, real estate actors, and residents, particularly as a decision aid tool (Sharifi and Murayama, 2013). • NSA results should be straightforward and transparent "to avoid green washing and ill-based decisions" (Sharifi and Murayama, 2013).	• It is important that the NSA results are not only used to inform future projects, but also communicated effectively to stakeholders that may want to be involved in a future project. These stakeholders might include architects, building contractors, prospective house buyers, investors, landowners, and policymakers.

Step 1.4. Design a framework for scoring the *alternative* NSATs against the *criteria*. The scoring framework is demonstrated in Table 19. Each criterion had a scoring system from 1 to 5 to evaluate the NSAT. A description is provided for scores 1, 3, and 5 to demonstrate the characteristics required of the NSAT to achieve that score. This provided scope for giving scores of 2 and 4 where it was felt that the NSAT demonstrated characteristics of the scoring descriptions both above and below.

Table 19. Framework for scoring NSATs against criteria

Criteria	**Score**	**Description**
Resource	5	The NSAT can be used effectively with low impact on staff hours[1] available to the client (5 hours or less per week[2]).
	3	The NSAT can be used effectively with some impact on staff hours[1] available to the client (6 to 10 hours per week[2]).
	1	The NSAT cannot be used effectively without exceeding staff hours[1] available to the client (11 hours or more per week[2]).
Alignment with Project Context and Objectives	5	The NSAT has the scope to evaluate the wide range of social, economic, and environmental objectives set out by the client in depth and can be adapted to suit its needs. It enables the client to prioritise and weight the objectives and indicators of success accordingly.
	3	The NSAT has the scope to evaluate social, economic, and environmental objectives but limits input from the client in terms of adapting it to suit its needs and prioritising objectives and indicators of success.
	1	The NSAT pre-defines the objectives and indicators of success and their weighting with a focus predominantly on one area of evaluation (e.g. economic sustainability). The NSAT cannot be adapted.
Stakeholder Engagement	5	The NSAT enables key project stakeholders to engage in the evaluation of project objectives. It further enables qualitative responses to understand their perspectives on aspects of the project and provide greater meaning behind quantitative scores. The NSAT requires a small amount of stakeholder engagement that is considered a reflective and valuable process to participants. If any stakeholders are unable to participate, the NSAT still has the flexibility to function effectively.
	3	The NSAT enables key project stakeholders to engage in the evaluation of project objectives but limits the opportunity for them to expand on quantitative responses. The NSAT requires a small amount of stakeholder engagement but lacks quality reflection or value for participants. If any stakeholders are unable to participate, the NSAT may not function effectively.

	1	The NSAT either does not enable key project stakeholders to engage in the evaluation of project objectives or it requires a large amount of stakeholder engagement and if any are unable to participate, the NSAT does not function.
Identifying Opportunities and Trade-offs	5	The NSAT facilitates a robust process of learning where opportunities for improvement and trade-offs are identified and investigated in sufficient depth to suggest potential solutions that can be implemented whilst the project is still ongoing.
	3	The NSAT facilitates a process of learning where opportunities for improvement and trade-offs are identified but require further investigation to suggest potential solutions that can be implemented whilst the project is still ongoing.
	1	The NSAT facilitates a limited process of learning where opportunities for improvement and trade-offs are implied but require further investigation to suggest potential solutions that can be implemented whilst the project is still ongoing.
Communicating Results	5	The NSAT provides high-level outputs that can be easily understood by a wide range of stakeholders and are clearly visually represented. It enables the client to highlight and promote aspects of the evaluation that are important to stakeholders. The detailed results and workings are accessible and relatively easy to interpret. The NSAT is highly credible and familiar to stakeholders, ensuring the results have the potential to have high impact.
	3	The NSAT provides outputs that can be mostly understood by stakeholders and are visually represented. It enables the client to highlight and promote aspects of the evaluation. The detailed results and workings are not easily accessible and difficult to interpret. The NSAT is credible and somewhat familiar to stakeholders, meaning the results have the potential to have a medium impact.
	1	The NSAT provides outputs that cannot be understood by all stakeholders and are not clearly visually represented. It is difficult for the client to highlight and promote aspects of the evaluation that are important to stakeholders. The detailed results and workings are not accessible or very difficult to interpret. The NSAT is not particularly credible or familiar to stakeholders, meaning the results only have the potential to have a low impact.

[1] Where some additional expertise is required, this is addressed in the discussion.

[2] The number of hours is relevant to the case study client and would be adapted to suit different contexts.

Step 1.5. Score the *alternative* NSATs against the *criteria* by applying the scoring framework to each NSAT. Both SPeAR and the Value Toolkit were scored against each criterion. SPeAR was tested to understand its capabilities but, since it is a well-established NSAT, evidence from the literature was primarily used for scoring. Table 20 shows the scores and justification through evidence from the literature. As the Value Toolkit was yet to be released publicly, there was limited literature available on its use. Therefore, scoring was based on pilot user testing reinforced by the literature. Table 21 shows the scores and justification through pilot testing experience and evidence from the literature. The scoring framework and specific definitions used for each score (1, 3 or 5) attempts to minimise the subjectivity of scoring.

Table 20. Application of scoring framework to SPeAR using evidence from the literature

Criteria	Score	Justification based on literature
Resource	5	The SPeAR software is free to use on the web (Arup, 2017). The “well-organised and readily accessible format” (Braithwaite, 2015) of the framework enables “a rapid review” (Cole, 2007) that “saves time and effort for all” (Braithwaite, 2015). It can be implemented in-house by an evaluator that has “a broad knowledge and appreciation of sustainability” (Cole, 2007). However, “the appraisal should be checked or approved by a sustainability professional” (Arup, 2017) and it is suggested that a “proper assessment team is required for effective results” (Raza, Alshameri and Jamil, 2021). Furthermore, a sustainability professional should assist with the materiality review when any indicators or sub-indicators are included or excluded from the appraisal” (Arup, 2017). On this evidence, SPeAR is considered relatively low cost and within the budget of the organisation. The evaluation can also be undertaken relatively quickly. The organisation has personnel with the broad knowledge and appreciation of sustainability required to undertake the evaluation, given its expertise in sustainable housing. However, it would require employing a sustainability professional to use the framework as effectively as possible.
Alignment with Project Context and Objectives	3	SPeAR demonstrates “the interaction between the various social, environmental, economic and natural resource indicators of sustainability” (Zargarian *et al.*, 2018) and covers the “diverse issues that need to be considered” (Cole, 2007). Furthermore, it “gives the flexibility to modify, add or remove any indicator as per the project’s nature” (Raza, Alshameri and Jamil, 2021) and the “logical and transparent methodology is fully adaptable for various applications” (Zargarian *et al.*, 2018). It can also be “applied at any stage within the project from planning to long-term monitoring” (Raza, Alshameri and Jamil, 2021). Therefore, the framework has the scope to evaluate the wide range of social, economic, and environmental objectives set out by the organisation and can be adapted to suit its needs. Although the framework can weight scores according to their relative importance, it cannot weight the categories (i.e. the indicators of sustainability) based on the importance to the organisation (Arup, 2017). A further weakness identified is that the “assessment is generic and not quantified” (Raza, Alshameri and Jamil, 2021). SPeAR is flexible in terms of what the client wants to evaluate, but it is rigid in terms of the how outcomes are benchmarked and scored.
Stakeholder Engagement	5	Arup states that “the views of key stakeholders should input to the assessment – either directly or indirectly” (Arup, 2017). Direct input could be early and ongoing participation or reviewing toward the end of evaluation, whereas indirect input could be gathering and representing the views of stakeholders during the evaluation (Arup, 2017). Furthermore, the assessment of sustainability issues may be quantitative, with scores from individual stakeholder groups weighted according to their relative importance, or qualitative, which involves a more conversational approach with stakeholders (Arup, 2017).

Identifying Opportunities and Trade-offs	3	SPeAR is able to identify areas for improvement and opportunities to optimise performance continuously throughout the project (Cole, 2007; Braithwaite, 2015; Zargarian *et al.*, 2018; Raza, Alshameri and Jamil, 2021), which "can inform organisational learning and approaches to future projects" (Arup, 2017). Furthermore, it recognises the trade-offs between indicators within the framework, for example "an improvement in energy consumption may require a significant investment, causing a change in the rating of both an economic and an environmental indicator" (Arup, 2017). These are substantial benefits, but it can be argued that a generic score based on a judgement call does not provide the specific metrics required to offer benchmarks for future projects.
Communicating Results	5	SPeAR provides a "graphic presentation of the project during all stages, indicating continual improvement and evolution of a project over time" with segments of a dartboard-like structure shaded to show the performance of groups of indicators (Zargarian *et al.*, 2018). It can "demonstrate to both internal (executive management, project team etc.) and external (planning authority, insurers, public etc.) stakeholders the overall performance in terms of sustainability" (Braithwaite, 2015). This means it provides high-level outputs that are clearly visually represented and can be easily understood by a wide range of stakeholders, who are able to focus on aspects of the evaluation that may be of particular importance to them. Furthermore, the software generates a summary of the input data to ensure the process is robust and assessments are audit traceable (Arup, 2017; Zargarian *et al.*, 2018). Therefore, the detailed results and workings are accessible and relatively easy to interpret. Moreover, the framework was developed to make "sustainability meaningful to a wide range of stakeholders" (Braithwaite, 2015) and involved consultation amongst "sustainability experts across the world" to ensure "the tool reflects best practice sustainability appraisal and is globally applicable" (Arup, 2017). The tool incorporates the UK Government's sustainability indicators, the UN Environment Programme indicators and the GRI (Global Reporting Initiative) indicators (Braithwaite, 2015). The framework demonstrates that it is highly credible and provides results that can have a high impact.
Total Score	**21**	

Table 21. Application of scoring framework to The Value Toolkit through evidence from the literature and pilot testing experience where evidence is limited

Criteria	Score	Justification based on pilot testing	Justification based on literature
Resource	3	The training and guidance material for pilot testing the Value Toolkit provided the resources required to undertake an evaluation by self-assessment. If needed, trained experts can facilitate The Value Toolkit's application. Considering the need to learn how to use the NSAT for self-assessment and the wide scope of evaluation criteria to potentially collect data on, in the context of this study, it is anticipated that it would result in 6 to 10 hours of staff time per week.	The Value Toolkit will be available in the public domain and includes an app, training and guidance (Bentley, 2022; Jenkins, 2022). Furthermore, it will include a library of metrics that clients can use to measure outcomes (Thompson, 2021).
Alignment with Project Context and Objectives	5	The Four Capitals (Human, Social, Environmental and Produced) and the categories nested within them provide a framework for the client to evaluate objectives across environmental, social, and economic sustainability criteria. By allowing the client to define the outcomes of the evaluation, rather than the outcomes be prescribed to them, the Value Toolkit is highly adaptable to the project context. Furthermore, the Value Toolkit includes a process to prioritise outcomes so they are weighted based on their relative importance to the project, as established by the client.	The Value Toolkit uses the Four Capitals approach, which provides a framework for clients to determine project outcomes covering multiple dimensions of sustainability (Jenkins, 2022). Clients set 'Value Profiles', which directs and evaluates projects on priority outcomes (Jenkins, 2022). Furthermore, the Value Toolkit provides "a flexible framework to shape project-level outcomes around the local context" (Jenkins, 2022).
Stakeholder Engagement	5	Given the flexibility of the framework, stakeholder engagement is dependent on the client's project outcomes, and the metrics used to measure them. There is scope to collect the data through surveys, interviews, or focus groups. As a result, the client has a high degree of control over how stakeholders are engaged, and the amount of time required of them.	The Value Toolkit acknowledges that stakeholder engagement is the first step to great place-making (Jenkins, 2022).

Identifying Opportunities and Trade-offs	3	Rather than evaluating a narrow range of criteria, the client sets project outcomes across a range of categories within the Human, Social, Environmental, and Produced capitals. Therefore, results are more likely to raise attention to potential trade-offs between diverging priorities. However, the ability to quantify the impact of these trade-offs is unclear.	The Value Toolkit enables a more holistic view of projects (Bentley, 2022) and uses data more effectively to drive more informed conversations and reflect on lessons learned (Jenkins, 2022).
Communicating Results	5	Like SPeAR, the Value Toolkit presents the overview of results in a dartboard-like structure, which clearly and simply communicates a project's performance against categories within the Four Capitals.	The Four Capitals approach used by the Value Toolkit aligns with the UN Sustainable Development Goals and enables transparent and integrated reporting that speaks to different stakeholders (Jenkins, 2022). Furthermore, the framework functions and will therefore be understood across national and local government and the private sector (Bentley, 2022). The toolkit will benefit private sector clients that intend to demonstrate the ESG credentials of their projects (Bentley, 2022). By linking project outcomes to national, regional, and local policy objectives, it can drive projects to realise policy ambitions at multiple levels (Jenkins, 2022).
Total Score	**21**		

Step 1.6. Design a survey for key decision-makers to determine the relative importance of *criteria*. A simple online survey was created in MS Forms. For each pair of criteria, the decision-maker was required to respond to a pairwise comparison question asking the relative importance of the two with respect to the goal. For example, "How important is 'Resource' (Criterion A) relative to 'Alignment of Project Context and Objectives' (Criterion B) with respect to 'selecting a suitable NSAT for application to Water Lilies' (Goal)?". Table 22 shows the survey response options presented to key decision-makers for each pair of criteria and the codified nine-point intensity scale, which is used in steps 1.7 and 1.8. Three key decision-makers were identified to complete the survey, including the founder, managing director, and project manager for Water Lilies. No personal data was collected in the survey.

Table 22. Survey response options for each pairwise comparison question and the corresponding preference indices assigned

How important is criterion A relative to criterion B?	**Preference index assigned**
Overwhelmingly less important	$^1/_9$
Very strongly less important	$^1/_7$
Strongly less important	$^1/_5$
Moderately less important	$^1/_3$
Equally important	1
Moderately more important	3
Strongly more important	5
Very strongly more important	7
Overwhelmingly more important	9

Step 1.7. Decision-makers complete survey. The three decision-makers completed the survey within nine days of each other in March 2022, taking an average of 5 minutes 40 seconds to complete.

Step 1.8. Analyse the data collected from the survey to weight each *criterion*. Decision-makers' responses were converted into the corresponding preference indices shown in Table 23. In Appendix C, Table C.1 presents an example of the pairwise comparison results for 'decision-maker 1' and Eqn. C.1 and Eqn. C.2 demonstrate the method used to calculate the weights. This process was repeated for each criterion for each decision-maker. The weights are shown in Table 23 along with the average weight of each criterion.

Table 23. Each criterion's weight from each decision-maker and average weight

Criteria	Weight			Average Weight
	Decision-maker 1	Decision-maker 2	Decision-maker 3	
A	0.060	0.088	0.312	0.153
B	0.428	0.496	0.204	0.376
C	0.249	0.170	0.053	0.157
D	0.160	0.189	0.375	0.241
E	0.103	0.057	0.056	0.072
				1.000

A = Resource; B = Alignment with Project Context and Objectives; C = Stakeholder Engagement; D = Identifying Opportunities and Trade-Offs; E = Communicating Results

Step 1.9. Calculate the results to determine which of the *alternative* NSATs should be selected to achieve the *goal*. In other words, which NSAT was the most suitable to evaluate Water Lilies. Table 24 shows the weights of the *alternatives*, SPeAR, and the Value Toolkit. Eqn. C.3 and Eqn. C.4 in Appendix C demonstrate the calculation method.

Table 24. Weight of the alternatives, SPeAR, and the Value Toolkit

Alternative	A	B	C	D	E	Total Score	Weight
SPeAR	0.767	1.127	0.786	0.724	0.361	3.766	0.472
Value Toolkit	0.460	1.879	0.786	0.724	0.361	4.210	0.528
						7.976	1.000

A = Resource; B = Alignment with Project Context and Objectives; C = Stakeholder Engagement; D = Identifying Opportunities and Trade-Offs; E = Communicating Results

As shown in Table 24, the Value Toolkit has the greatest weight of the alternatives and is therefore considered the most suitable NSAT to evaluate Water Lilies. Both NSATs had the same total score of 21 (out of 25) at step 1.5, but because the Value Toolkit had a higher score for 'Alignment with Project Context and Objectives' (Criterion B) and the client gave this criterion significantly more weight, the Value Toolkit outperformed SPeAR.

Step 1.10. Perform a sensitivity analysis to validate the results. There is subjectivity involved in both scoring NSATs against evaluation criteria and weighting the relative importance of different evaluation criteria. It is important to consider the risk of different assumptions for scores and weights on the overall results in order to check their robustness. Various sensitivity analyses, demonstrated in Figure 30, were performed to understand the circumstances in which SPeAR would be the preferred option. (a) is the base case, shown for comparison. One approach was to increase criteria scores related to SPeAR. SPeAR was only found to be the preferred option when (b) the score for ‘Alignment with Project Context and Objectives’ was increased from 3 to 5 and (c) the score for ‘Identifying Opportunities and Trade-offs’ was increased from 3 to 5. An increase of +1 in either scenario was insufficient. Additionally, a reduction of -1 to any of the criteria scores for Value Toolkit still resulted in Value Toolkit being the preferred option. Another approach was to change criteria weightings. In (d), SPeAR was the preferred option when it was assumed that all the decision-makers agreed with the criteria weightings ascribed by decision-maker 3 in which ‘Resource’ increased from 0.153 to 0.312 and ‘Alignment with Project Context and Objectives’ decreased from 0.376 to 0.204, therefore prioritising the criterion which SPeAR scored higher against. If ‘Resource’ and ‘Alignment with Project Context and Objectives’ were weighted with equal importance, then SPeAR and the Value Toolkit would achieve the same overall weighting because the tools scored equally against all other criteria.

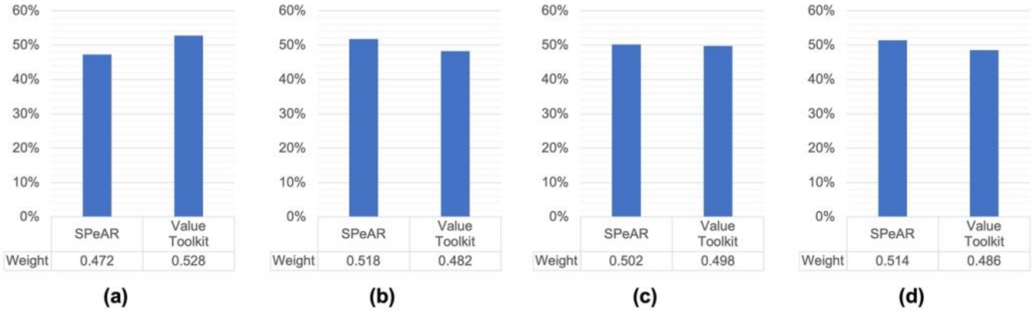


Figure 30. Sensitivity analysis: (a) base case, (b) +2 score increase of ‘Alignment with Project Objectives and Context’ for SPeAR, (c) +2 score increase of ‘Identifying Opportunities and Trade-offs’ for SPeAR, and (d) using decision-maker 3’s weightings (‘Resource’ prioritised over ‘Alignment with Project Context and Objectives’)

The sensitivity analysis shows that relatively significant changes to the scores or weightings need to occur for SPeAR to be the preferred option, yet the difference between the final weightings in the base case is still marginal. As a consequence, the decision to select the Value Toolkit based on the quantitative data alone was not straightforward. However, the application of the scoring framework highlighted the relative strengths and weaknesses of the tools through qualitative data that support this decision. As described in Chapter 2, Water Lilies requires homeowners to engage in the design and build phases of the project and associated workshops that are facilitated by the developer and other stakeholders, such as architects, builders, interior designers, and community energy experts. Therefore, the flexibility of the Value Toolkit was perceived as a major advantage in being able to evaluate the complex nature of the project. Like SPeAR, the Value Toolkit enables the client to set outcomes for evaluation across a range of sustainability criteria, but it also enables the client to weight the outcomes according to their importance to the project. As a result, it ensures the unique aspects of the project can be captured and prioritised in evaluation. On the other hand, SPeAR is relatively rigid in terms of its benchmarking and scoring system.

However, SPeAR does have the advantage of being relatively quick and easy to implement, which is particularly appealing for a small organisation that has limited financial resources and staff capacity. Furthermore, both the Value Toolkit and SPeAR have the advantage of being able to communicate results in a way that is engaging, transparent, and understood by a wide range of stakeholders, hence receiving equally high scores. But on balance, the Value Toolkit was perceived to potentially provide more impactful results due to the traction it is gaining through its development in partnership with over 200 experts in industry, academia, and government (Construction Innovation Hub, 2022). Overall, the advantages of the Value Toolkit were considered to be far more important as they provide detailed feedback on project outcomes that SPeAR cannot achieve to the same extent even though it is more straightforward to implement.

6.2.2 Phase 2: Specification of Implementation Measures for NSAT

Phase 2 involved the specification of implementation measures that would be required to perform an evaluation of Water Lilies using the Value Toolkit. It was an iterative process, undertaken in collaboration with the client in order to meet the aims of their prospective evaluation. The Value Toolkit facilitates the evaluation of outcomes from the ‘delivery’ and ‘in-use’ stages of a project. This paper focuses on the specification of implementation measures required to evaluate delivery stage outcomes using guidance and workbooks provided as part of the Value Toolkit’s Wave 3 pilot testing for evaluation and measurement. If SPeAR had been selected, a similar process would have been undertaken to specify implementation measures, including the identification of indicators (e.g. ‘energy’, ‘health and wellbeing’, ‘risk’, etc.) within environmental, social, and economic sustainability segments and the provision of definitions for each indicator and its best- and worst-case scenarios, which set the benchmarks for the highest and lowest scores achievable.

Value Definition

The ‘value definition’ stage is designed to enable clients to articulate their core values and drivers, which generates a unique ‘value profile’ for a project. This indicates the relative importance of value drivers and provides a reference point for value-based decision-making across the life cycle of the project. The first step undertaken in value definition was the development of measurable ‘outcome statements’. The outcome statements are based on ‘categories’ within the Four Capitals model – natural, human, social, and produced and can be linked to organisational, regional, or national policies and priorities. The first draft of outcome statements was produced by referring to the original project objectives that were extracted from various planning documents. Facilitated by the researcher, the outcome statements were then developed with three of the client’s senior decision-makers, including the founder, managing director, and project manager of Water Lilies, through a cycle of discussions and amendments to a shared document until the final list was agreed.

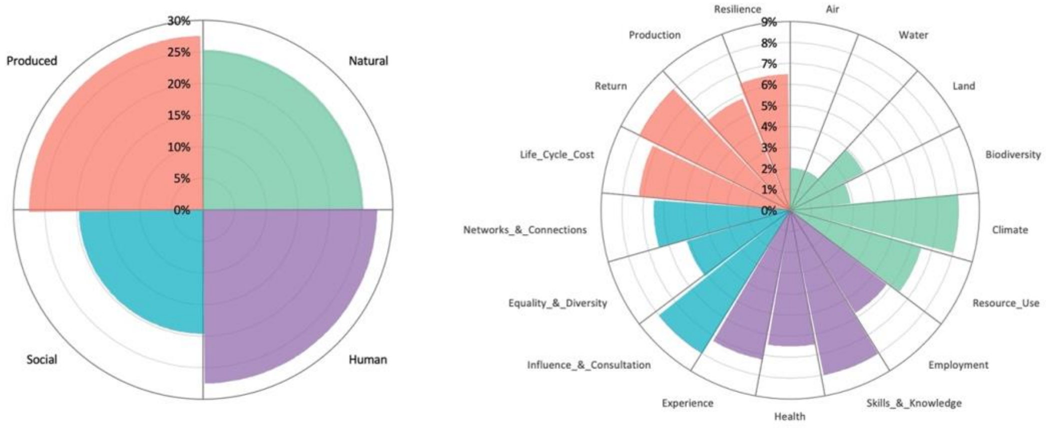
Following this, the outcome statements were prioritised against the criteria of ‘influence’ (the extent to which a specific project can influence a given outcome), ‘risk’ (the consequences arising from an outcome not being achieved), ‘capability/capacity’ (the client’s ability to deliver the project outcomes), and ‘driving change’ (the need for outcomes to drive desired change within the organisation) on a rating scale of 1 to 5. This meant each outcome statement had a maximum of 20 points from the four criteria, and the three senior decision-makers agreed upon ratings through a joint discussion. This enabled the team members to discuss and understand each other’s views on what aspects of the project they prioritise, highlighting any potential differences in opinion and helping to build consensus and align their priorities going forwards. Table 25 shows the outcome statements defined for the delivery phase of Water Lilies and the criteria ratings ascribed to each.

Table 25. Outcome statements and criteria ratings used to generate weighted scores

ID	Capital	Category	Outcome statement	Influence	Risk	Capability / Capacity	Driving Change	Count
OS-1	Natural	Air	High levels of satisfaction that the developer’s workshops enabled homeowners to make an informed decision on selecting either MVHR or natural ventilation.	3	2	3	2	10
OS-2		Climate	Low embodied carbon emissions during project delivery.	5	5	5	5	20
OS-3		Water	High levels of satisfaction that the developer’s workshops provided homeowners with an introduction to efficient water use to inform their product purchasing decisions.	3	2	3	2	10
OS-4		Land	Minimise levels of waste produced during construction.	4	3	4	3	14
OS-5		Resource Use	High use of sustainably sourced timber.	5	4	4	5	18
OS-6		Biodiversity	Minimise impact on existing trees and habitats.	4	2	5	1	12
OS-7	Human	Employment	High levels of empowerment, learning and growth for the developer and delivery team.	4	4	4	5	17
OS-8		Skills and Knowledge	Strong agreement that homeowners developed new skills and knowledge and a better understanding of sustainable technologies and ways of living.	5	5	5	5	20

OS-9		Health	High levels of mental wellbeing for homeowners, contractors and the developer team.	5	3	4	4	16
OS-10		Experience	High levels of satisfaction of the design and delivery process.	5	4	5	5	19
OS-11	Social	Influence and Consultation	High levels of productive engagement with the existing community, homeowners, contractors and the developer team in decision-making.	5	5	5	5	20
OS-12		Equality and Diversity	Inclusive and accessible housing (e.g. marginalised, disadvantaged or disabled groups).	5	3	4	4	16
OS-13		Networks and Connections	Strong agreement that homeowners have a sense of community in Water Lilies.	5	5	5	3	18
OS-14	Produced	Life Cycle Cost	Capital cost aligned with the industry standard benchmark unless life cycle cost savings justify increased investment at the start.	5	5	5	4	19
OS-15		Return	Deliver a profit margin to the industry standard benchmark to reinvest into the company vision.	5	5	5	5	20
OS-16		Production	Pace of build to deliver self-finish building shells for handover and custom build flats to practical completion aligned with expectations agreed between developer and main contractor.	5	4	4	4	17
OS-17		Resilience	Deliver a highly resilient delivery approach to manage potential threats and disruption during construction.	5	4	5	4	18

Finally, the average rating for each outcome statement was converted into a percentage representing the relative importance of achieving each outcome. This process provides a means to set the value profile for a project objectively. Figure 31 shows the capital value profile and category value profile defined by the client based on the weighted scores for outcome statements.



(a)

(b)

Figure 31. (a) Capital value profile and (b) category value profile

Produced and human capital have 27.52% of the weighting each, natural capital has 25.32% and social capital has 19.63%. In terms of individual categories, ‘climate’, ‘skills and knowledge’, ‘influence and consultation’, and ‘return’, have the highest weighting with 8%. ‘Air’ and ‘water’ have the lowest weighting with 2%. This does not mean to say that client considers the impact of construction on air and water to be intrinsically unimportant, but that the specific outcome statements associated with those categories are *not considered to be as important as others*.

Determining the Value Index

A ‘value index’ for the project is generated from the weighted scores shown in Figure 31. The value index demonstrates the range of points that can be awarded for each outcome statement based on achieving minimum, target, or maximum performance targets, which are described in the section ‘Setting Performance Ranges’. There are between 500 and 1,500 points available in total and 1,000 points would be scored if all outcome statements achieved target performance. Figure 32 illustrates the value index for Water Lilies related to the delivery stage outcome statements shown in Table 25. At the lower end of value index points, OS-1 (‘air’ category), for example, has a points range of 10 to 30 with a target of 20 points. At the higher end, OS-2 (‘climate’ category), for example, has a points range of 40 to 120 with a target of 80 points.

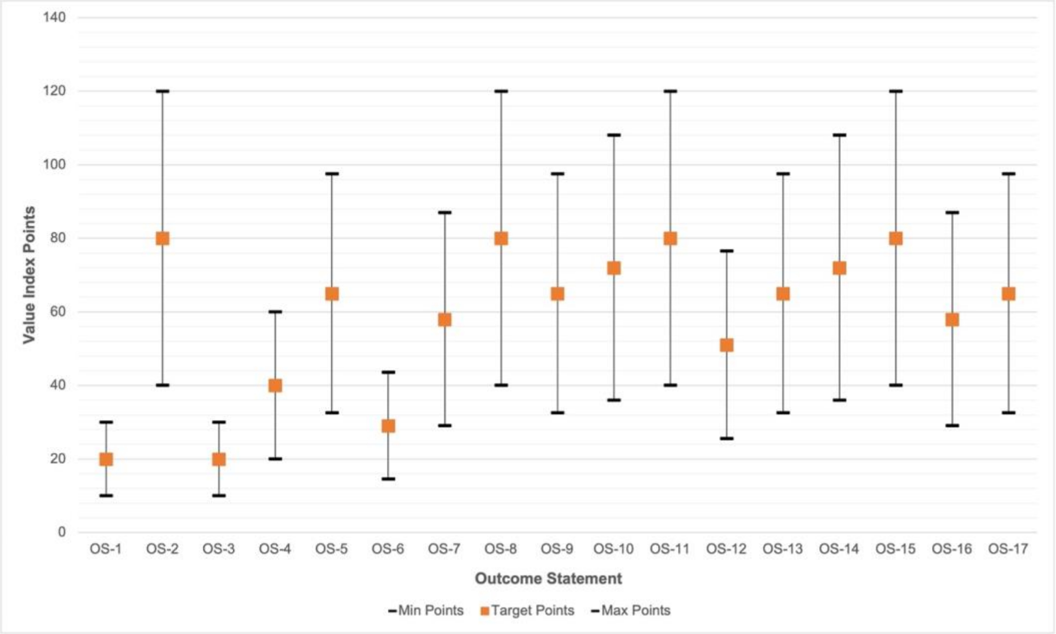


Figure 32. Value index: target points and points range by outcome statement

Selection of Performance Metrics

The aim of this activity is to identify appropriate metrics to measure the performance of outcome statements. For each, consideration should be given to what will be measured, how it will be measured, who will be responsible for collecting, processing, reporting and managing the data collected, how frequently it will be measured, how the validity of the results will be verified, what data sources will be required, and whether it will be a direct or proxy measure (i.e. measured as an output or input). Asking these questions helps the client to understand the practicality of measuring outcomes against constraining factors such as time, resources, and access to data and methods. In this way, outcome statements are steered by what is realistic in terms of evaluation. Table 26 shows an advanced iteration of the metrics selected to evaluate outcome statements for the delivery stage of Water Lilies and the proposed evaluation methods. Care was taken to choose metrics that could be measured using data/evidence available through the project.

Table 26. Metrics, units of measurement, and methods to evaluate outcome statements

ID	Capital	Category	Outcome statement	Metric name	Unit	Method
OS-1	Natural	Air	High levels of satisfaction that the developer's workshops enabled homeowners to make an informed decision on selecting either MVHR or natural ventilation.	Percentage of satisfied homeowners	%	Survey
OS-2		Climate	Low embodied carbon emissions during project delivery.	Level of embodied carbon per metre squared	Kg CO2e/m^2	Life cycle assessment
OS-3		Water	High levels of satisfaction that the developer's workshops provided homeowners with an introduction to efficient water use to inform their product purchasing decisions.	Percentage of satisfied homeowners	%	Survey
OS-4		Land	Minimise levels of waste produced during construction.	Tonnes of waste per £100k construction spend	tonnes/£100k	Calculation
OS-5		Resource Use	High use of sustainably sourced timber.	Volume of sustainably sourced timber as a percentage of total volume of timber used in construction	%	Calculation
OS-6		Biodiversity	Minimise impact on existing trees and habitats.	Urban Greening Factor (UGF)	Points	UGF tool
OS-7	Human	Employment	High levels of empowerment, learning and growth for the developer and delivery team.	Level of empowerment, learning and growth	Points	Survey
OS-8		Skills and Knowledge	Strong agreement that homeowners developed new skills and knowledge and a better understanding of sustainable technologies and ways of living.	Percentage of homeowners that agreed	%	Survey
OS-9		Health	High levels of mental wellbeing for homeowners, contractors and the developer team.	Short Warwick-Edinburgh Mental Wellbeing Scale (SWEMWS)	Points	Survey

OS-10		Experience	High levels of satisfaction of the design and delivery process.	Percentage of satisfied customers	%	Survey
OS-11	Social	Influence and Consultation	High levels of productive engagement with the existing community, homeowners, contractors and the developer team in decision-making.	Percentage of satisfied stakeholders	%	Survey
OS-12		Equality and Diversity	Inclusive and accessible housing (e.g. marginalised, disadvantaged or disabled groups).	Percentage of inclusivity and accessibility felt by homeowners	%	Survey
OS-13		Networks and Connections	Strong agreement that homeowners have a sense of community in Water Lilies.	Percentage of homeowners that agreed	%	Survey
OS-14	Produced	Life Cycle Cost	Capital cost aligned with the industry standard benchmark unless life cycle cost savings justify increased investment at the start.	Cost per square metre of floor area	£/m^2	Calculation
OS-15		Return	Deliver a profit margin to the industry standard benchmark to reinvest into the company vision.	Gross profit margin	%	Calculation
OS-16		Production	Pace of build to deliver self-finish building shells for handover and custom build flats to practical completion aligned with expectations agreed between developer and main contractor.	Metres squared per week to handover (self-finish houses) and practical completion (custom build flats)	m^2/week	Calculation
OS-17		Resilience	Deliver a highly resilient delivery approach to manage potential threats and disruption during construction.	Resilience score	%	Supply chain resilience stress test

Setting Performance Ranges

‘Performance ranges’ set the minimum, maximum and target performance against each metric and its associated outcome statement. Industry, geographical and organisational benchmark data, regulatory performance data, and site-specific baseline data are required to establish performance ranges. Minimum performance is the lowest performance against a metric that the client considers acceptable, target performance is what the client considers to be good performance for the project, and maximum performance is the highest performance against a metric that the client requires. It is recommended that a facilitator support a small group of key client decision-makers and project stakeholders to review and agree the performance ranges, bringing in experts to advise on performance ranges for certain metrics if necessary.

Table 27 demonstrates the performance ranges used for the case study. Many of the performance ranges are based on the client’s benchmarks because the metrics relate to an outcome that is specific to the project. For example, for OS-8, the percentage of homeowners that agreed they developed new skills and knowledge relates to workshops and support provided during the ‘self-finish’ design and build process. However, without a previous project to guide what this performance range is expected to be, the values provided reflect the client’s general expectations (i.e. 60% minimum performance, 80% target performance, and 100% maximum performance). Some metrics use existing benchmarks from the literature to set performance ranges. For example, the performance range for OS-2 is derived from the LETI Climate Emergency Design Guide, which sets out benchmarks for embodied carbon emissions including the ‘domestic baseline’ of 800kg CO_2e/m^2, ‘best practice 2020’ of 500kg CO_2e/m^2, and ‘best practice 2030’ of 300kg CO_2e/m^2 (LETI, 2020). For OS-4, The Waste and Resources Action Programme (WRAP, 2010) set out typical, good, and best practice waste generation benchmarks for residential new build projects, providing minimum, target, and maximum performance as 16 tonnes/£100k, 11 tonnes/£100k, and 6 tonnes/£100k, respectively. For OS-9, regarding the mental wellbeing of stakeholders, the performance range is defined by average scores on the Short Warwick-Edinburgh Mental Wellbeing Scale from national survey data, with the minimum set as the median of 23.2, the target as the 75th percentile of 26, and the maximum as the maximum possible score on the scale of 35 (SWEMWBS, 2011).

Other metrics combine existing benchmarks from the literature with the client's expectations to set performance ranges. For example, OS-6 uses the Urban Greening Factor target score for residential developments of 0.4 points set out in London Plan Guidance (GLA, 2023) as the benchmark for minimum performance and increases this to 0.6 as the target performance for Water Lilies given the scheme's biodiversity ambitions (Get Nature Positive, 2021). For OS-15, the 15-20% benchmark for suitable returns set out in Planning Practice Guidance (RICS, 2019) is used to set the minimum and target performance for gross profit margin, whilst the maximum performance is set to 5% above the benchmark and the highest performance the client requires.

Once the delivery stage outcome statements have been evaluated, actual performance against each metric converts to value index points within the ranges identified (described in the section 'Determining the Value Index').

Table 27. Performance ranges for metrics

ID	**Metric name**	**Unit**	**Performance range (min, target, max)**	**Description**	**Source**
OS-1	Percentage of satisfied homeowners	%	60, 80, 100	**Min:** Client requirements **Target:** Client requirements **Max:** Client requirements	Client benchmark
OS-2	Level of embodied carbon per metre squared	Kg CO2e/m^2	800, 500, 300	**Min:** Domestic baseline **Target:** Best practice 2020 **Max:** Best practice 2030	LETI Climate Emergency Design Guide (LETI, 2020)
OS-3	Percentage of satisfied homeowners	%	60, 80, 100	**Min:** Client requirements **Target:** Client requirements **Max:** Client requirements	Client benchmark
OS-4	Tonnes of waste per £100k construction spend	tonnes/£100k	16, 11, 6	**Min:** Typical practice for residential new build **Target:** Good practice for residential new build **Max:** Best practice for residential new build	The Construction Commitments: Halving Waste to Landfill (WRAP, 2010)
OS-5	Volume of sustainably sourced timber as a percentage of total volume of timber used in construction	%	80, 90, 100	**Min:** Client requirements **Target:** Client requirements **Max:** Client requirements	Client benchmark
OS-6	Urban Greening Factor (UGF)	Points	0.4, 0.6, 0.8	**Min:** UGF target score for residential developments set out in London Plan Guidance (relates to London Plan Policy G5 Urban Greening) **Target:** Client requirements above UGF target	London Plan Guidance: Urban Greening Factor (GLA, 2023)

				Max: Client requirements above UGF target	
OS-7	Level of empowerment, learning and growth	Points	5, 10, 15	**Min:** Client requirements **Target:** Client requirements **Max:** Client requirements (maximum points achievable)	Client benchmark
OS-8	Percentage of homeowners that agreed	%	60, 80, 100	**Min:** Client requirements **Target:** Client requirements **Max:** Client requirements	Client benchmark
OS-9	Short Warwick-Edinburgh Mental Wellbeing Scale (SWEMWS)	Points	23.2, 26, 35	**Min:** Median score on SWENWS from national survey data (from adults) in 2011 **Target:** 75th percentile score on SWENWS from national survey data (from adults) in 2011 **Max:** Maximum possible score from SWENWS	SWEMWBS Population Norms in Health Survey for England Data (SWEMWBS, 2011)
OS-10	Percentage of satisfied customers	%	60, 80, 100	**Min:** Client requirements **Target:** Client requirements **Max:** Client requirements	Client benchmark
OS-11	Percentage of satisfied stakeholders	%	60, 80, 100	**Min:** Client requirements **Target:** Client requirements **Max:** Client requirements	Client benchmark
OS-12	Percentage of inclusivity and accessibility felt by homeowners	%	60, 80, 100	**Min:** Client requirements **Target:** Client requirements **Max:** Client requirements	Client benchmark
OS-13	Percentage of homeowners that agreed	%	60, 80, 100	**Min:** Client requirements **Target:** Client requirements **Max:** Client requirements	Client benchmark
OS-14	Cost per square metre of floor area	£/m^2	2,160, 2,050, 1,940	**Min:** Higher end of average cost scale for small-medium scale housing developments	Typical UK Construction

				Target: Mid-point of average cost scale for small-medium scale housing developments **Max:** Lower end of average cost scale for small-medium scale housing developments	Costs of Buildings (Costmodelling, 2023)
OS-15	Gross profit margin	%	15, 20, 25	**Min:** Aligned with industry benchmark for suitable returns set out in Planning Practice Guidance **Target:** Aligned with industry benchmark for suitable returns set out in Planning Practice Guidance **Max:** Above industry benchmark for suitable returns set out in Planning Practice Guidance and the highest performance the client requires	Performance metrics, required returns and achieved returns for UK real estate development (RICS, 2019)
OS-16	Metres squared per week to handover (self-finish houses) and practical completion (custom build flats)	m^2/week	54, 45, 36	**Min:** Based on timeline for expected completion agreed between the developer and main contractor +20% contingency for disruption from external threats (e.g. extreme weather) **Target:** Based on timeline for expected completion agreed between the developer and main contractor **Max:** Based on timeline for expected completion agreed between the developer and main contractor -20%	Client benchmark
OS-17	Resilience score	%	60, 80, 100	**Min:** Client requirements **Target:** Client requirements **Max:** Client requirements	Client benchmark

6.3 Discussion

This section discusses the comprehensive evaluation of NSATs using the proposed AHP to select a suitable tool in Phase 1 and the specification of implementation measures for the chosen NSAT, the Value Toolkit, in Phase 2.

6.3.1 Phase 1: NSAT Selection Using AHP

The proposed AHP method, adapted from DCLG's (2009a) method, simplifies the process and requirement for complex algorithms using specialised software, making it an accessible, transparent, and robust decision-making approach for the client. Mahdi and Alreshaid (2005, p. 570) applied AHP to support the decision of construction project delivery methods, concluding that they have "distinct advantages and disadvantages with the best choice being governed by the requirements of the specific project." In the same way, the AHP proposed in this research supports decision-makers to acknowledge and prioritise the characteristics of NSATs for project evaluation (e.g. capabilities, outcomes, and implications for the client and stakeholders involved in the evaluation) based on the project needs and context.

AHP can be a subjective process and is dependent on the individuals involved in weighting the criteria, so they must be carefully selected to reflect the organisation's objectives and values (Nassar, Abourizk and Asce, 2014). To address this risk, the three decision-makers selected were fundamental to the management of the company and/or project. Furthermore, the AHP scoring system aimed to minimise the subjectivity of weighting by providing detailed score descriptions. Scores could be assigned based on a review of the literature and/or user-experience. It is anticipated that further evidence of the application of the NSATs (particularly the Value Toolkit) in the literature would lead to more robust justifications for the scores. Moreover, analysing plan-embedded tools that can be applied by self-assessment provides the opportunity for the client to test and score the tools themselves. Gaining a more in-depth understanding of the tools in this way can further assist the client in their decision-making.

A potential challenge of the method is if decision-makers significantly disagree with each other about the relative importance of criteria related to NSATs. To address this, there could be a further step in the AHP where the decision-makers try to resolve any points of contention together. The risk of disagreement occurring is likely to increase with the scale of the organisation and the number of key decision-makers involved in the process. In this case, it could be argued that a more collaborative process is required from the start where participants reach consensus on the relative importance of criteria in a facilitated group setting. Ultimately, the proposed AHP either using individual surveys or group discussions can clarify and potentially harmonise decision-makers' expectations for evaluation, regardless of the NSAT selected.

6.3.2 Phase 2: Specification of NSAT Implementation Measures

The Value Toolkit's utilisation of the Four Capitals model ensures that decision-makers consider the multiple dimensions of sustainability in assessing the value of their project. Furthermore, it enables decision-makers to define value in their own terms, which means that they can plan and deliver sustainability in a way that is appropriate to the nature of the project, responding to its specific context. For the Water Lilies case study, this turned out to be particularly advantageous, as the evaluation needed to be geared towards a unique development model that is community-oriented and includes homeowners in the design and build stages of the project (Newberry, Harper and Morgan, 2021). The outcome statements, shown in Table 25, that emerged through a cycle of discussions with key decision-makers demonstrate how important the participation and actions of homeowners and other stakeholders are to achieving sustainability in this scheme.

Additionally, the prioritisation of outcome statements against the criteria of 'influence', 'risk', 'capability/capacity', and 'driving change' ensures that the outcome statement weightings are assessed objectively, which in this case, was undertaken collectively by decision-makers involved in the evaluation. As applied to the case study, this process resulted in the delivery stage outcome statements associated with 'climate', 'skills and knowledge', 'influence and consultation', and 'return' being the highest priorities and 'air' and 'water' being the lowest priorities. Moreover, there can be at least 17 different outcome statements to evaluate across the categories in both the delivery and operational stages of the project, so it is possible there will be a range of different metrics and methods of data collection and analysis required to conduct the full evaluation. Therefore, it is crucial that the client carefully plans when and how the outcome statements are evaluated and who is going to evaluate them – a process that was facilitated by the Value Toolkit pilot testing material.

In this research, 9 out of 17 outcome statements required qualitative scores against metrics such as levels of satisfaction and agreement that could be attained through surveys to various stakeholders. Other outcome statements may be more difficult or costly to evaluate, for example undertaking a life cycle carbon assessment to calculate embodied carbon emissions for OS-2 or using the Urban Greening Factor Tool to assess biodiversity for OS-6. It could be argued giving the client a high level of control over these decisions may come at the risk of indicators of success being chosen to primarily serve their needs and more easily demonstrate high performance, whilst potentially neglecting sustainability factors that are arguably more important on a broader scale and avoiding difficult to achieve outcomes. Despite this, any interrogation of the evaluation results would reveal the indicators of performance used and highlight important areas that were neglected. Overall, the flexibility to choose outcome statements and appropriate metrics to measure them makes evaluation using the Value Toolkit more inclusive for developers that are less well-resourced than prescriptive third-party assessment tools that require high fees, large amounts of data collection, expert consultation, and burdensome documentation (Garde, 2009; Deakin, 2011; Reith and Orova, 2015; Lin and Shih, 2016; Boyle, Michell and Viruly, 2018).

Finally, performance ranges ensure that the project is evaluated against benchmark data. Several outcome statements for the delivery stage of Water Lilies were highly context specific, particularly those requiring qualitative scores related to metrics such as levels of satisfaction and agreement. In the absence of a previous eco self-build community housing development or comparable project to draw on for benchmark data, these performance ranges were purely based on the client’s general expectations. Hence, they may not be particularly accurate, but the evaluation of Water Lilies would provide benchmarks to set performance ranges for subsequent projects with similar objectives. Some existing benchmark data from the literature provided specific performance ranges that aligned with the client’s requirements, for instance, LETI Climate Emergency Design Guide’s embodied carbon benchmarks (LETI, 2020) and The Waste and Resources Action Programme’s waste generation benchmarks for residential new build projects (WRAP, 2010). Other benchmark data provided a guide from which to set the performance ranges, such as Short Warwick-Edinburgh Mental Wellbeing Scale’s national survey data (SWEMWBS, 2011), London Plan Guidance’s Urban Greening Factor target score for residential developments (GLA, 2023), and Planning Practice Guidance’s benchmark range for gross profit margin (RICS, 2019).

The main challenge encountered in setting performance ranges using existing literature was finding suitable benchmark data. Data can be difficult to access as it may exist across various webpages, reports, guidance, or policy documents that are unfamiliar to the user. Furthermore, benchmarks are not necessarily presented in a range to support the selection of minimum, target, and maximum performance values. Lastly, the benchmark data can also appear out of date, for example the sources for OS-4 and OS-9 were over ten years old.

6.4 Conclusion

NSATs can evaluate neighbourhood-scale developments across multiple dimensions of sustainability, supporting stakeholders to communicate and collaborate effectively in pursuit of clearly defined project objectives. However, there are issues related to their prescriptiveness, high costs associated with application and consultation fees, intensive data collection processes, burdensome certification procedures, and over-emphasis on environmental sustainability, which are mainly characterised by third-party rating systems, such as BREEAM Communities in the UK and LEED-ND in the USA. Plan-embedded tools, such as the Value Toolkit and SPeAR, present an opportunity to evaluate neighbourhood-scale developments by self-assessment, potentially eliminating or mitigating barriers to adoption and increasing their inclusivity. However, plan-embedded tools have not been widely researched.

In Phase 1, the paper sought to address this gap in the literature by providing a comprehensive evaluation of plan-embedded tools, the Value Toolkit and SPeAR, applying an original framework to help decision-makers select a suitable NSAT for their neighbourhood scheme. In its application to the case study, Water Lilies, the Value Toolkit performed marginally better than SPeAR, although the marginal difference in overall weighting led to a further qualitative discussion of their main strengths and weaknesses to validate its selection. Ultimately, the detailed feedback on project outcomes enabled by the Value Toolkit outweighed SPeAR’s more straightforward implementation. The data gathered about the plan-embedded tools through the selection process can inform both researchers and practitioners considering the Value Toolkit and SPeAR for evaluation purposes. Furthermore, it provides them with a decision-making framework to undertake their own analysis of NSATs, including both plan-embedded tools and third-party rating systems.

Phase 2 demonstrated how the Value Toolkit, which has not previously been studied in the academic literature, can be implemented for a particular neighbourhood-scale scheme. It utilised Wave 3 pilot testing material to specify the measures required to evaluate the case study project. Based on industry feedback from testing, it is anticipated that changes will be made to the tool before it becomes available for use online. Nevertheless, the Value

Toolkit provided clear guidance for: defining value that relates to the specific project context, prioritising outcomes, selecting appropriate metrics for evaluating outcomes, and setting performance ranges to create benchmarks for measuring success. Considering the challenges encountered in setting performance ranges, this research suggests that an open-source database of benchmark data could be developed to accompany plan-embedded tools such as the Value Toolkit. This growing set of data could inform the selection of performance ranges and support both the setting and evolution of industry standards for metrics used in evaluation. Ultimately, the Value Toolkit has the potential to encourage developers to embed sustainability across its multiple dimensions, demonstrate performance in a succinct and engaging way, identify opportunities for improvement, and inspire better practice.

Chapter 7 – Conclusions and Further Work

7.1 Conclusions

Water Lilies eco self-build community scheme in Bristol provides a potential proof of concept as a scalable housing model that can deliver sustainable homes and communities in the UK. Hence, this research used Water Lilies as a case study to investigate the key factors in enabling ESBC housing to become a sustainable and scalable housing solution in the UK. This thesis broke the research down into three main areas: investigating consumer preferences in the ESBC housing market and how effectively these are met by current ESBC schemes such as Water Lilies; investigating the environmental impacts of ESBC housing compared to conventional residential housing; and investigating how a comprehensive evaluation of the Water Lilies project can be conducted to drive future improvements in the design and implementation of ESBC housing schemes. The main conclusions and recommendations from these research areas are summarised below.

Chapter 4 gained a broad understanding of the market for ESBC housing by analysing and comparing survey data from potential ESBC housing consumers with data from a similar survey targeted at the market for conventional self-build and custom-build housing. The results identified a distinct market for ESBC housing where potential consumers prioritise the provision of eco-housing with a low environmental impact and a sense of community, whereas the market for conventional self-build and custom-build housing prioritise location and the need to tailor the house design to the owner's unique aesthetic and lifestyle preferences. Based on the results, it evaluated the extent to which ESBC housing satisfies the market, using Water Lilies as a case study. It found that:

- The percentage of 3-bedroom and 4+ bedroom homes within the Water Lilies scheme suitably reflect the level of demand for them. The percentage of 1-bedroom homes is high relative to the level of demand for them. The percentage of 2-bedroom homes is low relative to the level of demand for them. The data suggests that families offer the largest market for ESBC housing.
- Whilst the market is largely open to more than one build method, there is significant demand for purchasing a completed home, which was the most selected

single build route. Completed homes are not currently offered but flats are provided as custom-build, which only requires interior design input from buyers. If self-finish is perceived as too time-consuming and difficult, the custom-build option may provide a suitable alternative to potential consumers.

- Considerable sustainability features and community features are likely to satisfy the key priorities of ‘sustainable lifestyle’ and ‘community spirit’, respectively. Only once Water Lilies is complete, will it be known if another key priority, ‘construction quality’, is satisfied.
- The proportion of homes in the £150k–£200k, £200k–£300k and £300k–£400k budget categories is low relative to the proportion of demand for them. The proportion of homes in the £400k–£500k and £500k+ budget categories is high relative to the proportion of demand for them. The market for conventional self-build and custom-build tended to have higher budgets and consumers are willing to pay more for a sustainable home, which suggests a wider untapped market for the more expensive homes in Water Lilies.

Based on these conclusions, key recommendations for ESBC housing developers are as follows (some are repeated or adapted from section 4.5):

- Continue to offer a range of dwelling sizes and consider providing a greater proportion of 2-bedroom homes.
- Consider providing a certain percentage of houses that are completed and/or delivered through custom-build without compromising aspects that help to create a sense of community, which are mostly driven by workshops for residents undertaking the self-finish build route.
- Updates to Building Regulations through the Future Homes Standard may increase the quality and sustainability of new build housing. Therefore, a longer-term strategy could be to sharpen the focus on social sustainability and develop a scalable approach to delivering aspects that build a sense of community (e.g. a standardised and cost-effective approach to delivering community workshops and events).
- Seek to reduce the cost of housing (e.g. through alternative material choices and quicker, more cost-effective construction processes) whilst maintaining high sustainability standards (e.g. analysing the environmental impact of alternative material choices and construction processes).

- Target potential consumers with higher budgets that can afford homes that are more expensive.
- Highlight the carbon and monetary savings to consumers by evidencing and promoting how people can reduce their environmental impact and lower home running costs compared to conventional speculatively built housing. In terms of demonstrating carbon savings, this was addressed through the work in Chapter 5.

Chapter 5 developed a method that integrated building energy modelling (BEM) and life cycle assessment (LCA) tools to conduct a whole life cycle assessment of a typical ESBC housing building shell. Furthermore, it evaluated and compared the 60-year life operational and embodied carbon impacts of six design options using different insulation materials. The results were based on the application of different scenarios for the proportion of renewables in the energy supply over time, using the best- and worst-case Future Energy Scenarios, Leading the Way and Steady Progression, for connection to the national grid and the Water Lilies Community Energy scenario for connection to a localised operationally net-zero carbon microgrid. The integration of BEM and LCA tools, IES Virtual Environment and One Click LCA, was successful in streamlining a whole life cycle assessment from a technical building design to inform future ESBC housing design. In addition, it provided baseline data inputs to conduct a more proactive life cycle assessment in the early design phase of a future ESBC housing project. The results showed that:

- In the WLCE scenario and Leading the Way FES, the design option, hemp fibre (HF), produced the least life cycle carbon emissions, whereas in the Steady Progression FES, the baseline design option, polyisocyanurate (PIR 1), produced the least life cycle carbon emissions.
- Across design options, embodied carbon accounted for 75-80% of total emissions compared to 20-25% from operational carbon in Leading the Way FES, 59-66% compared to 34-41% in Steady Progression FES, and 100% compared to 0% in WLCE scenario. This showed that operational carbon emissions are highly sensitive to the percentage of renewables in the energy mix of the grid, which is difficult to predict, and can significantly influence the design choice.
- Across all design options, due to the operationally net-zero carbon energy supply in the WLCE scenario, life cycle carbon emissions were 25-33% lower than Leading the Way FES and 53-68% lower than Steady Progression FES.

Based on these conclusions, key recommendations for ESBC housing developers are as follows:

- Consider the use of bio-based insulation materials, such as hemp fibre, to reduce life cycle carbon emissions in the design of future ESBC building shells.
- Continue to deliver renewable microgrids because these significantly reduce life cycle carbon emissions, demonstrating up to 68% carbon reductions for homes over a 60-year life cycle compared to the worst-case FES, Steady Progression.
- In addition to carbon emissions, any design decisions should be weighed up against a range of other factors including cost, availability of materials and technologies, viability at different scales of development, and suitability of use with other building materials.

Chapter 6 provided a comprehensive evaluation of neighbourhood sustainability assessment tools (NSATs) and selected the most suitable for application to Water Lilies using the analytical hierarchy process (AHP) as a method of multi-criteria decision analysis (MCDA). Furthermore, it defined the specific implementation measures for the selected tool, the Value Toolkit, that would be required to successfully evaluate Water Lilies and drive future improvements in the design and implementation of ESBC housing schemes. The process of specifying implementation measures for the Value Toolkit in collaboration with senior decision-makers in Bright Green Futures showed that:

- The Value Toolkit, a ‘plan-embedded tool’ that can be applied by self-assessment, provides a flexible evaluation framework in which the client can define outcome statements and metrics to measure them. Thus, the Value Toolkit is a more accessible NSAT for developers that do not have the resources to use a ‘third-party assessment system’, such as BREEAM Communities, which is more prescriptive, costly and requires intensive data collection and expert consultation.
- The participation and actions of homeowners and other stakeholders are integral to achieving sustainability in ESBC housing, as reflected by the delivery stage outcome statements for Water Lilies.
- Delivery stage outcome statements related to ‘climate’, ‘skills and knowledge’, ‘influence and consultation’ and ‘return’ were the highest priorities. These factors were prioritised due to the developer’s focus on significantly reducing carbon emissions to achieve a net-zero carbon scheme, facilitating homeowners to develop the skills and knowledge required to manage the design and build process and

integrate sustainable solutions, engaging with a variety of stakeholders in decision-making to support the delivery of a complex project, and generating a sufficient profit margin to reinvest in the company vision. ‘Air’ and ‘water’ were the lowest priorities, largely because the associated outcome statements were of minor consequence to the overall success of the scheme (i.e. supporting homeowners to make informed decisions on their selection of ventilation solutions and efficient water use products).

- Setting performance ranges (i.e. benchmarks) to evaluate outcome statements against was difficult in the absence of a previous ESBC housing project or comparable project to draw on for benchmark data, particularly considering that many of the delivery stage outcome statements for Water Lilies were highly context specific.

Based on these conclusions, key recommendations for ESBC housing developers are as follows:

- The Value Toolkit should be implemented to embed sustainable practices, identify opportunities for improvement, and demonstrate performance across multiple indicators to landowners, local authorities, and investors in a succinct and engaging way.
- The developer should be careful not to overlook the inclusion of important indicators of sustainability, which are often mandatory in third-party assessment systems, in the interest of presenting results that demonstrate high performance.
- Use existing benchmark data to set performance targets where possible, for example LETI Climate Emergency Design Guide’s embodied carbon benchmarks and London Plan Guidance’s Urban Greening Factor benchmarks for biodiversity. An evaluation of Water Lilies can provide benchmarks for subsequent projects.

Overall, the findings from this thesis inform the home sizes, build routes, and price ranges to offer in future schemes to satisfy the existing market for ESBC housing, as well as indicating that a wider market could be attracted through the promotion of sustainability credentials. Furthermore, they inform the design of future ESBC housing to optimise energy efficiency and minimise life cycle carbon emissions, whilst making a compelling case for the continued delivery of operationally net-zero carbon microgrids. Finally, they establish a framework, including unique sustainability indicators related to ESBC housing, to drive improvements in the design and implementation of future schemes.

7.2 Limitations

There were several limitations related to the three research areas. In Chapter 4, the survey aimed at the market for ESBC housing (Survey 1) had a commercial as well as research purpose: for the developer to gather information about potential consumers that could be used to contact them regarding suitable home purchasing opportunities. Therefore, demographic data that could be perceived by respondents to influence the developer's decision to contact them (e.g. highest qualification) or lead to respondents not finishing the survey, were excluded from the survey. Furthermore, as the survey aimed at the market for conventional self-build and custom-build housing (Survey 2) was designed after Survey 1, some aspects were added and modified to improve on the shortcomings of Survey 1 and collect a wider body of evidence in some areas. Additionally, the sample for Survey 2 was relatively small (43 respondents) compared to Survey 1 (1,719 respondents). As a result of these discrepancies, the data in Survey 1 and Survey 2 could not be compared with complete confidence but it did provide a strong indication of the key differences between the market for ESBC housing and the market for conventional self-build and custom-build housing.

In Chapter 5, the BEM tool, IES Virtual Environment, interprets each construction layer in the model as a continuous mass of material. Therefore, a structural frame consisting of cavities cannot be included in the model to automatically transfer an accurate quantity of the material to the LCA tool, One Click LCA, for embodied carbon analysis. In this research, the timber frame had to be input manually to One Click LCA using technical design plans, which would not be available if conducting the method in the early design stages. Furthermore, the accuracy of results was limited because material assumptions needed to be made where material-specific data was unavailable, and some material life cycle data can be missing from Environmental Product Declarations. Finally, the uncertainty of future trends in terms of the percentage of renewables in the energy mix of the national grid reduces the reliability of the results and a margin for error should be considered when comparing them.

In Chapter 6, there was limited literature describing the experiences of using the plan-embedded tools being evaluated in Phase 1 of the research, which would have made the justifications for scores more robust. This was more of a limitation for the Value Toolkit, as a tool that was still in development, because it was scored predominantly through pilot testing experience and supported by the scarce literature available. Ideally, scoring for SPeAR would also have been reinforced by testing experience but this was not possible due to time constraints and the depth of literature was considered sufficient to suitably justify scores for this tool. Furthermore, individual surveys to decision-makers to establish the relative importance of criteria related to NSATs presented some disagreements that may have benefitted from collaboratively resolving any points of contention, though reaching consensus cannot be guaranteed. In Phase 2, implementation measures for the Value Toolkit were only specified for the 'delivery stage' of Water Lilies, whereas the same process would need to be repeated for the 'operational stage' to establish a full evaluation framework. Finally, it was difficult to identify suitable benchmark data to set performance ranges for several reasons: there were no previous ESBC schemes to extract benchmark data demonstrating past performance; some generic benchmark data were difficult to access in the literature; most benchmark data were not presented in a range (i.e. minimum, target, and maximum values); and some benchmark data appeared out of date (e.g. over ten years old).

7.3 Future Work

In addition to the specific recommendations provided in section 7.2, this research has opened up a variety of avenues for future work that would further support ESBC housing to become a sustainable and scalable solution in the UK. Building on the research undertaken in Chapters 4 and 5, future work could explore the trade-offs between life cycle carbon emissions, build costs, and home running costs for alternative building design options and energy scenarios to develop an optimal solution that is financially accessible to a greater proportion of the market whilst achieving sustainability objectives and returning a sufficient profit margin. Furthermore, beyond understanding the budget ranges of potential ESBC housing consumers, future work could investigate their financial situation in more detail (e.g. how much they are able to finance through their own resources). This would enable future ESBC schemes to offer potential consumers suitable financial incentives and support mechanisms from the outset. In addition, Water Lilies has a unique construction approach where the main contractor constructs the building shells of the self-finish houses with services attached and the homeowners complete the fit-out through a combination of employing contractors, project management, and DIY. Therefore, future work could seek to understand the challenges associated with this construction approach (e.g. managing access to multiple contractors working on separate self-finish projects). Finally, undertaking a post-occupancy survey for homeowners to reflect on their experiences of the Water Lilies project and provide feedback on areas such as the design and build process, workshops and individual support, communication of project updates and timescales, and community building activities would be highly valuable to informing the design and implementation of future ESBC housing schemes. A framework has already been put in place for this through the work outlined in Chapter 6.

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Appendix A

A.1 Housing Energy Consumption and Costs

Table A.1. Energy consumption and costs by housing type

Measurement	**Home 1 Average ESBC Home**	**Home 2 Average New Build (UK)**	**Home 3 Average Existing Home (UK)**
Electricity			
Electricity consumption (kWh/year)	6600 [1]	3100 [1]	3100
Electricity tariff (£/kWh)	0.12 [1]	0.155 [2]	0.155 [2]
Electricity standing charge (£/year)	80 [1]	80 [2]	80 [2]
Electricity cost (£/year)	872	561.74	561.74
Gas			
Gas consumption (kWh/year)	0	9000 [3]	12,500 [3]
Gas tariff (p/kWh)	0	0.028 [2]	0.028 [2]
Gas standing charge (£/year)	0	98 [2]	98 [2]
Gas cost (£/year)	0	353.60	453
Offsets			
ASHP RHI subsidy payments (7 years) (£/year)	552.50 [1]	0	0
PV ESCo payments (30 years) (£/year)	155 [1]	0	0
Totals			
Energy consumption (kWh/year)	**6600**	**121,000**	**156,000**
Energy cost (£/year)	**165**	**915**	**1015**

[1] Data provided by CEPRO on an average ESBC home using Water Lilies case study.

[2] (UK Power, 2020).

[3] (MHCLG, 2015b).

Appendix B

B.1 Embodied Carbon Emissions Including Biogenic Carbon Flows

Figure B.1 shows the embodied carbon emissions of each design option when biogenic carbon flows are included in the analysis (i.e. taking the '+1/-1 approach' instead of the '0/0 approach', as described in the section 'Life Cycle Stages'). From the results shown in section 5.3.3, 81 kg CO_2e/m^2 is subtracted from the product stage (A1-A3) and added to the end-of-life stage (C1-C4) for RW, GW, PIR 1, PIR2, and PUR, and 89 kg CO_2e/m^2 is subtracted from the product stage (A1-A3) and added to the end-of-life stage (C1-C4) for HF. Therefore, at the product stage, HF produces 5 kg CO_2e/m^2, 16 kg CO_2e/m^2 for RW, 17 kg CO_2e/m^2 for GW, 18 kg CO_2e/m^2 for PIR 1, 32 kg CO_2e/m^2 for PIR 2, and 43 kg CO_2e/m^2 for PUR. HF produces 99 kg CO_2e/m^2 at the end-of-life stage, whereas all other design options produce 90 kg CO_2e/m^2.

As explained in the section 'Life Cycle Stages', this reflects the uptake of CO_2 during biomass growth, transferred to the building system and reported as a negative emission in the product stage before it is released at the end-of-life stage. Significant carbon emissions are subtracted from the product stage for every design option because there is a high quantity of timber in the case study building shell, which sequesters CO_2 during tree growth. Further carbon emissions are deducted from the design option, HF, because hemp fibre is a bio-based insulation consisting of soft, woody fibres from hemp stems that also uptakes CO_2 during biomass growth. The overall embodied carbon emissions including biogenic carbon flows are equal to the results excluding biogenic carbon flows.

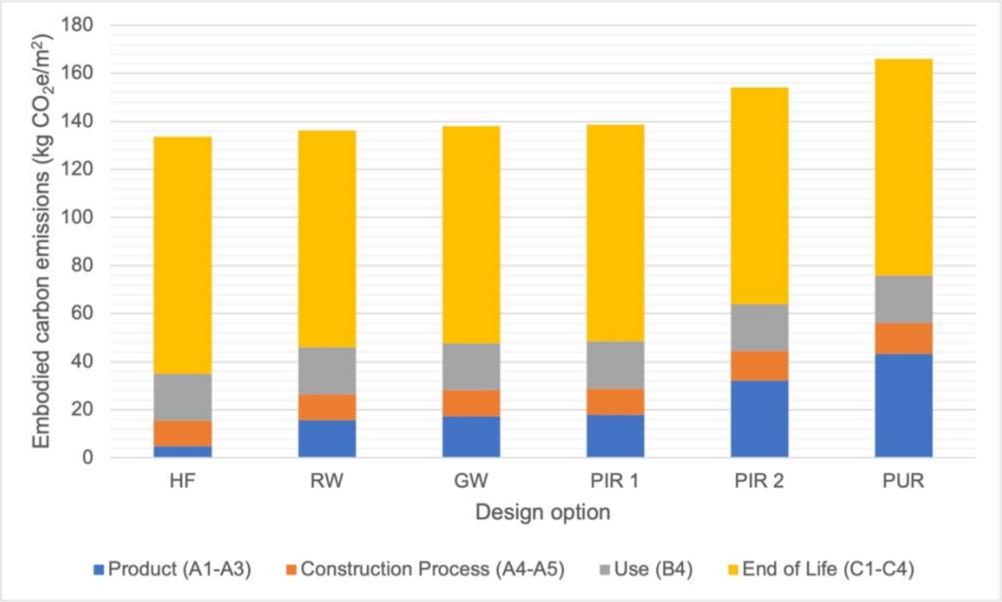

Figure B.1. Embodied carbon emissions of design options including biogenic carbon flows (accounting for the whole building)

Appendix C

C.1 Step 1.8 of Phase 1 Analytical Hierarchy Process

The following refers to step 1.8 of Phase 1.

Table C.1 presents the pairwise comparisons and the resulting weights for ‘decision-maker 1’.

Table C.1. Example of pairwise comparison results for decision-maker 1

Criteria	A	B	C	D	E	Geometric Mean	Weight
A	1	1/5	1/3	1/3	1/3	0.3749	0.060
B	5	1	3	3	3	2.6673	0.428
C	3	1/3	1	3	3	1.5518	0.249
D	3	1/3	1/3	1	3	1.0000	0.160
E	3	1/3	1/3	1/3	1	0.6444	0.103
						6.2384	1.000

A = Resource; B = Alignment with Project Context and Objectives; C = Stakeholder Engagement; D = Identifying Opportunities and Trade-Offs; E = Communicating Results

The weights were calculated by following the method described by Department for Communities and Local Government (2009a):

- Calculate the geometric mean of each row in the matrix by multiplying the values by one another to the power of the reciprocal of the number of criteria. Taking row A as an example, the calculation would be:

$$\left(1 \times {}^{1}\!/_{5} \times {}^{1}\!/_{3} \times {}^{1}\!/_{3} \times {}^{1}\!/_{3}\right)^{{}^{1}\!/_{5}} = 0.3749$$

(Eqn. C.1)

- Totalling the geometric means.

- Normalising each geometric mean by dividing by the total geometric mean. Using row A, for example:

$$0.3749 \div 6.2384 = 0.060$$

(Eqn. C.2)

C.2 Step 1.9 of Phase 1 Analytical Hierarchy Process

The following calculations refer to step 1.9 of Phase 1.

The weights for the alternative NSATs shown in Table 24 were calculated using the following steps:

- Multiply the *criteria* scores given to each *alternative* at step 1.5 with the average weight of the corresponding *criteria* from step 1.8. For example, for column A of the SPeAR, this would be:

$$5 \times 0.152 = 0.767$$

(Eqn. C.3)

- Total the scores.

- Normalise each score by dividing by the total score. Using the SPeAR row, for example:

$$3.766 \div 7.976 = 0.472$$

(Eqn. C.4)

Appendix D

D.1 Journal Paper Abstracts

D.1.1 Understanding the Market for Eco Self-Build Community Housing

Sustainability, Volume 13, October 2021, Pages 11823

This paper evaluates the potential of eco self-build community (ESBC) housing to act as a socially and environmentally sustainable housing solution that can address the demand for self-build and community housing whilst supporting the UK's 2050 net-zero-carbon commitment. This model of housing is being piloted through schemes such as the Water Lilies project, an upcoming ESBC scheme providing self-finish houses and custom-build flats. The research aims to gain a broad understanding of the market for ESBC housing by analysing the data from people who registered interest in a plot or home and comparing this with data from a similar survey targeted at the market for conventional self-build and custom-build housing. The key findings are that: (1) the ESBC housing market is largely open to more than one build method, but with a greater preference for purchasing a completed home and self-finish than self-build, compared to the conventional market for self-build and custom-build that is primarily interested in self-build; (2) the ESBC housing market is looking for a variety of home sizes, though predominantly 2 and 3 bedrooms, that could be provided through houses and flats, compared to the conventional market for self-build and custom-build that is mostly seeking larger houses on single plots; (3) the most important housing aspects to the ESBC housing market are 'green lifestyle', 'style and construction quality', and 'community spirit', which differ to the conventional self-build and custom-build market, where they are 'construction quality', 'internal appearance/layout' and 'location'; (4) living in a sustainable home is important to the market for conventional self-build and custom-build housing and on average, they would be willing to pay 27% more for a highly sustainable home than the average UK new build. The main drivers are that people want to reduce their environmental impact and reduce their home running costs. A key overall conclusion of the study is that a distinct market exists for ESBC schemes, where the priorities of prospective homeowners differ to those from the more general self-build market. For ESBC schemes, the provision of eco-housing and a sense of community are key priorities, whereas for the more general self-build market, location and the need to tailor the house design to the owner's unique aesthetic and

lifestyle preferences tend to be the most important factors. This paper discusses the implications of these findings and identifies opportunities for scaling up the delivery of ESBC housing.

D.1.2 Carbon assessment of building shell options for eco self-build community housing through the integration of building energy modelling and life cycle analysis tools

To achieve the UK's net-zero carbon transition by 2050, new homes need to be designed to high energy efficiency standards and minimise life cycle carbon emissions. This study develops a method that integrates building energy modelling (BEM) and life cycle assessment (LCA) tools, IES Virtual Environment (IES VE) and One Click LCA, to conduct a life cycle assessment of the operational and embodied carbon impacts of a typical terraced building shell in an eco self-build community housing (ESBC) project, using Water Lilies as a case study. It evaluates and compares the 60-year life cycle carbon impacts of six design options that apply different insulation materials to the case study building shell. The results are based on grid-connected Future Energy Scenarios (FES) that have different carbon intensities predicted over time and the microgrid-connected Water Lilies Community Energy (WLCE) scenario that is operationally net-zero carbon. Depending on the FES, embodied carbon accounted between 59-80% of total emissions compared to 20-41% from operational carbon across design options. The results show that operational carbon is highly sensitive to the percentage of renewables in the energy mix of the grid, which is difficult to predict, and can significantly influence the design choice. As such, future researchers should account for predicted changes to the carbon intensity of the grid by applying a similar method to that proposed. Overall, the integration of IES VE and One Click LCA provided a more streamlined life cycle assessment to help inform early design decisions by enabling energy consumption simulation in BEM to assess operational carbon emissions and the automated transfer of building materials from the BEM model to the LCA tool to assess embodied carbon emissions. The limitations included the unavailability of material-specific data in early design stage plans, the inability to automatically transfer the timber frame structure from IES VE to One Click LCA, and the uncertainty of future energy trends.