Enabling Net-Zero Buildings through Automated Compliance Checking, Driven by Energy and Life Cycle Assessment Co-Simulation

A thesis submitted in partial fulfilment

of the requirement for the degree of Doctor of Philosophy

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November 2023

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To Georgina ’Lai Fong’ Yeung
Whose dream was always to see me at University, my successes will always be yours.

Abstract

Net-zero is a key focus of the UK government, as it seeks to lead the world in the reduction of carbon emissions. Targets have been set in law to bring its greenhouse gas emissions to net zero by 2050 and committing to a 68 percent reduction in carbon emissions by 2030.

Currently, there is disparity between national government net zero strategy and industry and institution recommendations for whole life carbon assessment. This is evidenced by the differing language used and the scope of life cycle stages considered. Whilst government strategy has presented general environmental targets, there is no technical guidance for how this can be achieved. No research or work is available that integrates the software tools necessary to implement greenhouse gas emission design and assessment for UK buildings.

The challenge identified in this Thesis, is the development of an approach for how net-zero buildings can be designed and assessed, aligning national net zero requirements with industry and institutional recommendations for whole life carbon assessment.

To achieve this, an initial literature review is presented, describing the UK landscape in terms of net zero and whole life carbon assessment, underlying concepts such as specific regulatory texts, building energy simulation and life cycle assessment are introduced, as are enabling technologies and concepts including; building information modelling and automated compliance checking.

The remainder of this Thesis focusses on the development of a design and regulatory framework, that integrates a building energy simulation and life cycle assessment co-simulation for the purposes of greenhouse gas emission assessment of UK buildings. Regulatory uplifts are proposed alongside, that align current requirements with the recommendations made regarding net zero and whole life carbon assessment.

The framework is augmented and digitised following the latest UK automated compliance checking principles and a proof-of-concept implementation of the design and regulatory aspects of the developed framework and regulatory uplifts is explored against the current status quo.

This Thesis concludes by documenting findings and reflections from the implementation of the proof-of-concept, which validates this research by comparing the experience of the implementation against simulations of traditional processes. This Thesis is the first to, present a methodology for dynamic (time-differentiated) co-simulation results and a methodology for GHG emission design and assessment of UK buildings, and whilst doing so, aligning goverment requirements for net zero and industry and institutional recommendations for whole life carbon assessment. This research is exploratory, simulation research, with a key outcome being the findings and reflections to guide future research in implementing the framework developed in this research in the real-world.

Acknowledgements

I would like to first acknowledge my supervisors; Prof. Yacine Rezgui and Dr Thomas Beach. It has been said that when one sees far, it is from standing on the shoulders of giants and this Thesis is evidence to that. To Prof. Rezgui, thank you for always looking towards the future and the subsequent opportunities you have afforded me over the last few years. I have thoroughly enjoyed our intense discussions around research and I hope there are many more to come. To Dr Beach, who has always gone above and beyond, thank you for your; rigour, compassion and advice. I will always appreciate our ability to hold multiple complex discussions at once and it is a rare thing to find someone willing and able to jump with me from one concept to another.

I would be remiss if I did not acknowledge all of the friends and colleagues who have formed a part of this journey. Thank you for the laughs and your understanding.

Finally, to my fiancé Laura, who has supported me ever since we met at Cardiff University, thank you. I could not have done this without your love, empathy and consort. The night is darkest before the dawn, but with your support, the night is always a little brighter.

Contents

List of Publications

The work introduced in this thesis is based on the following publications.

- Jonathan Yeung, Alvaro J Hahn Menacho, Antonino Marvuglia, Tomas Navarrete Gutierrez, Thomas Beach, Yacine Rezgui. An open building information modelling based co-simulation architecture to model building energy and environmental life cycle assessment: A case study on two buildings in the United Kingdom and Luxembourg. Renewable and Sustainable Energy Reviews, 183:113419, June 2023.
- Thomas Beach, Jonathan Yeung, Nicholas Nisbet, and Yacine Rezgui. Digital approaches to construction compliance checking: Validating the suitability of an ecosystem approach to compliance checking. Advanced Engineering Informatics, 59:102288, January 2024.

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List of Acronyms

ACC	Automated Compliance Checking
BCB	Building Control Body
BCC	Building Construction Cost
BER	Building Emission Rate
BES	Building Energy Simulation
BGGER	Building Greenhouse Gas Emission Rate
BIM	Building Information Modelling
BPER	Building Primary Energy Rate
BRUKL	Building Regulations UK Part L
BW2	Brightway2
E+	EnergyPlus
GHG	Greenhouse Gas
GWP	Global Warming Potential
IFC	Industry Foundation Classes
LCA	Life Cycle Assessment

LCI Life Cycle Inventory

NCM National Calculation Methodology

TCC Target Construction Cost

TER Target Emission Rate

TGGER Target Greenhouse Gas Emission Rate

TPER Target Primary Energy Rate

WLCA Whole Life Carbon Assessment

Chapter 1

Introduction

The UK government seeks to 'move ahead of the pack' and position the UK as the home of the new Green Industrial revolution, having become the first major economy to legislate binding targets for net zero emissions by 2050 [1, p.15].

This legislation puts in place, targets to bring Greenhouse Gas (GHG) emissions to net zero by 2050 and committing to a 68 percent reduction in carbon emissions by 2030 [1, p.10].

The net zero vision, encompasses the strategy to which the UK hopes will combat the increasing global temperatures that enable the conditions causing flooding, torrential downpours, fires, failing crops and rising sea levels [1, p.14]. Buildings account for 40% of the UK's total energy usage and so, have a tremendous impact on the UK's ability to achieve net zero targets [2, p.14].

As the UK continues on its journey to net zero operating emissions by 2050, there is an increasing appetite to address the obvious flaw in net zero targets, that only operating emissions are assessed [3, p.3]. Whole Life Carbon Assessment (WLCA)'s are a proven and widely-supported way; to assess GHG potential and transition to a low-carbon built environment [3, p.4].

Life Cycle Assessment (LCA) is the compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle [4, p.1]. The modular LCA structure specified in EN 15978 is the basis upon which recommendations for WLCA is based, WLCA is the calculation and reporting of the quantity of carbon impacts expected throughout all life cycle stages of a project [5, p.10].

Throughout this Thesis, the acronym WLCA is used when referring to industry and institutional recommendations for assessment of buildings across all life cycles. LCA is used when referring to the calculation methodology underpinning WLCA. It is also referred to as the domain in which an object ranging from a singular product to a building is assessed to understand its environmental impact. This discussion will be revisited at the conclusion of this Thesis, which will consider whether the *'C'* in WLCA should refer to cycle instead of carbon.

This Thesis will explore this key area of research by developing a wider, design and regulation framework, integrating a Building Energy Simulation (BES) and LCA methodology for GHG assessment. BES software have been in use since the 1960s [6] and are an essential tool in achieving regulatory compliance with UK building regulations [7]. This framework will be augmented through automation and digitisation to enable a pathway to net zero buildings and WLCA, aligning government requirements with industry and institutional recommendations.

1.1 Motivation

At present, there is little guidance on how these targets can be met and criticism is common that they focus only on operational emissions, simultaneously, recommendations for mandatory whole life carbon assessments are being made [3, p.3].

It has been suggested that the single most significant policy that the government could introduce is the mandatory requirement for WLCA for buildings, which will then enable the introduction of progressively ratcheting carbon targets for buildings to match the pathway to net-zero [3, p.3]. Discussed in detail in Chapter 2, WLCA recommendations from industry and institutions are based on the modular structure for LCA across all building stages from EN 15978 [8, p.21]. The structure allocates specific 'modules' into each building life cycle stage (a figure illustrating the structure is presented later in Chapter 2):

1. Product Stage: A1 - raw material supply, A2 - transport, A3 - manufacturing
2. Construction Process Stage: A4 - transport, A5 - installation process
3. Use Stage: B1 - use, B2 - maintenance, B3 - repair, B4 - replacement, B5 - refurbishment, B6 - operational energy, B7 - operational water
4. End of Life Stage: C1 - de-construction, C2 - transport, C3 - waste processing, C4 - disposal

However, at present no work has been conducted towards the development of a fully fledged dynamic BES and LCA co-simulation methodology, with capabilities to enable both, embodied and dynamic operating emissions. Furthermore, no work nor policy has detailed how such a co-simulation can be incorporated and implemented within the wider UK building design and regulatory systems.

Co-simulation encapsulates the latest research in the coupling of building domain models to better describe building sub-system interactions, new approaches are necessary to achieve innovative and optimal multi-disciplinary solutions deriving from the integration of partial solutions developed independently [9].

UK regulatory systems for construction are complex and devolved [10], under the context of progressively ratcheting emissions targets, this system is not (in its present state), capable of provisioning net zero nor WLCA/GHG emission assessment, nor are designers able to readily implement BES and LCA co-simulation assessment into early design stages [11] without either, model duplication or applying simplified tools [12].

Net zero targets have been established however, consider only operational emissions whilst the sector is clearly demanding WLCA [3, p.3]. Net zero targets concern all GHG emissions and not only CO_2 [1, p.10], which current compliance processes are not provisioned to assess. WLCA is a well-supported method for assessing GHG emissions [3, p.4], however, no work exists integrating the underpinning LCA domain with the BES domain in a dynamic co-simulation [11] necessary to design and regulate for progressively ratcheting emission targets. Furthermore, no work exists that has considered the implementation of such a co-simulation within the wider design and regulatory compliance systems, nor how this can be implemented through Building Information Modelling (BIM) and Automated Compliance Checking (ACC).

1.2 Hypothesis and Research Questions

This thesis will tackle the following hypothesis and research questions established as part of this research. By way of investigating all the research gaps identified, this Thesis derives the following hypothesis:

The integration of BIM, ACC and (BES and LCA) co-simulation within a digital, design and regulatory building framework will provide a pathway to net zero buildings and whole life carbon assessment that aligns governmental strategy with industry and institutional recommendations.

In order to test the Hypothesis, the following Research Questions will be investigated:

1. What are the requirements in the UK regulatory landscape in terms of net zero and how can they be aligned with recommendations for WLCA to deliver GHG assessment of UK buildings?
2. What are the current accepted approaches for ACC within the UK regulatory building sector?
3. How would a BES and LCA co-simulation architecture be integrated into the wider UK building design and regulatory framework, to enable net zero and WLCA with regards to: (a) building design processes and (b) building regulatory processes

These research questions will be investigated and answered within this Thesis, the following section details the scope of the research conducted in this Thesis.

1.3 Research Scope

This section serves to detail the precise scope of the research conducted in this Thesis. The research scope is as follows:

1. This research is limited to non-domestic buildings - with their increased complexity allowing for a richer basis for this research [10].
2. This research is limited to the construction and operational phase. It is intended to be an initial exploration into the integration of BES and LCA co-simulation within a building design and regulatory framework to enable GHG assessment across all building life cycles. Net zero requirements currently focus only on the operational phase [1] and so, implementation across the construction and operational stages will be assessed, the end-of-life phase is left for future research.
3. This research implements modules: A1, A2, A3 and B6.
4. This research is limited to the design phase, prior to and including compliance submission.
5. This research is limited to the coupling of BES and LCA domains - for their relevancy to GHG assessment.
6. This research is limited to government documents, (more specifically those relevant to BES and LCA) and authoritative industry and institutional recommendations within the UK landscape.
7. This Thesis focusses on the development of an approach to co-simulation and ACC. Design and implementation of a production ready software system is out

> of scope, therefore, elements like quality assurance and error checking are left to future work. A proof-of-concept digital framework is produced to validate this work and provide enough implementation to prove the concept.

The next section provides an overarching summary of this Thesis' structure.

1.4 Thesis Summary

This Section serves to provide a brief summary of the Chapters presented in this Thesis.

Chapter 2 will present a thorough literature review concerning all aspects relevant to the implementation of a BES and LCA co-simulation methodology, enabling WLCA of buildings within UK design and regulatory systems. Initially, this review illustrates the current UK regulatory landscape, before the concept of net zero is then introduced and its place in the UK landscape discussed.

Widely-supported and proven domain models (LCA and BES) relevant to net zero are also introduced in this Chapter. Along with enabling technologies (BIM, ACC and co-simulation).

Chapter 3 will present the research methodology applied in this Thesis. This Chapter will introduce concepts relevant to the genesis of a research methodology and apply them with regards to the specifics of this research. This Chapter will also propose the hypothesis and research questions (in Section 2.9) derived from the research gaps identified in Section 3.3.

Chapter 4 will explore the requirements and recommendations made with regards to net zero and WLCA and in doing so investigate and answer Research Question 1. This Chapter builds upon the literature review and will examine how the requirements and recommendations made within the UK landscape can be aligned to enable GHG assessment. This Chapter culminates by illustrating the developed framework which will facilitate net zero GHG emission design and assessment, it will also describe the proposed regulatory uplifts that will directly enable net zero, aligning current requirements and recommendations.

Chapter 5 will undertake an Automation and Digitisation Feasibility Analysis exercise. This task takes input from the literature review and establish how automation and digitisation can enable the developed framework and explores the current accepted approaches for ACC in the UK regulatory building sector as applied to the net zero and WLCA context, this Chapter will address Research Question 2. The Chapter will also present the digitisation process for key regulatory documents, Approved Document Part L.

Chapter 6 will develop and present the co-simulation architecture development, before augmenting the co-simulation through the Automation and Digitisation Feasibility Analysis in the Co-simulation Automation and Digitisation Augmentation task.

The co-simulation architecture developed in this Chapter will be integrated within the digital framework and implemented as a proof-of-concept for validation in the following Chapter.

Chapter 7 will present the proof-of-concept and validation, applying the Digitised, Design and Regulatory Framework for BES and LCA Co-simulation to two building models that will demonstrate the design and regulatory aspects of the framework, before reflecting upon the results.

Finally, **Chapter 8** provides concluding remarks by re-visiting key elements of the research methodology and summarising the research conducted to address them in this Thesis.

1.5 Related Works

The research presented in this thesis has been conducted through two research projects:

1. Digitising Construction Regulations, funded by Construction Innovation Hub
2. Semantic LCA, funded by EPSRC

The Digitising Construction Regulations project aimed to meet the ever-increasing requirements for increased transparency and auditability in the building control and construction compliance processes. The project developed a new 'digital ecosystem' to support digitised compliance processes and help construction firms in navigating the complex regulatory landscape with greater ease and certainty.

This author's direct contributions to this project included: the digitisation of regulatory documents (Part L, Part M and BB100) and user interface design. The digitisation of Part L feeds directly into this Research and is expanded upon in Chapter 5. Contribution by others on this project include; Ecosystem design and implementation and Manual Compliance Checking.

The Semantic LCA project was conducted with the financial support of the Engineering and Physical Sciences Research Council (EPSRC) in the UK.

This author's direct contributions to this project included the development of the BES and LCA Co-simulation Methodology, which has been adapted for this research, and is presented in Chapter 6.

Chapter 2

Literature Review

This Chapter will present a thorough literature review concerning all aspects relevant to the implementation of a BES and LCA co-simulation architecture, enabling WLCA within UK design and regulatory systems.

Initially, this review illustrates the current UK regulatory landscape, describing the structure of UK regulatory processes and key documents that influence regulation and compliance, before describing in further detail regulations that influence energy and emissions assessment. In the following, Section 2.2 introduces the concept of net zero and its place in the UK landscape is discussed, Section 2.3 highlights relevant industrial and institutional recommendations surrounding net zero and WLCA.

Widely-supported and proven domain models (LCA and BES) relevant to net zero are then introduced, LCA is proven in its capabilities of assessing GHG emissions and assisting in the transition to low-carbon environments, whilst BES is essential in the design and regulation of buildings.

Enabling technologies (BIM, ACC and co-simulation) are discussed within the context of enabling the implementation of the net zero vision. BIM is the key enabling technology for digital building models and is widely used in practice, ACC encompasses the latest research surrounding the digitisation of regulations and automatic checking. Co-simulation encapsulates the latest research in the coupling of building domain models to better describe building sub-system interactions and is essential in the integration of LCA within BES design and compliance processes. Finally, this Chapter is concluded in Section 2.9 and the research gap is presented.

2.1 The UK Regulatory Landscape

The UK construction regulations are complex in nature, with a highly devolved structure in which legislation is different for each of; England, Northern Ireland, Scotland and Wales [10]. Technical building regulation in England is governed by the Building Act 1984 [13], which consolidated enactments concerning buildings and related matters. Secondary legislation - in the form of statutory instruments - have been legislated within the Building Regulations 2010 [14, 10] which are more specific towards building work [15]. Building Regulations are likely to apply when one: erects a new building, makes bigger an existing building, changes a buildings use or alters controlled building services [15, p.5]. The Building Regulations set out required standards for building work but do not dictate how they should be achieved [15]. For this, the government maintains Approved Documents which provide guidance and methods for demonstrating compliance with the Building Act and Regulations [10], general performance based guidance is provisioned alongside practical examples and solutions on achieving compliance for some common building situations, however compliance with the Approved Documents does not always guarantee compliance with the Building Regulations [15, p.9].

The following subsections will firstly, present an overview of the Approved Documents in Section 2.1.1, before examining in further depth, Approved Document Part L: Conservation of Fuel and Power in Section 2.1.2

2.1.1 Approved Documents

The Approved Documents consist of 18 overarching volumes, labelled A - R with an additional document numbered 7, these documents are [7, p.105]:

1. Approved Document 7 Materials and workmanship
2. Approved Document A Structure
3. Approved Document B Fire safety
4. Approved Document C Site preparation and resistance to contaminants and moisture
5. Approved Document D Toxic substances
6. Approved Document E Resistance to the passage of sound
7. Approved Document F Ventilation
8. Approved Document G Sanitation, hot water safety and water efficiency
9. Approved Document H Drainage and waste disposal
10. Approved Document J Combustion appliances and fuel storage systems
11. Approved Document K Protection from falling, collision and impact
12. Approved Document L Conservation of fuel and power
13. Approved Document M Access to and use of buildings
14. Approved Document P Electrical safety - dwellings
15. Approved Document Q Security - dwellings
16. Approved Document R Physical infrastructure for high speed electronic communications networks
17. Approved Document S Infrastructure for the charging of electric vehicles

Some Approved Documents are separated within themselves in terms of applicability towards domestic dwellings or non-domestic buildings. This Thesis is largely concerned with non-domestic buildings (due to their increased complexity allowing for a richer basis for these works [10]) and focusses solely on Approved Document Part L, which concerns the Conservation of Fuel Power and is the key document in providing compliance with respect to the energy efficiency of buildings [13].

2.1.2 Approved Document Part L Conservation of Fuel and Power

Approved Documents are updated as and when deemed necessary, for example, Part L has been existence (in various forms) since 2010, with separate amendments being made in; 2011, 2013, 2016, 2018, 2021 and most recently 2023 [16].

Whilst this Section serves to present a high level summation of this document, a detailed analysis of Part L is presented in Chapter 5, which concerns the digitisation of the same document.

In its present state - 2023 - Part L introduces some new requirements not present in previous editions, for example, the requirements concerning primary energy rate [7, p.9]. To summarise with broad strokes, the regulations towards which Part L provides guidance for compliance are:

Regulation 24 concerns the implementation of approved tools (under the Notice of Approval) for the calculation of energy performance of buildings [7, p.8].

Requirement 25 and 25B sets minimum energy performance requirements in the form of a Target Emission Rate (TER) and the new Target Primary Energy Rate (TPER), whilst 25B defines high performance rates and the requirements to fulfil such a definition, including, meeting the TER and the provision of a feasibility analysis [7, p.8].

Regulation 26 and 26C require calculations for new buildings, proving that the Building Emission Rate (BER) and Building Primary Energy Rate (BPER) are respectively less than TER and TPER [7, p.8].

Regulations 27 and 27C necessitate a notice of calculations being given to the Building Control Body (BCB), before and after a new construction [7, p.8].

Regulation 25A requires that new buildings must consider the feasibility of installing high-efficiency alternative systems [7, p.19].

Requirement L1(a) concerns limiting fabric gains and losses and places standards for; the building fabric, airtightness, pipework and services [7, p.21].

Requirements L1(b) and L2 dictate minimum operating efficiencies and controls for fixed building services and require on-site electricity generation is appropriately sized [7, p.34].

Regulation 43 dictates processes for pressure testing [7, p.56].

Regulation 44 and 44Z concerns commissioning of fixed building services [7, p.60].

Regulation 40 and 40a concern operating and maintenance instructions and documentation provision as part of a building log book [7, p.64].

Regulation 23(2) concerns the replacement of thermal elements [7, p.69].

Regulation 6, 22 and 23 set requirements when a material change of use or a change to energy status occurs [7, p.77].

Finally, **Regulation 28** applies to existing buildings with a total useful floor area over 1000m^2 carrying out consequential improvements [7, p.81].

Regulations 24, 25A, 27, 40, 40A and 43 are conceptually administrative tasks, requiring evidencing of some analysis or proof of implementation, whilst regulations 6, 22, 23 and 28 are relevant only to existing buildings.

For new buildings other than dwellings, requirements L1 and L2 put in place limiting standards and specifications whilst regulations 25, 25B, 26 and 26C can be considered performance based requirements.

Limiting standards, specifications and performance based requirements are at present, fulfilled by submission and assessment of a BRUKL document [7, p.93]. An example BRUKL documenting these requirements is presented in Appendix A. The BRUKL output is a six-page document split into sections, concerning: administrative information, CO_2 and primary energy rate targets, fabric and fixed building service performance, solar gain limits and controls, high efficiency alternative systems and finally a technical data sheet.

The sample BRUKL was produced using the iSBEM program, which is the user interface to the Simplified Building Energy Model (SBEM) software tool [17]. Together, these software tools allow for the calculation and demonstration of the National Calculation Methodology (NCM). The NCM was developed for the Health and Safety Executive, to assess building energy performance, for the purposes of building regulation compliance and energy certification [18]. The NCM provides the underlying calculation methodology that approved tools under the Notice of Approval must follow to satisfy Regulation 24 [19].

The key performance based targets satisfying Regulations 25, 25B, 26 and 26C are evidenced in the first table of the BRUKL document (illustrated in Appendix A). These targets comparisons are firstly, the BER vs TER (measured in $kgCO_2/m^2$.annum) and secondly BPER vs TPER (measured in kWh_{PE}/m^2.annum). Full calculation methodologies for these target comparisons are presented in Chapter 6.

The TER and TPER are both targets defined by the concept of a notional building, which has the same size, shape, zoning arrangements, orientation, services and space activities as the actual building being built (who's targets are represented by the BER and BPER) [19, p.10]. The TER and TPER are calculated by applying a set of standardised specifications (defined in the NCM) against the notional building, which are compared to the actual building applying specifications as designed by the design team.

Emission Rate (TER and BER) is defined by Part L as the maximum CO_2 emission rate for building over the course of a year [7, p.84], whilst primary energy is defined as energy from renewable and non-renewable sources, that has not undergone any conversion or transformation process [7, p.88].

Both factors are derived from electrical and fuel usage calculations based over a year, which are then multiplied by CO_2 and primary energy factors, given in the NCM [19, p.59]. This means that at present, in environmental terms, only carbon emissions are assessed under UK building regulations, and that their calculation and compliance checking is based on the application of simplified factors (reproduced in Appendix B).

2.2 Net Zero

Currently, net zero is a key focus of the UK government, as it seeks to lead the world in the race to net zero carbon emissions [1, p.15]. Having set in law, a target to bring its greenhouse gas emissions to net zero by 2050 and committing to a 68 percent reduction in carbon emissions by 2030 [1, p.10].

At present, there is little guidance on how these targets can be met and criticism is common that they focus only on operational emissions, simultaneously, recommendations for mandatory WLCA are being made [3, p.3]. The lack of detailed policy for how whole life carbon assessment is hampering progress towards the UK achieving its net zero goals [3, p.3].

The policy paper, Net Zero Strategy: Build Back Greener is as of present, the key document in informing the UK of the governments net zero strategy. This policy paper describes high level strategies and the overarching journey to net zero in 2050 across sectors including: Power, Fuel Supply, Industry, Buildings, Transport, Natural Resources and GHG Removals [1]. The strategy is littered with policies and plans for operational green house gas emissions, however no such specific policies are described for embodied carbon and more specifically, GHG emissions accrued in the construction phase of buildings. Whilst, high level operational emission strategies are described, the policy document does little to; provide a clear policy and define key terms relevant to net zero. When answering the question of, what is net zero?, the strategy does state that emissions of greenhouse gases will be ’net zero’ in 2050 when emissions are reduced to as close as zero as possible, with the remaining emissions absorbed by new technologies [1, p.14]. However, key technical terms are instead defined in the Environmental Audit Committee's 2022 report Building to net zero: costing carbon in construction, here [3, p.9], the following key terms defined are:

1. **Embodied Carbon**: all emissions associated with materials, construction, maintenance, repair, demolition, and disposal of a building.
2. **Operational Carbon**: all emissions associated with use of energy within a building.
3. **Whole-life Carbon**: the combined total of embodied and operational emissions over the whole life cycle of a building.
4. **Whole-life Cycle**: The entire life of a building from material sourcing, manufacture, construction, use over a given period, demolition and disposal, including transport emissions and waste disposal.

Revisiting the two key emissions targets within this context reveals some lack of consistency in the alignment of short and long term targets. This lack of clear policy is currently hampering the net zero strategy, where the targets are to [1, p.10]:

1. Reduce Greenhouse gas emissions to net zero by 2050
2. Reducing carbon emissions by 68% by 2030

As previously indicated, emissions refer only to operational carbon, which are only one cycle within the context of life cycle assessments (discussed at length in Section 2.4) [8, p.21]. At the same time, the 2030 target refers specifically only to carbon emissions whilst the 2050 targets refers to GHG emissions.

A GHG is one that that absorbs infra-red radiation in the region of the electromagnetic spectrum, and it is the greenhouse effect that maintains the planets average temperature, with GHG's absorbing heat from the earth and the sun [20, p.363]. The dominant

GHG's are water vapour (H_2O), carbon dioxide (CO_2), methane (CH_4) and Ozone (O_3) [20, p.363] of which CO_2 is only one type of gas classified as a GHG. Therefore, there is some level of misalignment when setting a short term CO_2 specific target alongside a long term GHG target.

It has been suggested that the single most significant policy that the government could introduce is the mandatory requirement for whole-life carbon assessments for buildings, which will then enable the introduction of progressively ratcheting carbon targets for buildings to match the pathway to net-zero [3, p.3]. WLCA's are a proven and widely-supported way to assess GHG potential and transition to a low-carbon built environment [3, p.4].

At a sub-national level, the London Plan 2020 is notable as a local government that maintains requirements beyond national requirements for net zero. The plan, is a spatial development strategy, which sets out an integrated economic, environmental, transport and social framework for the development of London over the next 20-25 year [21]. Regarding sustainable infrastructure, the London Plan's sustainable infrastructure Policy 2 requires the following [21, pp.380-382]:

1. Major development should be net zero-carbon. This means reducing greenhouse gas emissions in operation and minimising both annual and peak energy demand in accordance with the energy hierarchy.
2. Major development proposals should include a detailed energy strategy to demonstrate how the zero-carbon target will be met within the framework of the energy hierarchy.
3. A minimum on-site reduction of at least 35 per cent beyond Building Regulations152 is required for major development. Residential development should achieve 10 per cent, and non-residential development should achieve 15 per cent through energy efficiency measures.
4. Boroughs must establish and administer a carbon offset fund.

5. Major development proposals should calculate and minimise carbon emissions from any other part of the development, including plant or equipment, that are not covered by Building Regulations, i.e. unregulated emissions.
6. Development proposals referable to the Mayor should calculate whole life-cycle carbon emissions through a nationally recognised Whole Life-Cycle Carbon Assessment and demonstrate actions taken to reduce life-cycle carbon emissions.

The London Plan defines net zero-carbon as [21, p.601]:

Activity that causes no net release of carbon dioxide and other greenhouse gas emissions into the atmosphere.

Zero-emission as [21, p.601]:

Activity that causes no release of air pollutants and carbon dioxide or other greenhouse gases.

The London Plan also documents the Mayor of London's recognition that Building Regulations use outdated carbon emission factors [21, p.383].

This section has thus far discussed the Governmental net zero strategy at the national level and sub-national endeavours at the provincial level. Relevant Industrial and Institutional recommendations are discussed in the following Section.

2.3 Industrial and Institutional Recommendations for Net Zero and WLCA

At an industry level, organisations/associations are active in their pursuit of net zero. Part Z is an industry proposed amendment to the 2010 UK Building Regulations, which aims to serve as a proof-of-concept in demonstrating how embodied carbon could be assessed in UK regulations [22]. Part Z recommends that the whole life cycle of the building is to be assessed in accordance with the RICS Professional Standard Whole life carbon assessment for the built environment 2nd edition [5] for all modules except B6 (operational energy) [22, p.4]. Energy usage, regulated and unregulated, should be assessed in accordance with Approved Document L of the Building Regulations 2010, or an energy performance model, and then multiplied by the carbon factors present in the RICS Professional Standard for module B6 [22, p.4].

The RICS Professional Standard aims to provide a 'consistent approach to measuring and reporting carbon throughout the life cycle of a built asset' [5, p.9]. The life cycle stages considered by RICS, is based on the modular structure provided by standards such as; EN 15978, EN 17472, EN 15804, EN 15643, ISO 21931 Parts 1 and 2, and ISO 21930 [5, p.10]. The RICS standards recommend a reference study period (RSP) of 60 years for domestics and non-domestic projects [5, p.42]. Within the RICS domain, the terms, GHG and 'carbon emissions' are used interchangeably. The standard's methodology is named 'whole life carbon emissions', however is explicitly defined as the sum total of related GHG emissions [5, p.7].

Industry based organisations such as 'LETI' have formed to understand and clarify what a zero carbon future means in the built environment and develop actions to achieve UK climate targets [23]. LETI is a voluntary network of 1,000+ built environment professionals and alongside other organisations such as the: BRE, (Chartered Institution of Building Service Engineers) CIBSE, RICS, (Royal Institution of British Architects) RIBA and more, are working in collaboration to develop the Net Zero Carbon Building Standard [23, 24]. At present, again in alignment with the aforementioned organisations and EN 15978: 2011, EN 15804: 2019, LETI recommends WLCA through the modular life cycle structure [25].

Table 2.1 summarises and highlights the alignment and misalignment across governmental, industrial and institutional sources regarding the net zero agenda and WLCA.

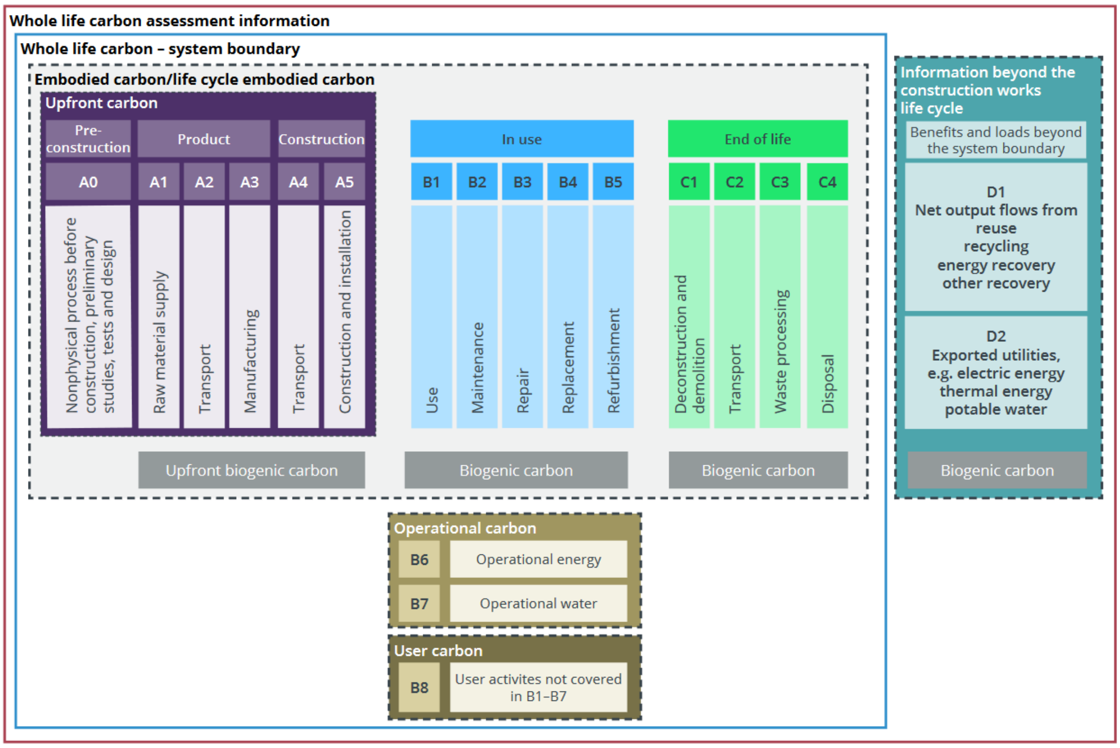


Figure 2.1: RICS' Building and infrastructure life cycle stages and information modules (adapted from EN 15978, EN 17472 and EN 15643) [5, p.19].

Table 2.1: Net Zero Views, Definitions and Considerations by organisation

	Source	**Net Zero Definition**	**Carbon / GHG?**	**Life Cycles?**	**Whole life?**	**RSP**
Net Zero Strategy [1]	Government	GHG as close as zero as possible to zero in 2050	Carbon / GHG	Operational	No	-

Continued on next page

Table 2.1: Net Zero Views, Definitions and Considerations by organisation (Continued)

	Source	**Net Zero Definition**	**Carbon / GHG?**	**Life Cycles?**	**Whole life?**	**RSP**
Environmental Audit Committee [3]	Government	-	Carbon + GHG	Embodied + Operational + End of Life	Yes	-
Part L	Government	-	- / -	Operational	No	per annum
London Plan [21]	Local Government	Zero-carbon activities cause no net release of carbon dioxide or greenhouse gas emissions into the atmosphere	Carbon = GHG	Operational	No	per annum

Continued on next page

Table 2.1: Net Zero Views, Definitions and Considerations by organisation (Continued)

	Source	**Net Zero Definition**	**Carbon / GHG?**	**Life Cycles?**	**Whole life?**	**RSP**
Future Buildings [2]	Government	-	Carbon / GHG (per net zero)	Operational	No	per annum
RICS [5]	Institution	-	Carbon = GHG	Whole life	Yes	60 years
Part Z (RICS + Part L) [22]	Industry	-	Carbon / GHG	Whole life	Yes	60 years
Leti [23] [25]	Industry	Whole Life Carbon emissions are the total of all GHG emissions	Carbon = GHG	Whole life	Yes	60 years

From the analysis presented in Table 2.1, it is apparent that interest in achieving and defining net zero is wide ranging.

Governing bodies generally refer to both carbon and GHG in relation to achieving net zero. However, industry and institutional sources refer to both interchangeably, but refer to the definition for GHG's.

Similarly, all organisations responsible for regulation (government and local government) consider only the operational life stage, which is assessed on a per-annum basis. The industrial and institutional sources consider and include the whole life cycle including end of life stages. The reference study period recommended by sources appealing for whole life assessment is 60 years.

The exception to the trends here are the views of the Environmental Audit Committee, as they are a governmental source that advocates for WLCA, this is not illogical as their advocacy is based on industrial and institutional considerations [3, p.3].

Overall, Table 2.1 indicates that Governmental sources trail those from institutions or industry. The latter sources recommend WLCA, in particular over a period of 60 years, however, it is accepted that the RSP is not an indication of the expected lifespan of the project, but simply a fixed limit to enable comparability between WLCA's for different projects [5, p.42].

2.4 Life Cycle Assessment

Environmental LCA is a well-known and widely used methodology for the calculation of the impacts generated, and the resources consumed by human activities (products, services, processes, policies) across their entire lifecycle. It is regulated by the ISO norms of the 14000 series (14040 to 14075), which outline the general framework for conducting a LCA study without providing specific operational guidelines on how to deal precisely with every decisional context [4].

The advantage of LCA is that, since the method takes a lifecycle-based perspective, it avoids burden shifting, where the improvements brought to a certain phase of the lifecycle can cause the reduction of the impacts caused by that phase but generate an increase of the impacts in a different phase. Moreover, since, when comparing alternatives it is very difficult to have one that dominates the others on every impact criterion, LCA is very useful to perform trade-off analysis.

In the building community LCA is a widely accepted approach [26] and countless studies have been carried out on buildings and building components, from the single building to districts or larger building stocks [27, 28]. When a single building is taken into account, LCA can be used to inform the design of the building in the early stage [29] to influence its construction, as well as in the operational phase, to select the best strategy for building operation [30].

The most commonly used professional LCA software packages include SimaPro [31], openLCA [32], GaBi [33], or Umberto [34]. Advanced use of LCA software through programming is possible using the stand-alone programming framework Brightway2 (BW2) [35], which has been recently enriched with a more user friendly interface called Activity Browser [36]. Regardless of the software package used, an important element in conducting LCA is background data - with good quality data being required - typically practitioners use life cycle inventory databases to access background data, with the ecoinvent database being the largest transparent Life Cycle Inventory (LCI) database worldwide [37]. BW2 is deemed to be the preferred LCA software for application in this research, primarily being a programming framework which better lends itself to automation, and being free and open source, is more transparent which will enable better co-simulation integration [38].

A comprehensive review of different applications of LCA in the building sector and future challenges and research directions in this field is provided by Fnais et al., [39]. Fnais et al., indicate that challenges (and promising research directions) are regarding the potential of BIM integration with LCA in providing more accurate and highly specific data to perform LCA [39, 40, 41]. This allows one to perform (co-)simulations using specific simulation models - to cover different aspects of the building-occupant interaction and integrate their results in the LCA [42]. A co-simulation - an approach that couples different domain models [9] - that can describe the interactions of building sub-systems are introduced and discussed in length in Section 2.8. An example of a co-simulation relevant to the realisation of net zero is the domain coupling of LCA with BES [11].

2.5 Building Energy Simulation

BES has been defined as a physics-based mathematical model which enables calculation of a building's energy performance and occupant thermal comfort, under the influence of various inputs such as; weather, building geometry, internal loads, HVAC systems and operational schedules [43].

The UK Government maintains a list of approved BES software, 'approved' regarding their adherence to the NCM [44]. Approved software programs are disseminated through the Notice of Approval, discussed in Section 2.1.2 in relation to Regulation 24 [44]. Several approved software programs are available, though many of these share the same calculation engine, which include: TAS, ApacheSim, EnergyPlus (E+) and SBEM [44]. Of these tools, only E+ is free and open-source, whilst the remaining tools are proprietary with closed formats. For energy modellers conducting their simulations in E+, a free graphical user interface (GUI) is available; the Open Studio Application [45]. E+ utilises an .idf as its native file format, whilst Open Studio Application utilises a .osm, later translated into a .idf at simulation time.

As in the case of LCA software, the preferred BES software for this research is E+. Like BW2, it is free and with its use of open formats, better lends itself to co-simulation integration.

BES software has been in use since the 1960s [6], however, remain insufficiently integrated into building design processes [46]. The lack of continuous information flow with BIM's, where information in the energy model has to be manually re-inserted, (which is considered labour intensive, therefore time consuming and costly) has led to the recent development of BIM to BES approaches [47, 46, 48].

Geometry creation is considered the most time-consuming task in energy modelling practices, whilst the assignment of key inputs (for example; constructions, internal gains and schedules) has also been indicated as time-consuming [47]. BIM to BES approaches addressing this problem differ in their levels of automation and information integrity, though no studies to date have successfully achieved fully automatic lossless application of BIM to BES.

2.6 Building Information Modelling

Building information model(ling) or BIM, represents buildings in a graphical three-dimensional model, covering information on a building including; geometry, properties, names and the functional peculiarities of components [49]. The construction industry is currently shifting towards BIM, away from traditional 2D drawing based information system [50].

Several papers have used BIM as a basis for BIM to BES and BIM to LCA approaches [51, 52]. The following subsections will explore BIM's role in these building domain models.

2.6.1 BIM based BES

For instance, O'Donnel et al., generated a BES model using the Lawrence Berkeley National Laboratory semi-automated tool [48]. The tool consists of three elements, the Space Boundary Tool (SBT-1), an Internal Load Generation Tool and Simergy for E+. A key limitation in this study was that Industry Foundation Classes (IFC) based exports of building geometry do not include explicit material definitions needed for BES processes [48]. The authors found the following benefits from this semi-automated process [48]; 1. the time and cost required to develop a whole building energy simulation model is reduced, 2. the process enables the ability to generate design alternatives rapidly, 3. the process improves the accuracy of BES, 4. the process outputs building models that exhibit significantly lower energy consumption than those typically produced from the traditional design process.

Of the benefits discussed, 1 and 2 can be generalised as efficiency increases whilst 3 and 4 are technical improvements. Other studies highlight efficiency increases as outcomes of BIM to BES, where the replicability and re-usability of information enables more time to be assigned to performance analysis and design optimisation [50].

Nonetheless, the processing and exchanging of BIM to BES remains a major challenge [47]. Many barriers prevent full integration and data exchange between both models, including geometry errors and missing data, which require human intervention, and so the process is still regarded as time, effort and cost consuming [47]. Elagiry surmises in a review study that the current barriers to full BIM to BES implementation [47] lie within two aspects; 1. IFC generation: is challenging with respect to accuracy, consistency and manual correction and 2. Energy data enrichment: is necessary with respect to; site, geometry, constructions, internal gains, systems, spaces controls, energy costs and renewables.

2.6.2 BIM based LCA

In terms of utilising BIM as a basis for LCA, studies have been advancing this research thread [52].

Santos et al., in 2019 proposed a BIM based LCA/Life Cycle Cost framework, focussing on development of an information delivery and model view definition, the authors conclude that whilst most recent IFC schemes already consider some required information, however, a considerable number of properties are still required for comprehensive

LCA analysis [53]. In the same year, Holberg et al., establish digitisation as having the potential to facilitate environmental performance assessment for buildings. The study suggests BIM quantity take-off tools as a basis for embodied Global Warming Potential (GWP) evaluation, interestingly, the study found that embodied GWP was twice as high in the early design stage as compared to the final building, attributed largely to the designer using placeholder materials [54].

In 2020, Carvalho et al., investigated BIM based LCA and it's relation to building sustainability assessment within the Portuguese context, the main barrier described by the authors regard the availability and disparity between environmental databases [55]. Also in 2020, Naneva et al., concur with previous work by Holberg et al., that digitisation is key to reducing GHG emissions and improving sustainability throughout a building's life cycle. The authors develop an automated BIM based LCA method and highlight the reduction in effort required to apply LCA, thus facilitating the integration of LCA within the design process by minimising both, the quantity of data re-entry and the quantity of software tools that characterize current practices [12].

The work done recently in BIM based LCA indicates that from a technical perspective, the methodology is valid and important to environmental building performance assessment, in particular GHG emission analysis [54]. Studies indicate that digitisation and automation is key to facilitating environmental performance assessment across a building's life cycle and will bring benefits upon implementation, such as reduction in effort, data re-entry and the number of software tools required [54, 12].

2.7 Automated Compliance Checking

The building regulatory compliance domain is a highly complicated process that affects the entire supply chain and often incurs significant costs [10]. This section summarises the current research landscape around ACC.

The first significant piece of work was in 2006 when DesignCheck, a tool for automated code checking, was developed [56]. DesignCheck used IFC models as a bridge between its internal model and third-party Computer-Aided Design tools. In 2007, Boukamp and Akinci conceptualised an approach to automatically extract inspection and quality control requirements from construction specifications, a schema was created for computer-interpretable construction specifications and used to check properties within the BIM [57].

In 2009, Eastman et al. [58], defined two general requirements for a rule checking system: a method to translate natural language statements into logic-based statements and a method to semantically enrich the design model with objects and relations required by the obtained rules. As a step forward beyond other work, the algorithm was benchmarked against the same compliance checking performed manually.

In his 2011 PhD thesis dissertation, Lee presented a new domain-specific programming language, the Building Environment Rule and Analysis (BERA) language, to define, analyse and check rules [59]. BERA was built on top of the Solibri Model Checker framework and embeds an object model that includes building objects and their relationships natively, achieving 'a human-centred abstraction of complex state of building model'. Whilst, Hjelseth and Nisbet, also in 2011, use the RASE concept to capture normative constraints, applying the methodology to extracts from the Norwegian accessibility standard, Dubai building regulation and US court design guidance document [60].

The LicA tool was also proposed in 2013 by Martins et al., a tool that automatically assesses the compliance of a building's water network design with a subset of the Portuguese domestic water systems regulations [61].

In 2014, Chen and Luo developed a BIM-based construction quality framework [62], whose methodology relied on the construction of a checklist database following the product, organisation, and process (POP) data definition structure. Combined with a BIM, the framework constitutes a BIM-based construction quality model where information collected on-site is used to perform quality analysis. In the same year, Cheng and Das presented a web service-based framework for green building code checking and simulation [63], implementing a rule engine, based on checking Green Building XML (gbXML) models. Also in 2014, Choi et al., present their development of an open BIM-based evacuation regulation checking system, specifically validated against the Korean Building Code for high-rise and complex buildings [64].

In 2015, Lee et al. applied the BERA language in automating rule-based checking to accessibility and visibility requirements [65]. Also in 2015, Ciribini et al. presented a BIM-based e-procurement framework [66], which consisted of converting existing tendering texts into computable rules using Solibri Office (following the RASE methodology) and conversion of tendering drawings into a BIM model using Revit. Zhang and El-Gohary used rule-based semantic natural language processing techniques to automate the extraction and the machine-process-able representation of regulatory requirements from the International Building Code [67]. Also in this year, Preidel and Borrmann introduced a semi-automated method for compliance checking using the Visual Code Checking Language (VCCL), demonstrated against German Fire codes [68]. Finally, in 2015, RegBIM [69] was developed as an end-to-end methodology for regulatory compliance, underpinned by using IFC as a data model. The methodology included; (a) regulatory experts applying RASE to regulatory documents [70], (b) BIM experts mapping regulations to IFC data models, (c) a rule-engine performing compliance checking, and (d) a user interface for compliance checking result navigation.

In 2018, Jiang et al. proposed a semi-automated green building evaluation framework based on an ontology that enriches BIM models with the required multidisciplinary data [71]. An ontology has been defined as an explicit specification of a conceptualization, where domain specific knowledge is formally declared alongside the relationships between that knowledge [72].

In 2019, Zhang used open standards to capture requirements in the building industry to automatically check building models [73]. An approach was developed with the ability to query related semantic and geometric information in building models. In the same year, Nawari defined a framework standardising the extraction of regulatory requirements from textual regulations for design review and proposed a modular architecture for the implementation of automated design review [74, 75]. Then, in 2020, Nawari et al. proposed the Generalised Adaptive Framework (GAF). GAF is a process for computerizing regulatory compliance checking based on an object-based representation of building regulations [76]. Using the GAF approach, Messaoudi presented the development of a virtual permitting process for the state of Florida [77]. This work was subsequently further expanded and deployed in the post disaster recovery use case [78]. Sydora and Stroulia presented a domain-specific language for computationally representing building interior design rules only (non-regulation) and a method for evaluating rules in this language against a BIM model [79].

Early work in 2019 by Beach et al., found that current adoption of digitised permitting processes and ACC in the UK is very limited and that all regulatory bodies still require PDF based documentation submissions with no adoption of model-based submissions. Many local authorities use the Planning Portal to manage the compliance submission via a web-based interface, though equally, some local authorities still require the submission of this data on a PDF form. National adoption of ACC in the UK has been conducted through the D-COM Network [80].

2.7.1 Automated Compliance Checking in the UK - D-COM

The D-COM network is led by Cardiff University and was formed to drive forward the adoption of the digitisation of regulations, requirements and compliance checking systems in the built environment. To further increase adoption, show the viability of the automated compliance checking approach, and conduct research into; (a) digitizing and subsequently managing requirements and regulations drawn from a variety of contexts and sources, (b) automatic and semi-automatic compliance systems, (c) underpinning data formats to store and subsequently analyse the result of regulatory compliance checking the D-COM network, together with the Construction Innovation Hub developed a set of prototype software tools, which are openly available on GitHub. These software tools include [81]:

1. A document server capable of serving the UK construction regulations in a machine-readable format with embedded rule data.
2. A rule engine that enables the compilation and execution of these documents in the DROOLS rule language.
3. A results server capable of storing compliance checking results.

The framework developed within Chapter 4 will be augmented to function within the vision for the future of automated regulatory compliance, first described by Beach et al., in 2020, which is reproduced in Figure 2.2 [81].

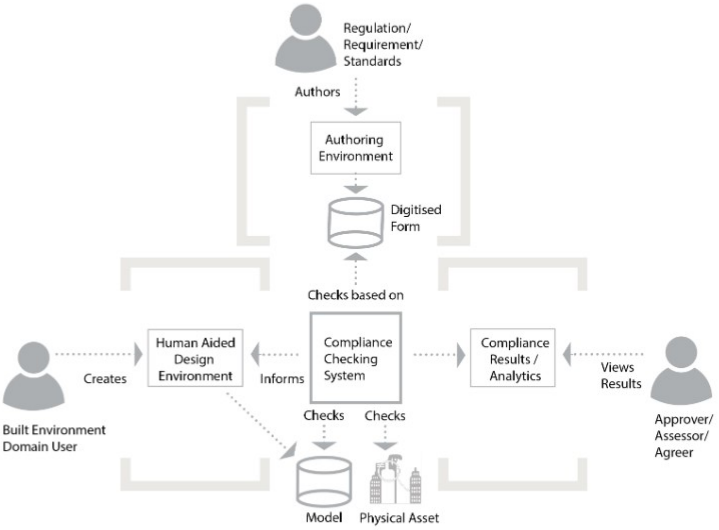


Figure 2.2: Vision for Automated Regulatory Compliance by Beach et al., [81]

In this vision, built environment regulatory authors specify regulations, requirements and standards within an authoring tool, producing digitised regulations. Subsequently, an actor within the built environment domain works on a virtual model of the physical asset, within a human-aided design package. This design package is able to utilise the compliance checking system to automate aspects of design ensuring regulations, requirements and standards are met. The digital model is then submitted to a compliance checking system for approval, by an assessor who is aided by the compliance checking ecosystem [81]. Not all decisions are necessarily automated and the assessor can be seen to be, assisted by the ecosystem as opposed to decisions being made by the ecosystem without human intervention.

The key changes between this vision and the current regulatory processes are [81]:

1. Regulations, requirements and standards being stored in digitised form, from which human readable documents can be generated
2. Compliance checking systems can aid or replace approved regulators in making decisions automatically
3. Compliance checking systems aid regulators by managing the overall checking processes
4. Compliance checking systems are able to check the physical asset in addition to the building model

Further work on this ecosystem in 2023 by Beach et al., defined an ecosystem architecture for such a compliance checking ecosystem [10]. In this work, the ecosystem was defined by a series of micro-services with a clear separation of components, lending itself to a separation of responsibilities. This work further specified a set of compliance checking services to meet current requirements, including an Energy Simulation service corresponding to Approved Document Part L and conceptually envisages a set of services that may be expanded as required [10]. A flowchart illustrating the compliance checking ecosystem is reproduced in Figure 2.3.

Figure 2.3 details the following components [10]:

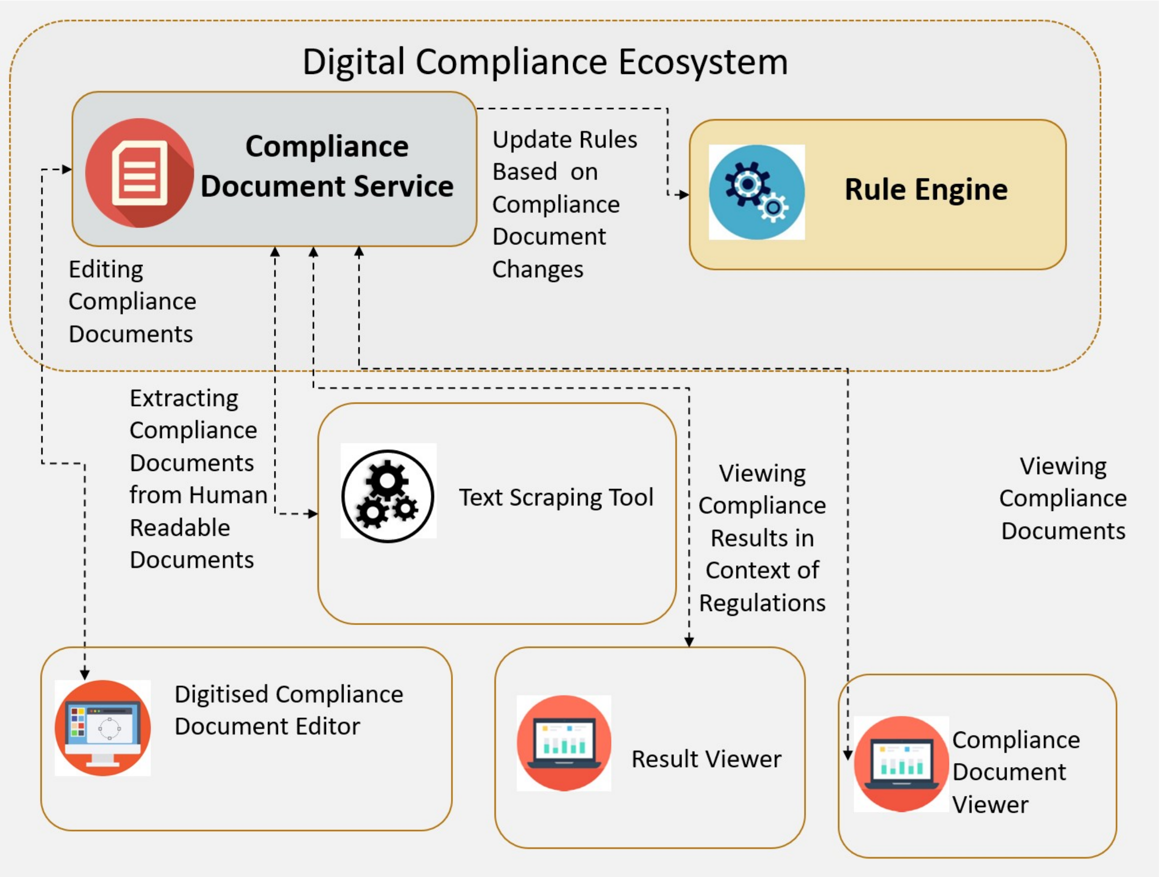


Figure 2.3: Compliance Ecosystem Architecture by Beach et al., [10]

Compliance Document Service: Provides the storage, retrieval, querying, updating, and management of multiple versions of digitised compliance documents. This is the core service required for updating compliance documents and the retrieval and transmission of compliance documents to and from the other components of the ecosystem.

Rule Engine: The rule engine provides a compliance checking engine. Specifically, the rule engine will interface with the compliance document service to retrieve compliance documents (structured following the compliance document schema), then, from the logic embedded within them, it can execute compliance checking.

Text Scraping Tool: This will enable the extraction of a machine-readable compliance document from a human readable document. This represents the first step in the process of creating a compliance document, with later human intervention needed to validate the automatic extraction and add logic.

Digitised Compliance Document Editor: A software client designed to allow the user to create and update digitised compliance documents, their content and embedded logic.

Compliance Document Viewer: A software client that is able to render a digitised compliance document in a human readable form.

Result Viewer: While the overall scope of the result viewer is wider, one important element of its functionality is to be able to display results for an asset in the context of the compliance document that it was checked against.

The digitisation process, illustrated in Figure 2.3, is as follows [10]:

1. Firstly, the original PDF source is scraped, and the text, tables and images are extracted. This is then formulated into a compliance document and transmitted to the compliance document service.
2. A compliance document editor is then used to perform any required editing (in case any text, tables or images are not able to be automatically extracted) and verification of the results of step 1.
3. Finally, logic is embedded into the compliance document using the RASE logical specification (discussed in Section 2.7.3) and the Require1 software as a digitised compliance document editor.

The development of the ACC ecosystem included the digitisation of three regulatory documents, which were [10]:

1. Approved Document L2A: Conservation of fuel and power
2. Approved Document M2: Access to and use of buildings
3. Building Bulletin 100 (BB100): Design for Fire Safety in School

These documents were selected for digitisation based on a compromise between; industry surveys and practical piloting reasons [10].

The research also categorised the types of regulation clauses present within each document, which has been reproduced here, in Table 2.2. The categories were [10]:

1. BIM Data - checks against data stored in a BIM model.
2. Product Data - checks again product data-sheets or data-sets.
3. Colour Contrast - calculation of colour contrast values.
4. Cross-reference - cross-references to other documents.
5. Geometric - compliance checks that require geometric calculation.
6. Energy Simulations - compliance checks that require the results of energy simulations.
7. Other - compliance checks that are; (a) not checkable automatically mainly because assessment criteria are not specified, or (b) are specifically related to on site checks only.

Table 2.2: Regulatory Document Clause Classification [10]

Category	**L2A**	**M2**	**BB100**	**Total**
BIM Data	62	391	398	856
Product Data	13	20	47	80
Colour Contrast	0	26	3	29
Cross-References	1	12	13	26

Continued on next page

Table 2.2: Regulatory Document Clause Classification [10] (Continued)

Category	**L2A**	**M2**	**BB100**	**Total**
BIM Data	62	391	398	856
Geometric	2	244	147	393
Energy Simulation	30	0	0	30
Other	80	96	65	246
Total	193	794	673	1660

The study concludes that it is simply not possible to rely on one computer system to perform all aspects of ACC and that through an ecosystem approach, more actors can contribute expertise in a more collaborative and scalable manner.

2.7.2 D-COM approach to Regulation Digitisation

This Section will firstly discuss general principles for digitisation of regulation documents before introducing the D-COM Open schema. The digitisation approach described here, is later implemented in Chapter 5. The definition given for a digitised Compliance Document is [10]:

A digitised form of a document containing construction industry, regulations, requirements, standards and guidance. A compliance document contains both human readable text, figures/tables, a machine-readable structure and logic to enable automated compliance checking.

An Open Schema is essential in allowing the transmission of construction regulations, recommendations, guidance and standards between different software tools and service [10]. The schema was developed with several key guiding principles:

1. The schema should be open, and thus, should also depend only on other open

standards and not utilise any closed formats.

2. The schema should be flexible enough to allow the embedding of multiple logic formats to cater for the variety of use cases in the built environment.

3. The schema should re-use existing open standards as far as possible to avoid 're-inventing the wheel'. This enables software developers developing tools/services using the schema to leverage existing software libraries. This reduces both development time and costs.

4. The machine-readable format should be seen as the native format of a compliance document, with other formats being generated from it.

5. The machine-readable format should ensure the separation of content and presentation.

The compliance documents are serialised as both XML and JSON formats, which are utilised for the prevalence of software tools and services that support these formats [10]. This Section will now discuss the process of converting human readable documents into machine readable compliance documents.

The structure of the compliance document is presented in Figure 2.4.

2.7.3 RASE Methodology

This section will describe RASE, the logic schema that can be used to embed knowledge within a compliance document. RASE is a formal conceptualisation of knowledge, used to structure new knowledge resources and can be embedded in existing knowledge resources. Knowledge resources include databases, written text, tables and structured vector drawings. Other images and diagrams may need to be interpreted into text if they contain significant content [10].

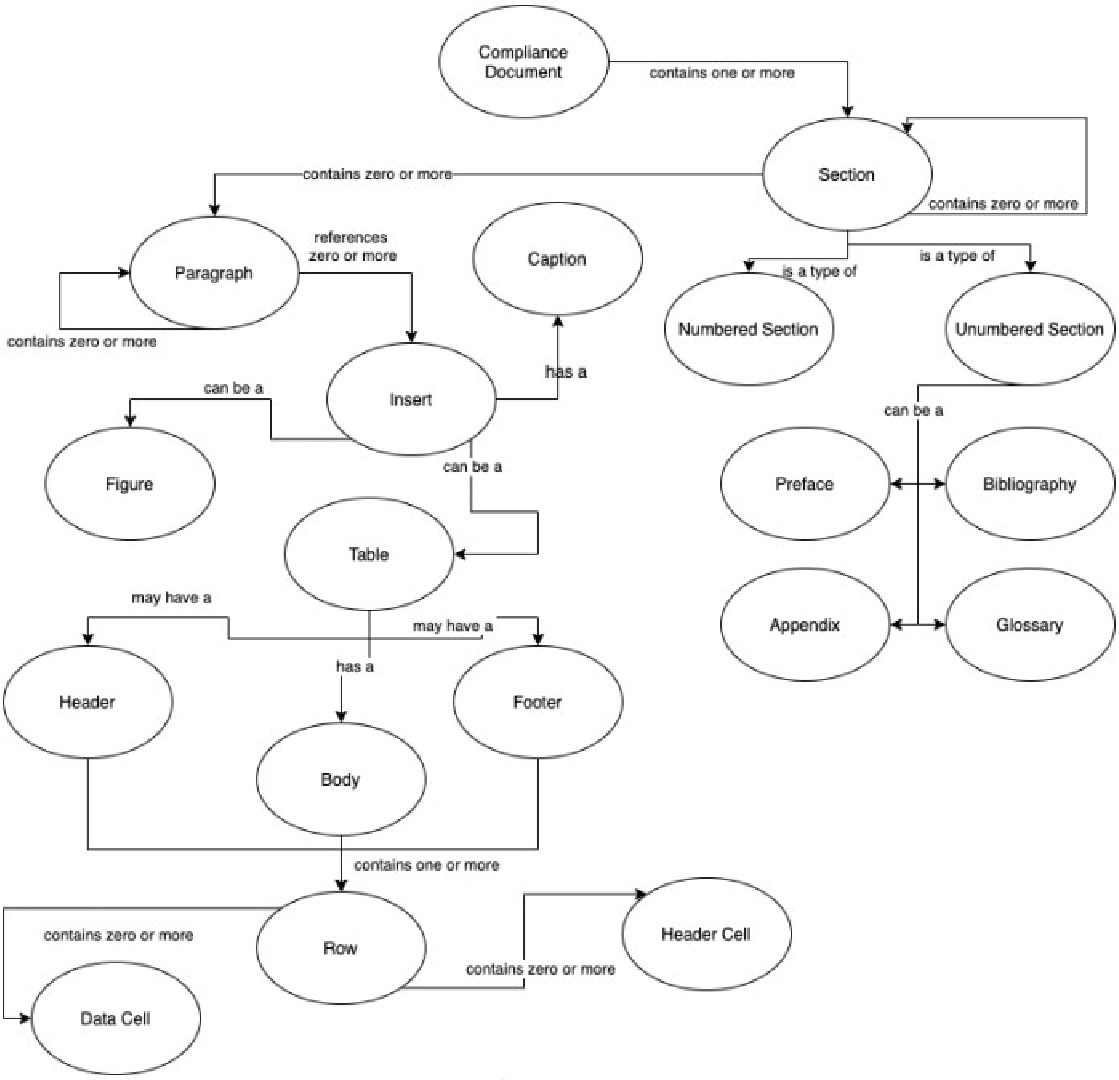


Figure 2.4: Compliance Document Structure [10]

RASE aims to make explicit the logical structure of knowledge as a top-down hierarchy of intermediate objectives and final metrics. Objectives contain other objectives and metrics. Metrics do not, but each must contain a testable concept. Each objective and metric are assigned one of four semantic classifications [10]:

1. Requirement: May be an expectation, definition or assertion.

2. Applicability: Narrows the scope.

3. Selection: Broadens the scope by identifying one of several alternatives.
4. Exception: Eliminates scope.

Metrics embody a testable concept that is potentially true, false or unknown. In addition to its type each rase metric contains four items of metadata [10]:

1. Property: Represents the testable concept described in free text.
2. Comparator: Represents the comparator used to evaluate the concept. This can be any standard comparison operator (>, <, >=, <=, =, and !=) or the term 'is'. If absent = is assumed as default.
3. Target: The value against which the property is compared using the comparator. If absent this is assumed to be true.
4. Unit: The unit of the target variable (i.e., an SI unit).

A logical formula for how these interrelate is shown in Figure 2.5 and an example is shown in Figure 2.6. In this example, highlighted text represent RASE metrics and boxes represent RASE objectives [10].

2.8 Co-simulation

In this Section, the concept of co-simulation is introduced, before the review of co-simulations (coupling specialised domain models) applied to buildings is presented, existing efforts in co-simulation are examined and areas in which this work advances the state of the art are identified.

Co-simulation is applied in different fields, although the communication and information sharing among them has not been efficient so far, as highlighted by Gomes et al. [9], who realised an inter sector survey spanning applications from 2011 to 2016.

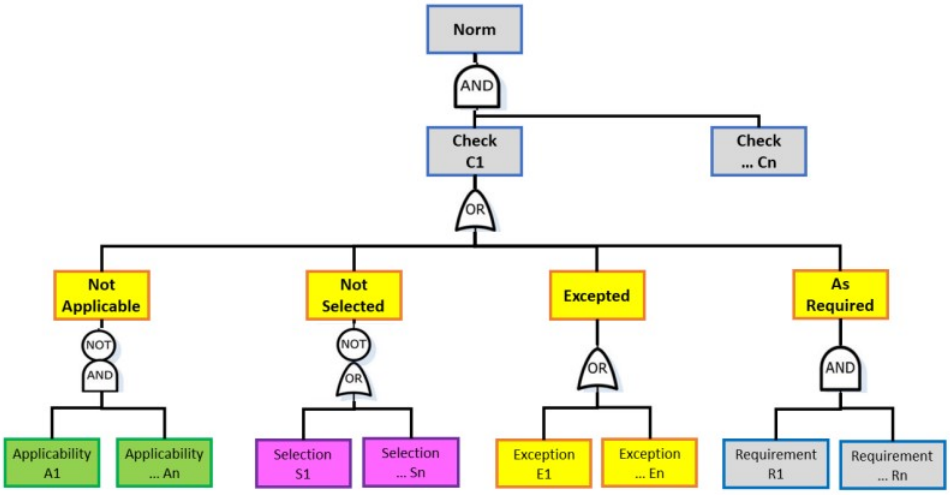
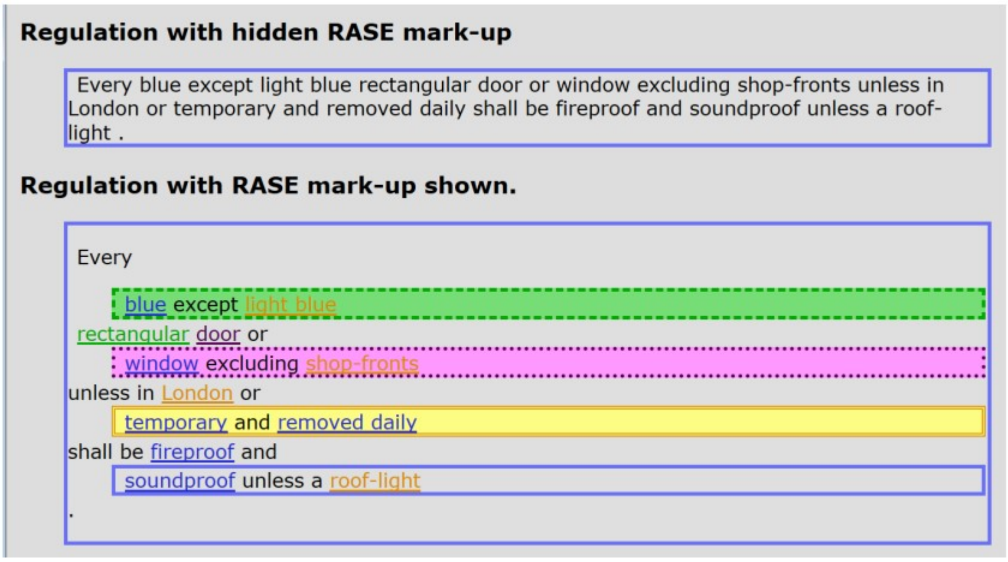


Figure 2.5: RASE Logic [10]


Regulation with hidden RASE mark-up

Every blue except light blue rectangular door or window excluding shop-fronts unless in London or temporary and removed daily shall be fireproof and soundproof unless a roof-light .

Regulation with RASE mark-up shown.

Every
blue except light blue
rectangular door or
window excluding shop-fronts
unless in London or
temporary and removed daily
shall be fireproof and
soundproof unless a roof-light
.

Figure 2.6: RASE Illustrative Example [10]

The fields where co simulation approaches have been found are: Automotive; Electricity Production and Distribution; HVAC, Information and Communication (IC) and system-on-chip (SoC) Design, Maritime, and Robotics [9].

Co-simulation approaches are necessary to achieve innovative and optimal multi disciplinary solutions deriving from the integration of partial solutions developed independently (to cover different aspects of the studied problem) [9]. In fact, in composite simulations where different aspects of the problem must be solved simultaneously, partial solution developed by different specialised single purpose tools are difficult to integrate [82]. Co-simulation has emerged as a solution to these challenges and enables global simulation of a system that integrates various simulators. Each simulator is a black box mock-up of a constituent system and may be managed separately, even by different teams.

According to Trcka [83], the advantages of co-simulation are: (a) the possibilities in the combination of simulation and approaches using tools suited to the sub-system modelled, (b) the ability to achieve rapid testing of software prototypes, (c) the facilitation of work distribution among parallel teams, including the option to retain closed file formats and APIs, and (d) the access to multi-scale simulations which address the interactions between different sub systems (where each are modelled with an appropriate level-of-detail). In building simulation, co-simulation is usually used to couple sub models that exchange simulation data during runtime and describe different aspects of the building envelope and its interaction with occupants (namely, thermal models, airflow models, daylighting models etc.) [82]. An advantage of co-simulation lies in the possibility of coupling occupant behaviour with building performance, it is estimated that occupants' behaviour can be responsible for a high share of the performance gap in buildings, heavily influencing the final energy use [84, 85].

Furthermore, co simulation is the only viable solution when sub-system trade-offs must be evaluated [82]. This is the case, for example, in scenarios that interlink energy performance, user requirements and indoor environmental quality performances. Co-simulation can be used in real time simulations of advanced building envelopes, since many of these systems are characterized by dynamic behaviours [86]. In the building domain, E+ and TRNSYS are the most widely used tools in this category. Recently, machine learning techniques - such as predictive control and deep reinforcement learning linked to parametric generation - have been adopted in this field [87, 88, 89].

Although the interest towards co simulation approaches is growing fast (especially since 2013 [86]), there are still existing hurdles to their systematic application. Taveres-Cachat et al. [82] identifies them as mainly two interrelated issues: standardization gap and a knowledge gap. The former stems from the lack of interoperability between different BES software, mostly since BES tools have different levels of detail and different ways to process inputs. This brings to the tightly related issue of the standardization gap. Co-simulation is currently mostly carried out by experienced BES users, but their application is not widely pursued, due to the lack of accessible shared documentation, the need for strong programming skills and a deep knowledge of the governing laws of the phenomena modelled in BES tools.

In the buildings sector, some existing BES tools are compatible with architectural software and interoperable with BIM, from which inputs can be imported through IFC. Parametric scripting platforms such as Grasshopper in the Rhinoceros 3D modelling environment have become very popular in architecture and offer several opportunities for the integration of loosely coupled co-simulation approaches. In particular, the Ladybug Tools [90] support performance-based designs. Beyond this, Grasshopper allows for structural engineering analysis and optimisation approaches. However, regarding co-simulation, this information could be further integrated into a multi-domain workflow spanning the entire development of a building envelop [82]. In this way, the information processed through co-simulation can be directly linked to costs or GHG emissions from materials and building operational phases [91].

The remainder of this section is structured in sub-sections organised by domain-to-domain classifications. Within each classification, studies are presented chronologically concluding with the latest studies.

2.8.1 Co-simulation of Energy and Climate domains

Since 2017 the first study to couple energy and indoor climate domains was Ferroukhi et al., the authors developed a BES and heat, air and moisture co-simulation approach [92]. Co-simulation was enabled through Matlab and the simulation tools coupled were TRNSYS (a building energy simulation software) and COMSOL (a multiphysics simulation software). The thermophysical properties of walls were analysed and the approach validated by results comparing predicted and measured data. Conversely, the first study to couple building energy and urban climate domains was Morakinyo, in this study, E+ and ENVI-met (a micro-climatological and computational fluid dynamics model) were integrated to study temperature and electricity reduction from green roof configurations in various urban climates and configurations [93].

In 2018, Benzaama et al., developed a co-simulation approach coupling TRNSYS and FLUENT (a computational fluid dynamics software) to simulate both; the temperature of air and surfaces in a space and the dynamic behaviour of indoor air in that space [94]. Also coupling TRNSYS and FLUENT, Shen et al., developed an approach in 2019, coupling building energy and neighbourhood level computational fluid dynamics to assess the impact of external convective heat transfer on building thermal performance, the approach utilised the BCVTB [95]. Lassandro and Turi again used E+ and ENVI-met as an interrelated tool to support decision-making around heat wave mitigation, the tool was applied to the energy retrofit of building and urban area in Bari, Italy [96].

In 2019, Less et al., developed an approach co-simulating energy and ventilation domains, the authors investigated the application of smart ventilation controls on homes in California co-simulating E+ and CONTAM [97]. A similar study was conducted in 2020, O'Neill et al., investigated the energy and ventilation performance of a C02 based demand-controlled ventilation system. This study used the FMI to co-simulate E+ and CONTAM (an indoor air quality and ventilation software), with the study finding that the control strategy achieved 'good' compliance against ASHRAE Standard 62.1 [98]. Underhill et al., also conducted a E+ and CONTAM co-simulation to quantify health and energy costs, again in relation to energy retrofit in a midrise multi family building [99], the authors found that weatherization retrofits reduced energy consumption and outdoor emissions, though without ventilation/filtration, particulate matter concentrations were increased indoors.

Zhang and Gao investigated the effects of floor area ratio, surface area ratio and mean sky view factor of eight generic residential districts in 2021 using a E+ and ENVI-met co-simulation [100]. The study concluded that both the ratio factors were negatively correlated with heating and cooling loads, whilst the mean sky view factor was positively correlated. Abuseif et al., also used E+ and ENVI-met to study the effect of green roof configurations on indoor and outdoor temperatures alongside cooling demand, this study found that green roof performance had a greater performance on indoor temperature than outdoor [101].

Lou et al., coupled E+ with Radiance (a ray tracing, lighting simulation software) to study energy and daylight performance for air-conditioned atriums [102]. Results from Radiance were imported into E+ for evaluation, finding that for hot and humid climates, skylight coverage ratio must be controlled to avoid overheating.

In 2022, Kharbouch et al., used a co-simulation approach to evaluate the performance of an earth-to-air heat exchanger [103], the heat exchanger was modelled in Matlab and the BCVTB was used to exchange information with E+. The authors were able to validate the use of an earth-to-air heat exchanger through sensors installed in the building. Whilst the classification of domains in this study are debatable, the co-simulation can be said to couple energy and heat transfer and evaluates the performance of a building sub-system not representable within a single domain software tool. Another instance of this can be seen in Zhang et al., where the authors have coupled a dynamic heat transfer model with E+ to evaluate vertical green facades [104].

2.8.2 Co-simulation of Energy and Occupant; Behaviour and Health domains

In 2017, Chen et al., developed an occupant behaviour and energy co-simulation and visualisation approach - coupling Occupant Simulator, obFMU and E+ to estimate the mutual effect between occupant behaviour and energy performance in buildings, beyond this the authors developed AnyLogic, a visualisation module enabling the communication of occupant behaviour energy effect with stakeholders [105]. With conceptual similarities but technical differences, in 2020, Yi developed another visualised co-simulation approach, considering adaptive human behaviour and dynamic building performance [106], in this approach, co-simulation was achieved through the BCVTB, interfacing E+ and Radiance, coupled with an agent-based model to describe occupant behaviour, visualisation was implemented through Grasshopper. In another study that pushed the state of the art one step forwards, Jia et al., coupled E+ with an agent-based model for occupant behaviour in a study comparing building performance with actual occupant behaviour information against a multi-based model. The study found that the agent-based model reported lower energy-consumption and may be used to plan or encourage energy conservation measures [107].

Mokhtari and Jahangir in 2020 presented the first study to couple building energy and human health domains, investigating the effect of building occupants on energy consumption and COVID-2019 infection [108]. Matlab was used as a communicator, whilst E+ provides energy consumption values and the infection of COVID-2019 is solved by a NSGA-II algorithm. The study concluded with findings of up to 56% reduction in infection and 32% reduction in energy consumption when an optimal population distribution was found. William et al., made a step forward in this area of work in 2022, developing a BES and computational fluid dynamics model to assess the reconfiguration of indoor spaces in response to COVID-2019, the study found that underfloor air distribution systems reduced the likelihood of infection and transmission [109].

2.8.3 Co-simulation of Energy and Acoustics domains

Ferrara et al., were the first (and only) authors to couple energy and acoustic domains in 2021, this study developed an approach that coupled sound insulation performance, energy performance and cost optimisation [110]. The approach was applied to the design of comfort-driven, nearly zero energy single family buildings, addressing the low sound insulation performance of traditional cost-optimised nearly zero energy buildings.

2.8.4 Co-simulation of Energy and Environmental Life Cycle domains

Cellura et al., authored the first (and only) study since 2017 coupling energy and the environmental life cycle domains, here, the authors developed a LCA tool applied to TRNSYS building models capable of performing LCA studies. The tool was validated against a case study simulation of a residential house in Italy [11]. Cellura et al., states that, when it comes to the integration of fully-fledged LCA with BES, studies are lacking and in most cases the components are used as distinct methodological approaches, not including the co-simulation of different tools or development of innovative instruments. In fact, they surmise that enhancing the potential to couple different domain models to effectively describe the interaction between different sections and parts of the building is key for the advancement in building related research. Based on this insight, this research seeks to integrate and co-simulate 'fully fledged' domain models.

2.9 Conclusion

This Chapter has described a picture of the UK regulatory landscape and has introduced the concept of the net zero strategy which focusses on two key targets; net zero GHG emissions by 2050 and a 68% reduction in carbon emissions by 2030. The UK regulatory landscape is highly complex and devolved, with 18 overarching Approved Documents providing guidance for how compliance can be prescriptively achieved. Approved Document Part L is the key document with relevancy to net zero, however, at present is provisioned only to assess operating carbon emissions which are calculated with simplified factors based on energy usage.

This is problematic, as the net zero vision sets targets for GHG emissions not only CO_2. Table 2.1 summarises the interest in defining and achieving net zero, from both; governmental, institutional and industrial sources. Whilst this interest evidences the engagement and consensus of net zero importance from key organisational bodies in construction, there is disparity among these sources regarding definitions and the extent of assessments.

In general, governmental sources refer to both carbon and GHG's in relation to net zero, whilst institutional and industrial sources equate the two in reference to GHG's (Table 2.1). Similarly, only the operational life stage (assessed on a per-annum basis) is considered by governmental sources, whilst, institutional and industrial sources recommend assessment of embodied and end of life stages in addition (assessed over an RSP of 60 years) (Table 2.1). Overall, Table 2.1 indicates that governmental sources are focussed on operational net zero, however trail institutions or industry in their commitment to whole life carbon or whole life cycle assessment. Governmental sources are not in total alignment either, with the London Plan critical of the use of simplified factors, applied at the national level [21, p.383].

Well-supported methodologies for measuring environmental impact and GHG emissions do exist - namely LCA - however, only one study has attempted to integrate BES and LCA. No work has attempted this co-simulation integration in a dynamic manner, much less considered how such a co-simulation methodology can be implemented within the context of a national regulatory system, nor how technologies such as BIM and ACC can technically deliver the net zero vision. Institutional and industrial sources share consensus on the structure of the LCA to be applied to whole life cycle/carbon assessments, which is the modular structure prescribed by EN 15978 [5, 22, 25].

This Chapter now concludes by summarising the clear research gaps identified within this Chapter that fall within scope of the Thesis (Section 1.3):

1. Net Zero targets have been established by the UK Government, however there is no clear methodology for how this can be achieved for buildings [3, p.3], nor is there consensus with institutions and industry on the life cycles that should be assessed.
2. Calculation methodologies for LCA and WLCA exist, however there is no technical methodology/architecture integrating this with BES in a co-simulation necessary to design and regulate for progressively ratcheting emission targets [11]
3. No work exists that has enabled such a WLCA and BES co-simulation through BIM and ACC.

Chapter 3

Research Methodology

This Chapter will present the research methodology applied to this Thesis. Initially, this Chapter will introduce, in Section 3.1, concepts relevant to the genesis of a research methodology and its overarching study. Concepts are introduced in Section 3.1 through the ’Research Onion’ by Saunders et al., which serves as a solid foundation for discussion around research methods [111, p.130]. Relevant research methodology concepts with domain specificity are introduced in Section 3.2.

Secondarily, this Chapter will then propose the hypothesis and research questions derived from the research gap identified in Section 2.9 in Section 3.3. Thirdly, the concepts presented in Section 3.1 are applied and discussed with regards to the specifics of this research in Section 3.4. Finally, this Chapter will then illustrate in detail the research methodology applied in this thesis and the underlying choices made to develop the overarching methodology in Section 3.5.

3.1 Research Onion

The ’Research Onion’ - as depicted by Saunders et al. [111, p.130] - illustrates the underlying issues surrounding the choice of data collection techniques and analysis procedures applied in research and is presented in Figure 3.1. The research onion is well accepted and with over 60,000 citations, forms a solid foundation for discussion on research philosophies and approaches, and so, for the research methodologies applied in this thesis, the research onion formed an initial starting point for discussion. Though aimed at business students, the research onion draws its theoretical base from a mixture of social, natural and applied sciences [111, p.132] and whilst being on its eighth edition, provides a holistic and up-to-date perspective on general research methodologies. Saunders et al. describe that each layer of the onion is important and that each layer describes a choice made whilst traversing through each layer to the central point. The following sections will describe and illustrate this traversal process through the layers of the research onion, beginning with the outer layer (philosophy) and concluding this Section in the centre of the research onion, in which techniques and procedures for data collection and analysis are discussed.

The following sections discuss at length the theoretical perspective, whilst the specific decisions made are described and elaborated in Section 3.5

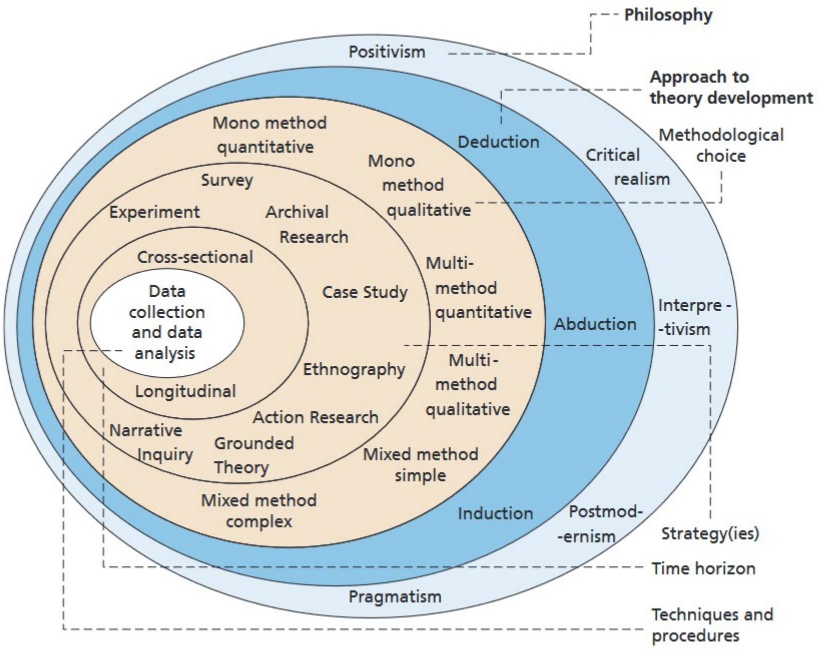


Figure 3.1: Research Onion, as illustrated by Saunders et al. [111, p.130]

3.1.1 Research Philosophy

The term research philosophy relates to the development and nature of knowledge, the philosophy adopted can be interpreted as the assumptions in a given world-view [111, p.130]. A given research philosophy is not better nor worse than another, but simply more appropriate to achieving a given task depending on the perspective.

As a pre-cursor to discussion on individual research philosophies, one must consider the philosophical assumptions made by researchers in their work. Within the boundaries of the research onion as described in Figure 3.1, there are three sets of assumptions used to distinguish individual research philosophies, namely ontological, epistemological and axiological.

Though traditionally viewed in competition with one another, recent trends suggest it is appropriate to apply research philosophies as a multi-dimensional set of continua rather than a singular stance applied to all research elements [111, p.134]. Where this is the case, one would be considered to be applying a philosophy of Pragmatism, where for a specific aim, the underlying research questions are individually addressed with the most appropriate philosophical stance. Saunders et al., purport that pragmatists recognise there are many ways to interpret the world (and research) and therefore, multiple realities [111, p.151].

Ontological philosophical assumptions concern themselves with the nature of reality, i.e. what is and how it is [111, p.133]. Epistemological assumptions however, are concerned with the nature of knowledge, how we know what we know and what is considered acceptable knowledge [111, p.133]. Finally, axiological assumptions are concerned with the role of values and ethics within research [111, p.134]. In previous editions, Saunders et al., distinguish individual research philosophies as falling within these three trains of thought, however, in the most recent edition (illustrating the increasing; trend of pragmatism and value within a set of multi-dimensional continua), individual research philosophy can be described as extremes of one another, with ontological, epistemological and axiological perspectives within themselves.

Two such research philosophies that embody diametric extremes are Objectivism and Subjectivism. With the key difference being found in the view in which the nature of thing itself is considered, for example, when considering the environmental impact associated with given product, an objectivist view would say the impact is something the product has, whilst a subjectivist view would consider that the overall impact is made up of the impacts of each of the components of the product over various life stages. Whilst most comparisons on ontological philosophies are described in terms of social sciences, a scientific example has been described here for relevancy to the Thesis topic. From an ontological perspective, objectivism concerns itself with what is real and true, whilst subjectivism considers what is nominal and accepts multiple realities [111, p.135]. From an epistemological perspective, objectivism considers facts, numbers and observable phenomena, whilst on the other hand, subjectivism considers that which are thought to be opinions, recorded accounts and attributed meanings [111, p.135]. From the axiological perspective, objectivist research is value free, whereas subjectivist research would be considered value bound [111, p.135].

Within the boundaries of the research onion, five major individual philosophies are considered, Positivism, (Critical) Realism, Interpretivism, Postmodernism and Pragmatism (which has already been defined).

Positivist research considers data on observable realities and identifies generalised relationships within that data. Saunders et al., describe a key aspect of positivist research, that the emphasis is on quantifiable observations that lead to statistical analysis [111, p.147].

Similarly, Critical Realism is based within scientific approaches and observable realities, however, does not aim to generalise relationships within the observed reality. The focus in this philosophy is to effectively describe and understand the reality at hand.

In contrast, an Interpretivist approach concerns itself with not the view on reality, but the perspective of a given entity. Saunders et al., emphasise the importance of the viewpoints of social actors, as they themselves create or derive meaning and describe that Interpretivist researchers must understand and empathise with research subjects [111, p.149]. In stark contrast with Positivism, generalised relationships are considered to reduce the complexity of human insight [111, p.149].

Developed more recently, Postmodernism research seeks to question accepted ways of thinking and gives voice to marginalised views [111, p.149]. Postmodernist views go beyond those of the Interpretivist, viewing any form of order as provisional, brought about only through language and its tendency to classify and categorise [111, p.150]. A key aspect of postmodernism is the recognition that power relations between the researcher and subject shape the knowledge created as part of the research process [111, p.150].

3.1.2 Research Approaches

The research onion (Figure 3.1) details three approaches to theory development; deduction, abduction and induction. Similarly to philosophies, the approaches described have an extremist element, with deduction and induction being contrasts of one another.

Deductive reasoning occurs where a conclusion is logically derived from a set of theory-driven premises, with the conclusion being true when each of the premises are true [111, p.152].

On the other hand, inductive reasoning occurs when there is some separation between premises and the conclusion, here the conclusion is determined to be true as supported by some observations made on the premises, but without guarantees [111, p.152].

With abductive reasoning, a conclusion is observed and then a set of possible premises is determined that sufficiently explains the observed conclusion, the term 'plausible theory' is key in this approach [111, p.155].

3.1.3 Methodological Choice

Methodological choices described within the Research Onion (Figure 3.1) include; mono methods, multi-methods and mixed methods, though within each type of choice there exists, further, more granular decisions to be made. Methodological choices form the first of three layers that focus on the process of research design, which is the general plan that dictates how each research question is answered [111, p.175].

The first choice to be made concerns whether the research design is to be quantitative, qualitative or one following a mixed method. Quantitative and qualitative research are generally distinguished by the type of data collected [111, p.175], in that quantitative data is numerically based, whilst conversely qualitative data is non-numeric, for example, free text responses to a given survey. Often, research is conducted with a mix of quantitative and qualitative data, qualitative data may even be analysed quantitatively [111, p.175], and so, again quantitative and qualitative research can be viewed as extremes of one another.

In research that considers only one choice for one given dataset, it may be termed "mono". Singular research may be designated as mono method quantitative or mono method qualitative. Broader research utilising multiple forms of data collection may be termed multi-method, and similarly may be multi-method quantitative or multi-method qualitative, where the different data types are utilised independently. Where methods are mixed within the same data, this is considered to be a mixed method study.

3.1.4 Strategy

A research strategy may be defined as a plan for how a researcher will answer a given research question [111, p.189]. Within the boundaries of the research onion, presented in Figure 3.1, research may be conducted as an: experiment, survey, archival research, case study, ethnography, action research, grounded theory and a narrative inquiry.

Experiments are grounded within the natural sciences and laboratory-based research, where the effects of an independent variable on a dependent variable is analysed based on a hypothesis assuming some relationship between the two [111, p.190].

Survey strategies are implemented in research where data collection from a populous is required. Questionnaires are often utilised and is perceived as largely authoritative [111, p.193].

Archival research leans heavily on digitised secondary sources, of which there is a large range, including; communications, records and documents [111, p.195]. These may originate publicly or privately and from individuals, businesses, organisations or governments.

A case study presents an inquiry into a particular topic, set within its true setting [111, p.196]. Innumerable topics may be the "case" and the "study" will seek to understand the dynamics of the case (or topic) being studied [111, p.196]. A distinguishing factor of a case study is the real life context in which the topic is set [111, p.196].

Ethnography is a strategy which is implemented to study the culture of a group, where the written accounts of people or groups are considered [111, p.199].

Action research is an emergent and iterative process of inquiry, where the goal is to develop a solution to a given real world problem [111, p.201].

Grounded theory refers to a theory that is developed inductively from data and was developed as a process to analyse, interpret and understand the meanings that social actors construct to make sense of experiences in certain situations [111, p.205].

Finally, a narrative inquiry is implemented where the preservation of chronology and sequencing within participant responses is important in aiding understanding and analysis [111, p.209].

3.1.5 Time Horizon

This layer of the research onion presented in Figure 3.1, considers only two types of studies, cross-sectional and longitudinal.

Most studies are likely to be cross-sectional, where a particular phenomenon is studied at a particular time [111, p.212].

Conversely, on the opposing extreme, longitudinal studies considers a particular phenomenon (or phenomena) over a period of time [111, p.212].

3.2 Additional Research Methods

The Research Onion, introduced in the previous Section, provides a solid foundation for discussion around research methodologies, with its theoretical mix drawing from social, natural and applied sciences [111, p.132]. However, of the research gaps (identified in Chapter 2), 2 and 3 refer specifically to (co-)simulations, and more specifically, BES simulations and LCA. Building energy research involving simulations are highly domain specific and so general research methodologies may not suffice in describing the research conducted in this Thesis. For this reason, architectural and building energy research methods are discussed in this Section, the discussion draws from the methods consolidated by Groat and Wang [112] and Azari and Rashed-Ali [113].

Published in 2013, Architectural Research Methods is intended as a comprehensive entry point to architectural research, the authors identify seven strategies applied to architectural research [112]:

1. Historical Research [112, p.173]
2. Qualitative Research [112, p.215]
3. Correlational Research [112, p.263]

4. Experimental and Quasi-Experimental Research [112, p.313]
5. Simulation Research [112, p.349]
6. Logical Argumentation [112, p.379]
7. Case Studies and Combined Strategies [112, p.415]

Research Methods in Building Science and Technology extends the discussion in relation to building energy performance, from the seven strategies identified by Groat and Wang, Azari and Rashed-Ali highlight three as offering potential for building and energy, performance research [113, p.53]:

1. Experimental and Quasi-Experimental Research
2. Simulation Research
3. Case Studies and Combined Strategies

Experimental and Case Study strategies have been introduced in the previous Section through the Research Onion and so, only Simulation Research is discussed here in this Section.

Simulation Research is ubiquitous and within Western ideas, extend back to Plato, who warned of the deceptive nature of copies of reality and Aristotle who perceived value in the ability to experience how something could be [112, p.349]. Aristotle's perspective indicates the key strength of simulation research, to be able to experience a 'representation', without undergoing the dangers of the real things they represent [112, p.349].

Citing architectural drawings as an example, Groat and Wang define 'representation' as [112, pp.356-357]:

A fixed image that stands for a real object because the image has measurable qualities that describe and depict the real thing

A simulation takes place when, *data from various scenario inputs can be generated from representations* [112, p.357].

A model is *the overall system that simulates the reality being studied* [112, p.357].

Furthermore, Groat and Wang describe simulation research in contrast to classical experiments, in which a key limitation is the isolation of real-world variables in order to study casual relationships, simulations however, aim to replicate in a holistic manner all the relevant variables in a setting or phenomenon [112, p.360].

Azari and Rashed-Ali provide an explicit definition of Simulation Research [113, pp.53-54]:

Simulation and Modelling Research replicates real-world conditions in either a physical or digital environment, Simulation Research is distinguished from Modelling (or Representation) Research by the replication and collection of dynamic interactions for application into the real-world context.

This Section has discussed additional Research Methods beyond the Research Onion. Though a good basis for discussion, the strategies presented within the Research Onion lack suitability with regards to Research 2 and 3, due to their simulation dependant nature, and so, the Simulation Research Strategy has been introduced here.

3.3 Hypothesis and Research Questions

This Section will present the hypothesis and research questions established as part of this research. This Section begins with a recap of the clear research gaps (within the scope of this Thesis) identified in Section 2.9, which are:

1. Net Zero targets have been established by the UK Government, however there is no clear methodology for how this can be achieved for buildings [3, p.3]., nor is there consensus with institutions and industry on the life cycles that should be assessed.

2. Calculation methodologies for LCA and WLCA exist, however there is no technical methodology/architecture integrating this with BES in a co-simulation necessary to design and regulate for progressively ratcheting emission targets [11]

3. No work exists that has enabled such a WLCA and BES co-simulation through BIM and ACC.

To do this, the following hypothesis will be tested:

The integration of BIM, ACC and (BES and LCA) co-simulation within a digital, design and regulatory building framework will provide a pathway to net zero buildings and whole life carbon assessment that aligns governmental strategy with industry and institutional recommendations.

In order to test the hypothesis, the following research questions will be investigated:

1. What are the requirements in the UK regulatory landscape in terms of net zero and how can they be aligned with recommendations for WLCA to deliver GHG assessment of UK buildings?

2. What are the current accepted approaches for ACC within the UK regulatory building sector?

3. How would a BES and LCA co-simulation architecture be integrated into the wider UK building design and regulatory framework, to enable net zero and WLCA with regards to: (a) building design processes and (b) building regulatory processes

3.4 Methodological Choices

This Section serves to describe and document the concepts presented in Section 3.1 as applied within the contexts of this research. In order to simplify the discussion around the methodological process, this Section presents Table 3.1 summarising the choices made through each stage of the traversal process through the research onion. A flow chart illustrating the overarching thesis methodology is presented in Subsection 3.5, though a holistic view incorporating the Thesis methodology and methodological choices is available to view in Appendix C.

This Section will now describe the decisions and discussions captured within Table 3.1. Initially, a global view will be discussed before addressing at a more granular level the specific research perspectives of each research question in the following subsections.

Table 3.1: Research Questions and their Associated Research Strategy

	RQ1	**RQ2**	**RQ3**
Philosophy: Overarching Pragmatist View	Critical Realism	Critical Realism	Critical Realism with Postmodernist Aspects
Approach	Deductive	Deductive	Deductive
Choice	Qualitative	Qualitative	Quantitative and Qualitative
Strategy	Archival Research	Archival Research	Simulation Research
Time Horizon	Cross-Sectional	Cross-Sectional	Cross-Sectional

The research underpinning this Thesis has applied an overarching research philosophy of Pragmatism, as no single philosophical stance has been selected to address all research questions. The aim of this research will be achieved by addressing each research question with the most appropriate philosophical stance, as dictated by the nature of the question itself.

This Thesis follows a deductive research approach as a hypothesis has been described, which provide the theory-driven premises that a conclusion will be derived from. This element will not be replicated in the following subsections.

Qualitative methods will be applied in Research Questions 1 and 2, whilst Research Question 3 is a mixed method study as qualitative and quantitative data is mixed in the same study/dataset, this element is discussed specifically with respect to each research question in the following subsections, alongside discussion around strategy and time-horizon.

3.4.1 Research Question 1

Research Question 1 concerns itself with what the current requirements, within the UK regulatory landscape, are in relation to net zero and WLCA. It is also concerned with the relevant recommendations made by institutions and industry in the building sector, and in this sense, this question is seeking only to understand what the observable reality is, in this instance the UK regulatory landscape, encompassing governmental, institutional and industrial sources.

As this question is only concerned with describing and understanding the UK regulatory landscape in terms of BES and LCA and not seeking to generalise relationships, it can be described as following a philosophy of Critical Realism.

Research Questions 1 is dependent on secondary sources of information (in particular governmental) and so the data collected here will be qualitative in nature, following a strategy of Archival Research. This question is concerned with what is currently is - a snapshot of the present - and so should be considered a cross-sectional study in terms of time horizons.

Research Question 1 will be addressed by the definition of a framework encapsulating the design and regulatory aspects of GHG assessment through BES and LCA co-simulation, current requirements and recommendations will be discussed and the uplifts necessary to align recommendations with requirements are proposed alongside the framework.

3.4.2 Research Question 2

Research Question 2 concerns itself with describing and understanding what the current level of ACC within the UK regulatory building sector and so, follows a philosophy of Critical Realism.

Research Questions 2 is dependent on secondary sources of information (especially governmental and academic) and so the data collected here will be qualitative in nature, following a strategy of Archival Research. This question is concerned with what is current and proposed - a snapshot of the present - and so should be considered a cross-sectional study in terms of time horizons.

Research Question 2 will be addressed by the augmentation of the framework (using principles elicited from current accepted approaches to ACC), alongside the digitisation of necessary requirements (both existing and proposed by this Thesis).

3.4.3 Research Question 3

Research Question 3 is concerned with describing and understanding how a BES and LCA co-simulation methodology would be integrated into the wider UK building design and regulatory framework to enable net zero and WLCA. This Research Question is greater in complexity than Research Question 1 and 2, however is dependent on them for input.

There are multiple elements within this question, and in order to describe the methodological choices, this question has been decomposed into more granular work or validation elements, which are:

1. **Work Element**: Development of a BES and LCA co-simulation methodology

2. **Work Element**: Integration of the developed BES and LCA co-simulation methodology within the defined framework as a proof-of-concept
3. **Validation Element**: Validation of the proof-of-concept, by demonstrating the benefits arising from the **Design** aspects of the proposed framework when compared against existing processes
4. **Validation Element**: Validation of the proof-of-concept, by demonstrating the **Regulatory** aspects of the proof-of-concept and comparing existing requirements against those proposed in this work
5. **Validation Element** Reflection and evaluation of the proof-of-concept, focussing on the role automation and digitisation as enablers

Taking input from Research Questions 1 and 2, the requirements and recommendations surrounding net zero and WLCA and the current accepted approaches for ACC will directly feed into the definition of both current design and regulatory processes and the definition of a new digitised framework to enable net zero and WLCA and development of a new BES and LCA co-simulation methodology.

This question fundamentally seeks to describe and understand the potential impact of this digital framework and so, the framework, it's underpinning co-simulation, models and results, provide the observable reality, and in this sense follows a philosophy of Critical Realism.

However, this question also seeks to re-evaluate accepted ways of thinking (current UK building design and regulatory processes) and explore how they can be adapted to provision GHG emission assessment, taking into account industry and institutional recommendations, which when considering governmental national requirements as accepted views, are marginal. In both these aspects, this Research Question contains Postmodernist traits. In essence, these aspects question the status quo of current processes.

This question will involve development of a proof-of-concept implementation, used to co-simulate two BIMs.

Research Question 3, concerns not only the dynamic interactions within energy simulation, but co-simulation with LCA, and so simulation (as opposed to modelling) research is particularly applicable.

The methodological choice for this question is both Quantitative and Qualitative as the data collected from (co-)simulations is in most instances quantitative in nature, however, this question will also document findings and reflections from 'experiencing' the proof-of-concept implementation, and so, qualitative data is collected aswell.

With regards to time horizons, this Question compares a snapshot of the present with a snapshot of a potential future in which the proof-of-concept Framework is implemented and so is a cross-sectional comparison, whilst there are elements of dynamacity and time dimensioning in (co-)simulation, it lacks the nature of a study conducted over an extended period of real-world time to be considered a longitudinal study.

Research Question 3 will be addressed using simulation research to implement and analyse the proof-of-concept BES and LCA co-simulation integrated into the developed design and regulatory framework. This is achieved when the design and regulatory aspects of the implementation has been demonstrated and evaluated. The evaluation will be based on a reflection on whether a pathway aligning government requirements and industry and institutional recommendations is possible, the implications and outcomes of implementation and future research necessary to implement this research in the real-world context.

3.5 Research Methodology Implementation

This section presents and describes the overarching Research Methodology applied to this research. The methodological flowchart illustrating this process is presented in

Figure 3.2.

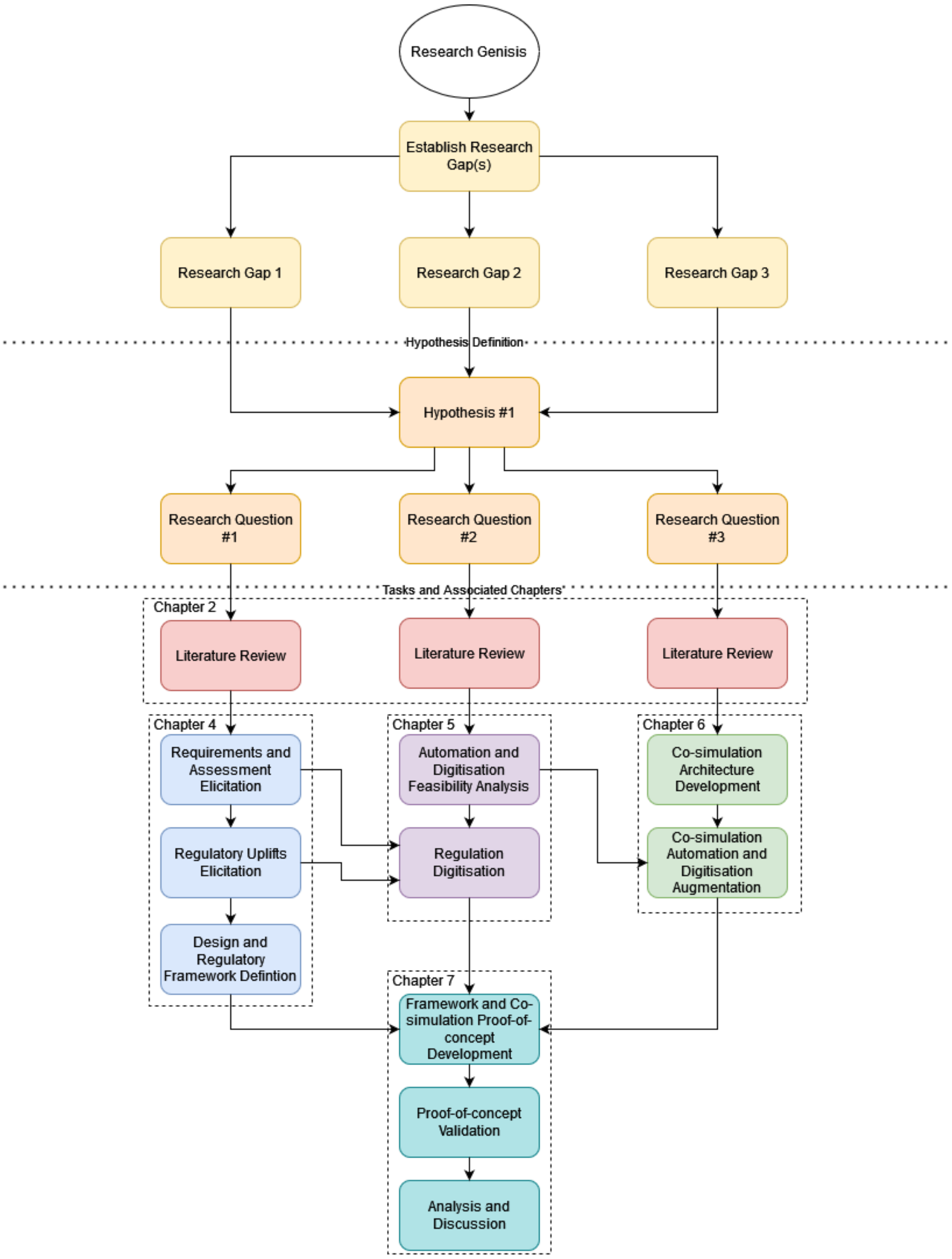


Figure 3.2: Research Methodology Flowchart

As a starting point, research gaps have been established in Section 2.9. A hypothesis was established, to address research gaps 1, 2 and 3 (Section 3.3).

This section will now discuss the Tasks illustrated in Figure 3.2, as separated by

Chapter.

The first element of which is the **Literature Review**, providing the knowledge base that will feed into all remaining tasks. Specifically, the **Literature Review** will provide the background information and state-of-the-art innovations required to address Research Questions 1, 2 and 3.

The **Requirements and Assessment Elicitation** task, will identify current and proposed requirements surrounding net zero and WLCA for buildings. It will also identify the recommendations being made from relevant institutional bodies and industry. This task will build on the key requirements and recommendations identified in the **Literature Review** and summarise and analyse to feed into the remaining tasks.

The **Regulatory Uplift Elicitation** task will take input from the **Requirements and Assessment Elicitation** task and establish the necessary regulatory uplifts that will enable net zero and whole life cycle assessment within current regulatory processes. This task will inform the **Design and Regulatory Framework Definition** and **Automation and Digitisation Feasibility Analysis** tasks.

Analysis will be presented to describe and understand the UK landscape in relation to requirements and recommendations surrounding net zero and WLCA, which will culminate in the development of regulatory uplifts aligning governmental requirements and institutional and industry recommendations. A framework will be developed in the following task to describe and facilitate the proposed uplifts.

The **Design and Regulatory Framework Definition** task will detail the definition of the wider design and regulatory framework enabling a pathway towards net zero GHG emission design and assessment. This task builds on the requirements and necessary uplifts elicited from the previous two tasks and will feed into the **Regulation Digitisation** and **Framework and Co-simulation Integration** task.

The framework proposed will address the *how?* element of Research Question 1, with the regulatory uplifts proposed, aligning the requirements and recommendations surrounding net zero and WLCA.

The **Automation and Digitisation Feasibility Analysis** will establish how automation and digitisation can enable the framework defined in the **Design and Regulatory Framework Definition** task and explore the applicability and feasibility of current accepted approaches for ACC in the UK regulatory building sector.

Regulation Digitisation encompasses the digitisation process for the key regulatory document, Approved Document Part L and will feed into the **Framework and Co-simulation Integration** task.

Co-simulation Architecture Development documents the development the BES and LCA co-simulation architecture, which will provide the methodology for which design and regulation of GHG emissions will be underpinned by.

This methodology will be augmented through the **Co-simulation Automation and Digitisation Augmentation** task which will apply the findings from the **Automation and Digitisation Feasibility Analysis** task that serves to address Research Question 2.

The **Framework and Co-simulation Proof-of-concept Development** task will integrate; the wider design and regulatory framework defined in the **Design and Regulatory Framework Definition** task and the BES and LCA co-simulation architecture developed from the **Co-simulation Architecture Development** and **Co-simulation Automation and Digitisation Augmentation** tasks as a proof-of-concept. The proof-of-concept forms the basis for validation of Research Question 3.

The **Proof-of-concept Validation** task seeks to validate the individual validation elements of Research Question 3 which are:

1. Validation of the proof-of-concept, demonstrating the **Design** aspects of the Framework
2. Validation of the proof-of-concept, demonstrating the **Regulatory** aspects of the Framework

The **Design** aspects of the framework are demonstrated against a BIM model of a University building during the early design phase. Three co-simulation scenarios are applied to illustrate typical design usage of energy performance simulation work/research. The BIM and simulation scenarios are conducted in two manners, firstly, per current processes and practices and secondly, per the proposed digital framework.

The **Regulatory** aspects of the framework are demonstrated against an exemplar BIM model of an office building, ready for compliance checking. The BIM is assessed under two regulatory paradigms; firstly, that of current regulations and secondly, that of the regulations and uplifts proposed in this Thesis.

Finally, the **Analysis and Discussion** task reflects upon the proof-of-concept implementation of the **Design** and **Regulatory** aspects and discusses the analysis of the results and findings.

Both aspects are conducted through a strategy of Simulation Research which will contrast the proposed against the existing (or current) which forms the key basis for analysis and reflection. The correctness of the representation of the proposed will be discussed in relation to the representation of the current. Benefits and pitfalls of the proposed will be discussed, alongside an evaluation of the role of automation and digitisation in enabling the framework.

The analysis and discussion of the proof-of-concept co-simulation will seek to answer the final Research Question and the hypothesis. Ultimately, discussion around whether Research Question 3 is addressed will reflect upon; whether a pathway aligning government strategy and industry and institutional recommendations is indeed possible and the potential implications, the role of BIM and ACC in enabling GHG emission assessment and, future research that may be conducted to implement the proof-of-concept in the real-world.

3.6 Conclusion

This Chapter has introduced and described concepts relevant to the genesis of a research methodology and documented those concepts as applied to the contexts of this Thesis. This Chapter has also established, hypothesis, research questions and tasks, designed to address the research gaps identified in Section 2.9. The remaining Chapters in this Thesis will now in turn document the work done in answering each research question and hypothesis.

Chapter 4

Definition of a Net Zero and WLCA Design and Regulatory Framework

This Chapter serves to define the wider framework, encapsulating, regulatory authors, assessors and designers.

This Chapter further seeks to address Research Question 1, which is:

What are the requirements in the UK regulatory landscape in terms of net zero and how can they be aligned with recommendations for WLCA to deliver GHG assessment of UK buildings across the whole life cycle?

This Chapter builds from Table 2.1 and elaborates further in relation to the motivations to extend Approved Document Part L to include mandatory WLCA. Secondly, Section 4.2 will consolidate all the current and proposed, requirements that have the potential to facilitate net zero and WLCA. This Chapter will then take these requirements as input to establish how current requirements may facilitate the assessment of GHG emissions in Section 4.3, which will described uplifts to current regulations that enable GHG assessment, whilst aligning with recommendations from industry and institution. Finally, Section 4.4 will define the wider, design and regulatory framework that will facilitate this assessment. The developed framework and regulatory uplifts in unison will address Research Question 1, where, the framework addresses the *how?* and the uplifts address the alignment of governmental requirements and industry and institutional recommendations surrounding net zero and WLCA.

4.1 Motivation to include LCA and Co-simulation as an addendum to Part L

As described in Chapter 2, the UK construction regulations are complex and highly devolved [10]. The government maintains Approved Documents which provide methods for demonstrating compliance with the Building Act and Regulations [10]. This Thesis focusses solely on Approved Document Part L, which concerns the Conservation of Fuel Power and is the key document in providing compliance with respect to energy and emissions. Non-domestic buildings are considered due to their increased complexity allowing for a richer basis for this work.

Net Zero Strategy: Build Back Greener, is the policy paper that describes the UK governments strategy for net zero. The strategy aims to set out policies and proposals for decarbonising all sectors of the UK economy to meet net zero targets by 2050 [1]. When answering the question of, what is net zero?, the strategy states that emissions of GHG will be 'net zero' in 2050 when emissions are to be reduced to as close as zero as possible, with the remaining emissions absorbed by new technologies [1, p.14].

Though the term emissions is not clearly and explicitly defined, policies set forth in this document include oil and gas supplies halving its operational emissions by 2030. The strategy is littered with policies and plans for operational green house gas emissions, however no such specific policies are described for embodied carbon and more specifically, GHG emissions accrued in the construction phase of buildings.

This focus only on operational emissions has been criticised by the Environmental Audit Committee, who have indicated that the lack of policy on assessing or controlling embodied carbon has led to no progress on reducing these emissions in the built environment [3, p.3]. The committee summarises that the single most significant policy that the government could introduce is the mandatory requirement for whole-life carbon assessments for buildings, which will then enable the introduction of progressively ratcheting carbon targets for buildings to match the pathway to net-zero [3, p.3].

WLCA are a proven and widely-supported way to transition to a low-carbon built environment [3, p.4].

Net zero 2050 is already set out in targets [1, p.10], however policies and targets are loosely defined and do not meet industry demands for WLCA [3, p.3]. The following sections will elicit requirements necessary to enable both net zero and WLCA of GHG emissions within current processes.

4.2 Requirements and Assessment Identification

This Section will identify current and proposed requirements with the potential to facilitate net zero and WLCA and in doing so, answer Research Question 1.

This Section builds upon the literature review conducted in Chapter 2 and (as discussed in Section 4.1) is concerned only with non-domestic buildings and focusses solely on Approved Document Part L: Conservation of Fuel Power, which is the key document in providing compliance with respect to the energy efficiency of buildings [13]. A summary of the regulations presented in Part L is available in Section 2.1.2. This Section will discuss in detail performance based requirements that have the potential to facilitate GHG emission assessment in new buildings other than dwellings.

Regulations 24, 25A, 27, 40, 40A and 43 are conceptually administrative tasks, requiring evidencing of some analysis or proof of implementation, whilst regulations 6, 22, 23 and 28 are relevant only to existing buildings. Requirements L1 and L2 put in place limiting standards and specifications.

Regulations 25, 25B, 26 and 26C are the only performance based requirements that can facilitate the assessment of GHG emissions in new buildings other than dwellings. These regulations are as follows [7]:

Regulation 25: Requires the Secretary of State to approve minimum energy performance requirements. These requirements are in the form of a target primary energy rate

(TPER) and a target emission rate (TER) [7, p.8].

In essence, this regulation establishes the TPER and TER as the minimum energy performance requirements for new buildings other than dwellings.

Regulation 25B: The Secretary of State considers that a building has a very high performance rate for the purposes of the definition of a nearly zero-energy building if both of the following are met [7, p.8].

1. The building meets the TER required under regulation 26.
2. Both:
    (a) An analysis is made of the technical, environmental and economic feasibility of using high efficiency alternative systems, which include decentralised energy supply systems based on energy from renewable sources.
    (b) This analysis is considered as required by regulation 25A.

The first element of this regulation is the quantitative performance based check, requiring that the building emission rate (BER) meet the TER. The second element is a largely a qualitative evidencing exercise. This requirement is covered by a checkbox in the BRUKL document, and so the remaining work in this Thesis focusses on the performance based element of this requirement.

Regulations 26 and 26C: A newly constructed building must be shown to meet regulations 26 and 26C by producing calculations to show that the building meets both of the following [7, p.8].

1. TPER.
2. TER.

This requirement simply requires that the calculations that derive the performance based requirement checks in Regulations 25 and 25B are evidenced and documented.

To summarise, the key performance based checks that form the focus of these works is **Regulation 25**, which sets the TER and TPER as the minimum performance requirement.

Clause 2.3 of Part L provides the guidance and requirements related to this regulation: *'building primary energy rate (BPER) and building emission rate (BER) must not exceed the target primary energy rate TPER and the target emission rate TER'* [7, p.10].

Approved Documents are updated as and when deemed necessary, for example, Part L has been existence (in various forms) since 2010, with separate editions and amendments being made in; 2011, 2013, 2016, 2018, 2021 and most recently 2023 [16]. However, the Future Buildings Standard (currently in development) is envisaged to replace Part L in 2025, it seeks to deliver highly efficient non-domestic buildings which use low-carbon heat, ensuring they are better for the environment and fit for the future [2, p.4]. The scope of the proposed standard is to ensure that future standards are ambitious enough to put us on the right track to meet net zero GHG emissions by 2050 [2, p.4].

Most recently, the consultation period for the Future Buildings Standard began in January 2021 and concluded by publishing interim uplifts to Part L in a Summary of Responses document in December 2021 [2]. The consultation included a high level vision for what the Future Buildings Standard could be and the steps required to implement it, elements of which were interim uplifts to Part L in 2021 [2]. Full technical consultation is expected to begin in 2023 [2].

At present the interim uplifts from the Summary of Responses have been enacted in Part L 2021. The edition discussed at length in Chapter 2 is a further amendment made in 2023, therefore, with no planned amendments or new editions until the Future Buildings Standard is released in 2025, Part L 2023 is the key document that presents requirements related to energy and emissions and will be until 2025 [2].

Therefore, the discussion around Part L 2023 (presented in Chapter 2), provides an up-to-date account of the current and proposed requirements in terms of net zero and WLCA. A summation of which, is presented in Table 4.1.

This table illustrates several elements, firstly the 2016 and 2023 editions are included to detail the change in regulations that are applicable since Part L1 and L2 were consolidated into a single Part L document. Secondly, the pertaining regulations are indicated in the first column, and their applicability to each version of Part L indicated in the respective columns. The final column, indicates the potential of the regulation to facilitate GHG emission assessment, in order to be determined as indicating potential, the regulation must be performance based and measure a relevant metric for energy or emissions. For example, as in the case of Regulation 26, it currently assesses CO_2, and so it has the ability to be broadened to assess GHG.

Regulations are broadly classified as several requirement types in Table 4.1, Applicability Definitions give guidance as to what requirements apply in a particular situation. A Calculation Methodology requires that a particular calculation follows a certain methodology. A Performance Based requirement is a metric that ensures compliance by meeting a particular value. An Administrative or Evidencing requirement necessitates that certain compliance protocols be followed with regards to the application. Finally, a Limit on Application, places limiting standards for a particular element in the building.

Table 4.1: Assessment of Part L Regulations

Regulation	**Requirement Type**	**Part L2A 2016**	**Part L 2023**	**Potential for GHG**
Regulation 6	Applicability Definition		Applicable	
Regulation 22	Applicability Definition		Applicable	

Continued on next page

Table 4.1: Assessment of Part L Regulations (Continued)

Regulation	Requirement Type	Part L2A 2016	Part L 2023	Potential for GHG
Regulation 23	Applicability Definition		Applicable	
Regulation 24	Calculation methodology	Applicable	Applicable	
Regulation 25	Limits on application	Applicable	Applicable	
Regulation 25A	Calculation methodology	Applicable	Applicable	
Regulation 25B	Calculation methodology	Applicable	Applicable	
Regulation 25C	Calculation methodology		Applicable	
Regulation 26	Performance based emission	Applicable	Applicable	Yes
Regulation 26C	Performance based energy		Applicable	Yes
Regulation 27	Administrative or evidencing	Applicable	Applicable	
Regulation 27C	Administrative or evidencing		Applicable	
Regulation 28	Limits on application		Applicable	

Continued on next page

Table 4.1: Assessment of Part L Regulations (Continued)

Regulation	**Requirement Type**	**Part L2A 2016**	**Part L 2023**	**Potential for GHG**
Regulation 35	Calculation methodology	Applicable		
Regulation 40	Administrative or evidencing	Applicable	Applicable	
Regulation 43	On-site	Applicable	Applicable	
Regulation 44	Commissioning	Applicable	Applicable	
Schedule 1	Limits on application	Applicable	Applicable	

Table 4.2 consolidates these regulations and indicates the relevant Clauses with respect to both the 2016 and 2023 editions of Part L.

Table 4.2: Relevant Clauses for Performance Based Requirements

Regulation	**Part L2A 2016**	**Part L 2023**
Regulation 26	Clause 2.7	Clause 2.3
Regulation 26C	n/a	Clause 2.3

These Tables have shown, the only performance based requirement with the potential to facilitate GHG emission assessment is given in Clause 2.3 of Part L. Again, Clause 2.3 of Part L provides the requirement that the:

’BPER and BER must not exceed the TPER and the TER’ [7, p.10].

Whilst Clause 2.3 provides requirements that capture both the primary energy rate (Regulation 26C) and emission rate (Regulation 26), the emission rate is the most suitable metric as it currently assesses CO_2 emissions, and so it has the ability to be broadened to assess GHG emissions. This Clause is currently in effect and there are no expected changes until 2025.

The consultations for the Future Buildings Standard have not indicated in any way that GHG emissions will be covered in 2025 [2]. Which is important as it gives longevity to the applicability of this work. Furthermore, this lack of indication, further strengthens the need for this research, with the lack of consideration demonstrating the clear need for this research.

This Section has identified the key performance based requirement with the potential to facilitate GHG emission assessment, the following section will investigate how this requirement may be best adapted to facilitate GHG emission assessment and in doing so, enable a pathway to net zero and WLCA.

4.3 Regulatory Uplifts Elicitation

This Section investigates the gap between the requirement identified in the previous Section (Clause 3.2) and the net zero targets and WLCA. It will establish the necessary regulatory uplifts that will enable net zero and WLCA within current regulatory processes. The uplifts, together with the framework defined in the following section, will address Research Question 1.

Uplift 1: The net zero strategy, is targetting net zero GHG emissions by 2050 and a 68 percent reduction in CO_2 by 2030 [1, p.10].. Whilst, emission rate calculations at present consider only CO_2 emissions, with the other GHG's being ignored [7, p.84]. In order to align current requirements to the net zero strategy, this requirement should be extended to include emissions from other non-carbon GHG's. To achieve this, the unit rate should be adjusted from $kgCO_2$/m2 to $kgCO_{2eq}$/m2. This would extend the metric to capture GHG emissions as LCA has the capability to report GHG's as equivalenced to CO_2.

Uplift 2: The UK Governments net zero strategy considers only the operational life cycle stage [3, p.3]. In order to extend the current assessment processes to include a whole life cycle view, this study will consider the inclusion of emissions accrued in the construction stage of buildings. This inclusion will enable a pathway to the assessment of WLCA, which the industry is demanding in net zero consultations and responses [3, p.4]. This uplift will necessitate a new metric for assessment, which this work proposes to be the Target Construction Cost (TCC) vs the Building Construction Cost (BCC). These proposed metrics are discussed in the following paragraphs.

This Thesis presents the following definition for the new assessment metric:

Construction Cost: The (building's or target's) environmental impact due to construction, measured in $kgCO_{2eq}/m^2$.annum, determined using the approved methodology.

The new proposed metrics are envisaged to be an extension of the notional building approved methodology concept from which the existing performance targets (TER and TPER) are defined. The concept of the notional building was introduced in Section 2.1.2 and is a fundamental building block in the assessment of buildings under Part L.

The notional building derives a limiting benchmark for the performance of the real building (in terms of energy and CO_2), and so this work proposes that the notional building be also used as a benchmark for the environmental cost of construction of the real building. Therefore, as well as being used to demonstrate current requirements for operating emissions, the notional building should remain as an exemplar to how construction emissions can be assessed. In the proposed Construction Cost metric, the materials making up the notional building fabric will be assessed against those in the actual building. Inline with recommendations from institutions and industry, a 60-year life span/RSP is utilised for comparison [5, p.42].

In summary, the uplifts required to enable net zero and WLCA GHG emission assessment within current regulatory processes are:

For enabling the net zero strategy:

1. **Uplift 1**: The TER and BER metrics should be adjusted from a unit rate of $kgCO_2/m^2$ to $kgCO_{2eq}/m^2$, in doing so, this requirement will assess all GHG emissions and not only CO_2. The uplifted metric test should be termed the Building Greenhouse Gas Emission Rate (BGGER) vs Target Greenhouse Gas Emission Rate (TGGER) metric test.

For enabling WLCA:

1. **Uplift 2**: A new metric test should be introduced, the TCC ($kgCO_{2eq}/m^2$) vs BCC ($kgCO_{2eq}/m^2$.annum) metric test, to assess the embodied carbon cost from construction.

Whilst these uplifts are presented respectively, in relation to the net zero strategy and WLCA, it should be noted that the uplifts that apply to the net zero strategy also apply to WLCA, i.e. Uplift 2 requires Uplift 1 to be in place.

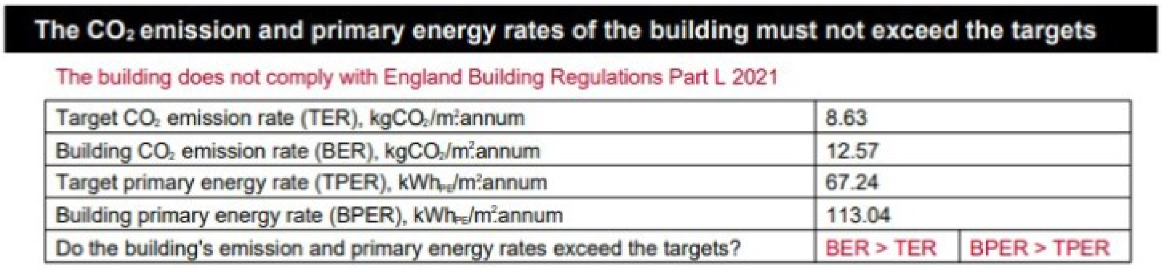
Both of these uplifts may be encapsulated in an extension to Clause 2.3, which is:

'BPER and BER must not exceed the TPER and the TER' [7, p.10].

The new, extended Clause should state:

'BPER, BGGER and BCC must not exceed the TPER, TGGER and TCC'.

An adapted BRUKL document could cover this change, from the old document presented in Figure 4.1 to the proposed section in Figure 4.2.

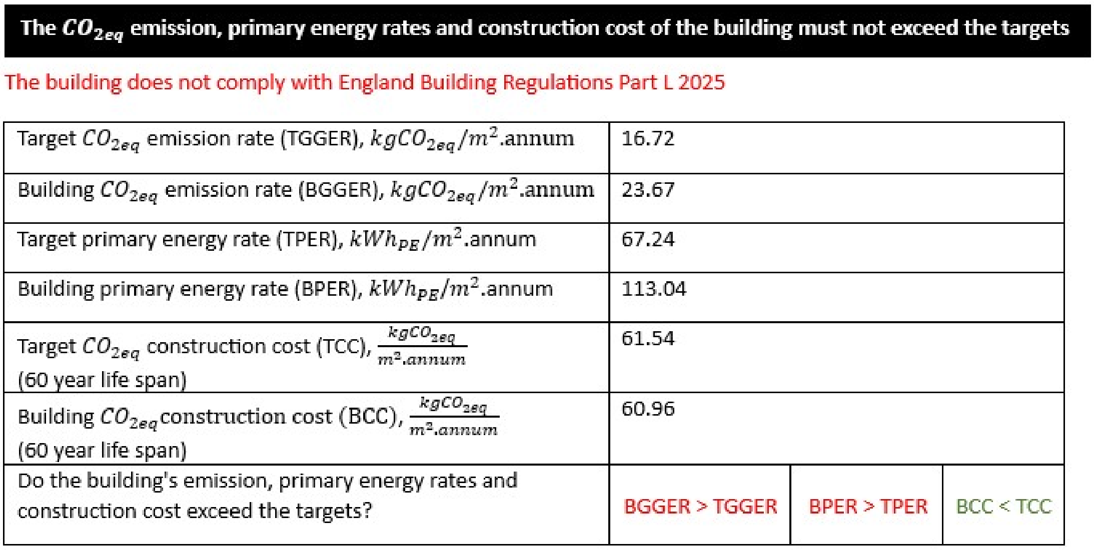


The CO_2 emission and primary energy rates of the building must not exceed the targets

The building does not comply with England Building Regulations Part L 2021

Target CO_2 emission rate (TER), $kgCO_2/m^2$annum	8.63	
Building CO_2 emission rate (BER), $kgCO_2/m^2$annum	12.57	
Target primary energy rate (TPER), kWh_{PE}/m^2annum	67.24	
Building primary energy rate (BPER), kWh_{PE}/m^2annum	113.04	
Do the building's emission and primary energy rates exceed the targets?	BER > TER	BPER > TPER

Figure 4.1: Current BRUKL targets section



The CO_{2eq} emission, primary energy rates and construction cost of the building must not exceed the targets

The building does not comply with England Building Regulations Part L 2025

Target CO_{2eq} emission rate (TGGER), $kgCO_{2eq}/m^2$.annum	16.72		
Building CO_{2eq} emission rate (BGGER), $kgCO_{2eq}/m^2$.annum	23.67		
Target primary energy rate (TPER), kWh_{PE}/m^2.annum	67.24		
Building primary energy rate (BPER), kWh_{PE}/m^2.annum	113.04		
Target CO_{2eq} construction cost (TCC), $\frac{kgCO_{2eq}}{m^2.annum}$ (60 year life span)	61.54		
Building CO_{2eq}construction cost (BCC), $\frac{kgCO_{2eq}}{m^2.annum}$ (60 year life span)	60.96		
Do the building's emission, primary energy rates and construction cost exceed the targets?	BGGER > TGGER	BPER > TPER	BCC < TCC

Figure 4.2: Proposed BRUKL targets section

This section has analysed in depth the current and proposed regulations and requirements relevant to energy and emissions, it has identified that the key and only requirement with the potential to facilitate GHG emission assessment and thus enable a pathway to net zero and WLCA is Clause 2.3. As the present regulations and requirements will apply until 2025, and with no indication of what the Future Buildings Standard will look like, this Thesis has identified the uplifts required to enable GHG emission assessment.

The following Sections will define the wider design and regulatory framework and discuss how current regulations and the uplifts proposed in this Section may be assessed for compliance.

4.4 Design and Regulatory Framework Definition

This Section will detail the definition of the wider, design and regulatory framework enabling a pathway towards net zero GHG emission design and assessment. The framework proposed will address the *how?* element of Research Question 1, with the uplifts elicited in the previous section aligning net zero requirements with WLCA recommendations.

This Section builds on the requirements and necessary uplifts elicited from the previous two sections. The framework developed in this Section will integrate LCA into a holistic view of building design and regulatory processes.

The wider, designer and regulatory framework, will encapsulate the following domain actors: regulatory authors, assessors and designers. Within the framework, authors may dictate regulations which assessors check buildings against and which designers design to. The following sections will describe the development of the framework.

4.4.1 Current process

In order to describe the process changes required to implement the two uplifts elicited, the current processes within design and regulation of buildings will be described. Figure 4.3 illustrates the high level processes which the building domain actors engage with. In this figure, green elements denominate general processes, whilst orange elements refer specifically to processes relating to compliance with Part L. The following paragraphs discuss the processes captured within Figure 4.3 from the perspectives of each building domain actor, which help provide the contexts of this research.

Regulatory Authors: Establish high level regulations (Building Act 1984 and Building Regulations 2010) and prescribe methods to achieve compliance, in the form of Approved Documents [7].

Assessors: Check PDF submissions of building designs and make a decision as to whether they are in compliance with current regulations.

Designers: May author a BIM, capturing a digital 3D model of a building design. At a high level, the BIM is used to generate PDF floor plans which are submitted for compliance checking. For the designer that specialises in BES, they must recreate the

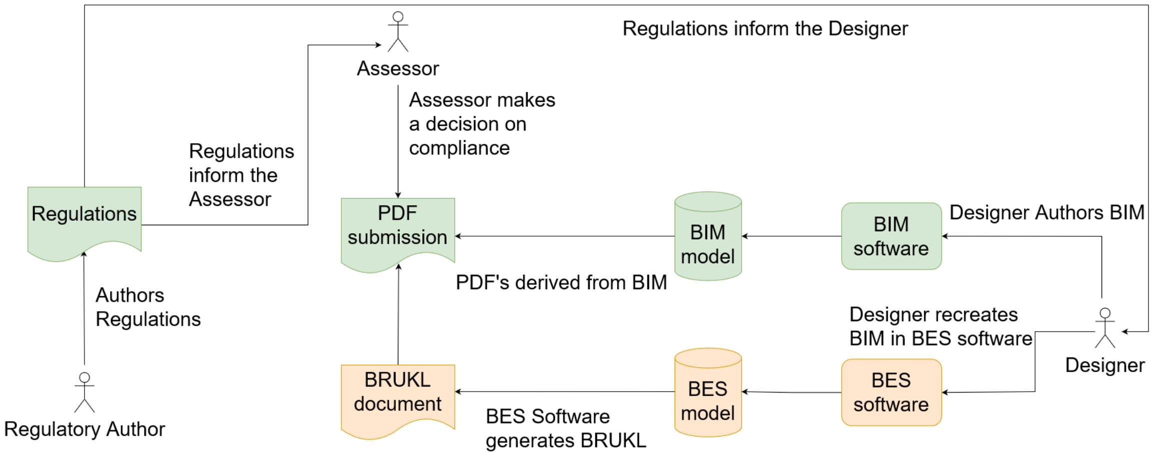


Figure 4.3: Current High Level Design and Regulatory Process for Buildings (green), with Part L specific processes (orange).

BIM in an appropriate SBEM software and then generate a PDF BRUKL document to be included in the PDF submission.

4.4.2 A Framework to enable LCA within existing processes as a pathway to net zero and WLCA

Figure 4.4 illustrates the developed framework which will facilitate net zero and WLCA through a BES and LCA co-simulation integration. Here, elements which are proposed by this Thesis and not yet applied within design and regulatory processes are represented in purple.

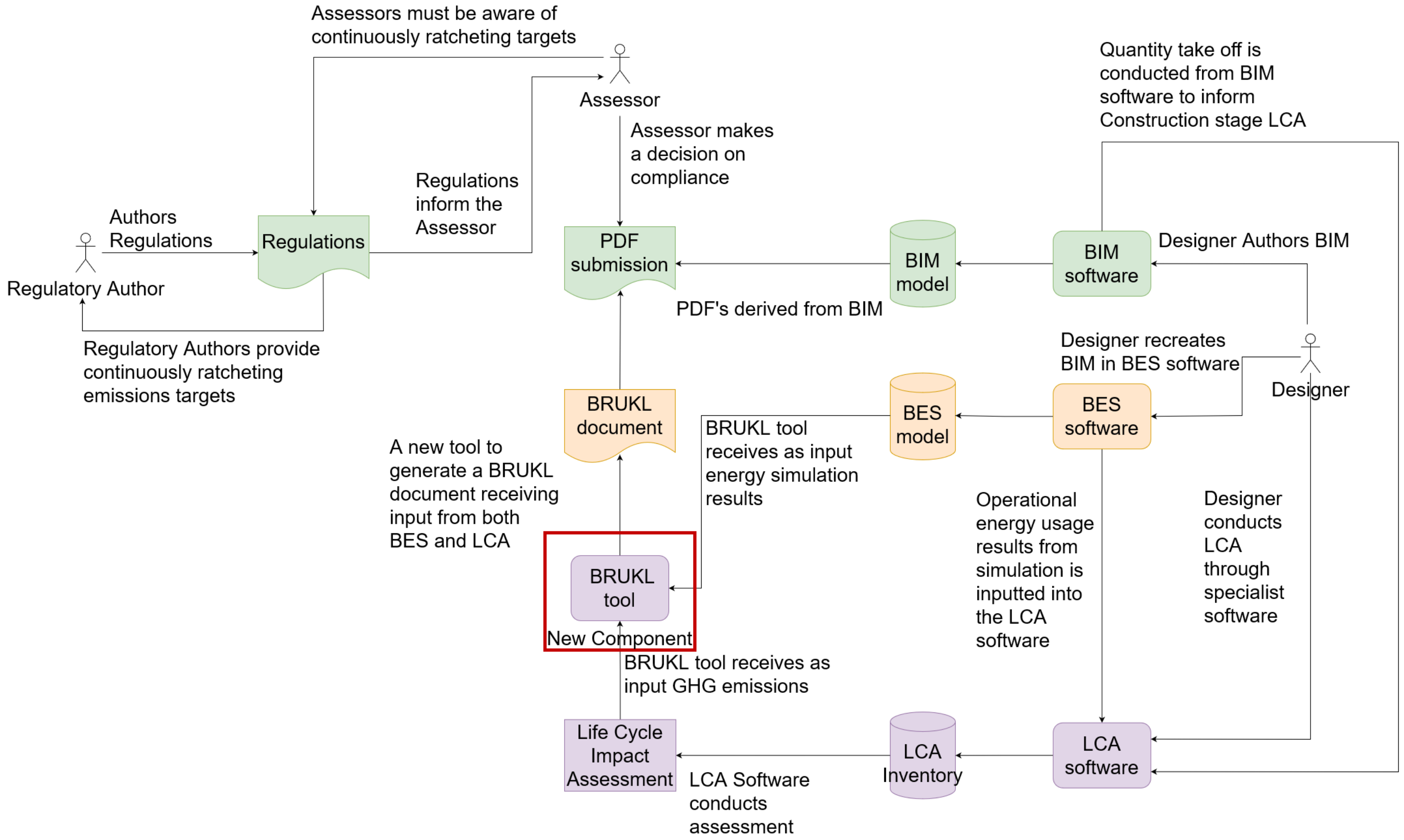


Figure 4.4: Proposed, wider, Design and Regulatory Framework, proposed elements (purple)

In this framework, the processes for the **Assessor** remain as before in Figure 4.3. For the **Regulatory Author** an additional process has been indicated to provide the progressively ratcheting emissions targets necessary to achieve net zero.

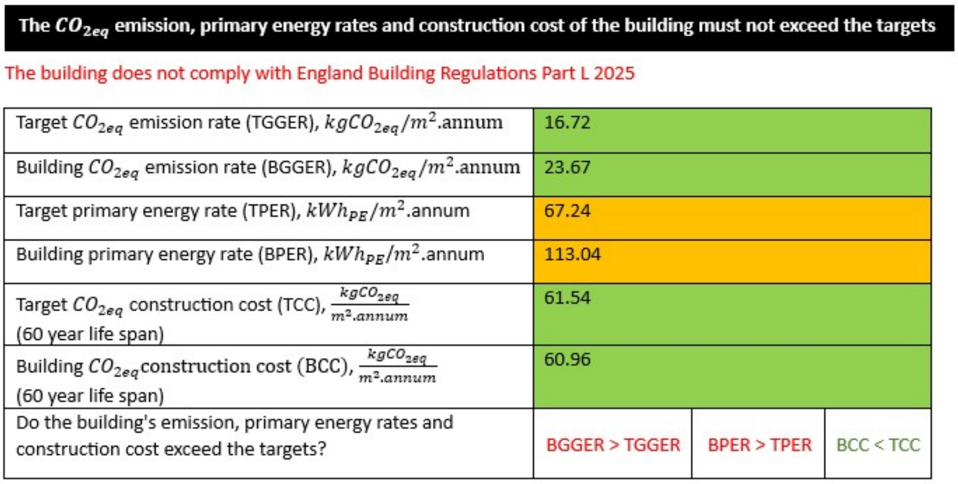
The **Designer** will conduct LCA's through specialised LCA software. If the designer is able to leverage quantity take-off via the BIM they are able to feed this into the LCA software to conduct the construction stage assessment. As in the current framework, the designer will recreate the building geometry in the BES software. In the proposed framework, an additional process is shared between the BES and LCA software to share energy usage results which enable the operational stage assessment. Figure 4.4 illustrates the integration of BES and LCA software and in doing so, presents a BES and LCA co-simulation.

Results from both the BES and LCA software are required to generate the new BRUKL document, as current BES software is not capable of receiving input from LCA, nor can it output the proposed BRUKL document, a new tool has been developed to do this.

The new, BES and LCA BRUKL tool (denoted in a red box in Figure 4.4) takes input from both BES and LCA software and outputs the new BRUKL document in PDF format. An annotated version of Figure 4.2 is provided in Figure 4.5 for clarity. Here, the cells have been coloured to indicate whether the required inputs originate from the BES (orange) or LCA software (green).

4.5 Considerations for Implementation

Whilst the developed framework (presented in Section 4.4.2), enables a pathway for GHG assessment through the integration of LCA software within the wider, Design and Regulatory Framework, there are already at this stage, considerations for implementation. This section will discuss the different considerations for both the design and regulatory aspects of the framework.



The CO_{2eq} emission, primary energy rates and construction cost of the building must not exceed the targets

The building does not comply with England Building Regulations Part L 2025

Target CO_{2eq} emission rate (TGGER), $kgCO_{2eq}/m^2$.annum	16.72		
Building CO_{2eq} emission rate (BGGER), $kgCO_{2eq}/m^2$.annum	23.67		
Target primary energy rate (TPER), kWh_{PE}/m^2.annum	67.24		
Building primary energy rate (BPER), kWh_{PE}/m^2.annum	113.04		
Target CO_{2eq} construction cost (TCC), $\frac{kgCO_{2eq}}{m^2.annum}$ (60 year life span)	61.54		
Building CO_{2eq} construction cost (BCC), $\frac{kgCO_{2eq}}{m^2.annum}$ (60 year life span)	60.96		
Do the building's emission, primary energy rates and construction cost exceed the targets?	BGGER > TGGER	BPER > TPER	BCC < TCC

Figure 4.5: Proposed BRUKL targets section, colour coded by input data origin; BES (orange) or LCA (green).

Assessor: The proposed Framework does not change the underlying processes for the Assessor. However, the regulatory uplifts introduce an additional check to be made (Construction Cost), this has little effect on the assessor, as the decision on this check is still calculated and produced by the BRUKL, and so the assessor still must only check the BRUKL document.

The **Regulatory Author** will provide progressively ratcheting targets (inline with the net zero strategy [1, 3]) and the Assessor will need to be aware of them. The Regulatory Author will need to produce and adjust these targets based on the most up-to-date forecasts on emissions. These forecasts should be informed by building compliance submissions and approvals in the prior period, however there is no obvious mechanism at present to facilitate this.

For the **Designer**, they must manage an additional LCA tool in addition to already having to recreate the BIM in the BES software (which is the current status quo). The addition of this workflow means that designers will need LCA skills and able to exchange information between two domain models (BES and LCA). This workflow brings with it an additional time requirement and therefore cost. Either; designers absorb this cost and the process is treated as a burden created from compliance requirements, or, the cost is passed on to the client, which may stifle the construction sector.

The time related overheads for applying LCA to buildings is well documented [114, 115] and often does not align well with the needs and time constraints of the designer [115]. Furthermore, it is estimated that 60% more time is required to conduct LCA's, primarily due to re-entry of information [116].

4.6 Conclusion

This Chapter has discussed the motivations to extend Approved Document Part L to include LCA in Section 4.1. It has presented an analysis of current requirements and identified the specific Clause (2.3) that has the potential to facilitate net zero in Section 4.2, in order to address Research Question 1. Research Question 1 was:

What are the requirements in the UK regulatory landscape in terms of net zero and how can they be aligned with recommendations for WLCA to deliver GHG assessment of UK buildings?

Table 2.1 summarised the relevant government requirements and industry and institutional recommendations surrounding net zero and WLCA. This Chapter has discussed the motivations to extend Approved Document Part L to include BES and LCA co-simulation. This Chapter has identified current requirements that have the capacity to facilitate GHG emission assessment, in such a manner that aligns government net zero requirements with recommendations for WLCA. Clause 2.3 has been identified as having potential to facility GHG emission assessment which will enable net zero and WLCA.

Two uplifts to current regulations have been formulated, to enable GHG emission assessment and WLCA and presented in Section 4.3. Section 4.4 presented the wider, design and regulatory framework that could facilitate the two uplifts and in tandem with the uplifts, provide a pathway towards GHG emission assessment and thus, net zero and WLCA.

This Chapter has now addressed Research Question 1, with the definition and development of the framework encapsulating the design and regulatory aspects of GHG emission assessment providing the *how?* element, the regulatory uplifts presented in this Chapter facilitate the alignment of current requirements and recommendations around net zero and WLCA.

This Chapter has developed a wider, design and regulatory framework that integrates BES and LCA co-simulation. By developing a clear framework within existing design and compliance processes, this Chapter has illustrated how a BES and LCA co-simulation can technically enable a pathway towards GHG emission assessment and thus, net zero and WLCA. This framework will be validated in Chapter 7.

Finally, considerations for implementation of the developed framework have been discussed, the additional time, cost and skill required to implement BES and LCA co-simulation for GHG emission design and assessment, provides the motivation to automate and digitise the framework proposed in this Chapter. The following Chapter seeks to investigate and implement the automation and digitisation of the framework.

Chapter 5

Automation and Digitisation for Net Zero and WLCA

This Chapter seeks to address Research Question 2, which was:

What are the current accepted approaches for automatic compliance checking within the UK regulatory building sector?

Chapter 2 established that national adoption of ACC in the UK has been conducted through the D-COM Network [80]. Chapter 2 also introduced the latest developments in this area, the ecosystem architecture (Figure 2.3) for ACC and the digitisation methodology, RASE (Section 2.7.3). This forms the *current accepted approaches for ACC* element of Research Question 2.

Research Question 2 will be addressed, through the augmentation of the framework (Figure 4.4) developed in Chapter 4 (to function within the ecosystem architecture developed by D-COM) and the digitisation of: the current requirements relevant to GHG assessment and the uplifts proposed in Chapter 4 (Section 4.3), to be compatible with the D-COM digitisation approach. Digitisation of the current requirements indicating potential for GHG assessment and the uplifts are done to facilitate the simulation research validation conducted in Chapter 7.

In the following Section, this Chapter revisits the motivation for automation and digitisation of the developed framework, before conducting a feasibility analysis of automation and digitisation. Secondly, in Section 5.2, this Chapter presents the augmentation of the wider, design and regulatory framework for BES and LCA co-simulation through automation and digitisation. This Chapter will then conduct the digitisation process on Approved Document Part L and the uplifts (developed in the Chapter 4) in Section 5.3. Finally, this Chapter concludes in Section 5.4, which will revisit Research Question 2.

5.1 Motivations for Automation and Digitisation

Chapter 4 discussed the motivations to extend Approved Document Part L to include LCA in Section 4.1. It established that there are no current or proposed requirements in the UK regulatory landscape that address net zero nor, WLCA and established two uplifts to current regulations, to enable GHG emission and WLCA. Chapter 4 then presented the wider, design and regulatory framework (integrating a BES and LCA co-simulation) that could facilitate the two uplifts.

Automation and digitisation of compliance checking processes have been identified as critical to the delivery of a safer and more efficient alternative to current manual based checking processes, which are timely, costly and have room for error [81].

There is a definite appetite within the building industry for automation and digitisation and this is achievable by 2025, highlighting the feasibility and desirability of such processes, the industry is clear that full automation (without human intervention) is not desirable [81].

Section 5.2 will augment the Framework developed in Chapter 4, based on the findings in Section 2.7.1, through automation and digitisation. Section 5.3 will conduct the digitisation process for regulatory documents (presented in Section 2.7.2) on Approved Document Part L. Section 5.4 concludes this Chapter by revisiting Research Question 2, which will lay the foundations to answer Research Question 3.

5.2 Automation and Digitisation augmentation of the wider, Design and Regulatory Framework for BES and LCA co-simulation

The motivation for Automation and digitisation arise from the additional time, cost and skill resulting from integrating BES and LCA co-simulation within UK design and regulation of buildings, discussed in Chapter 4.

The automation and digitisation augmentation of the framework for BES and LCA co-simulation, builds on the vision for a ACC ecosystem, and aligns the framework with the D-COM vision, to function within the ecosystem. The digitised framework is presented in Figure 5.1.

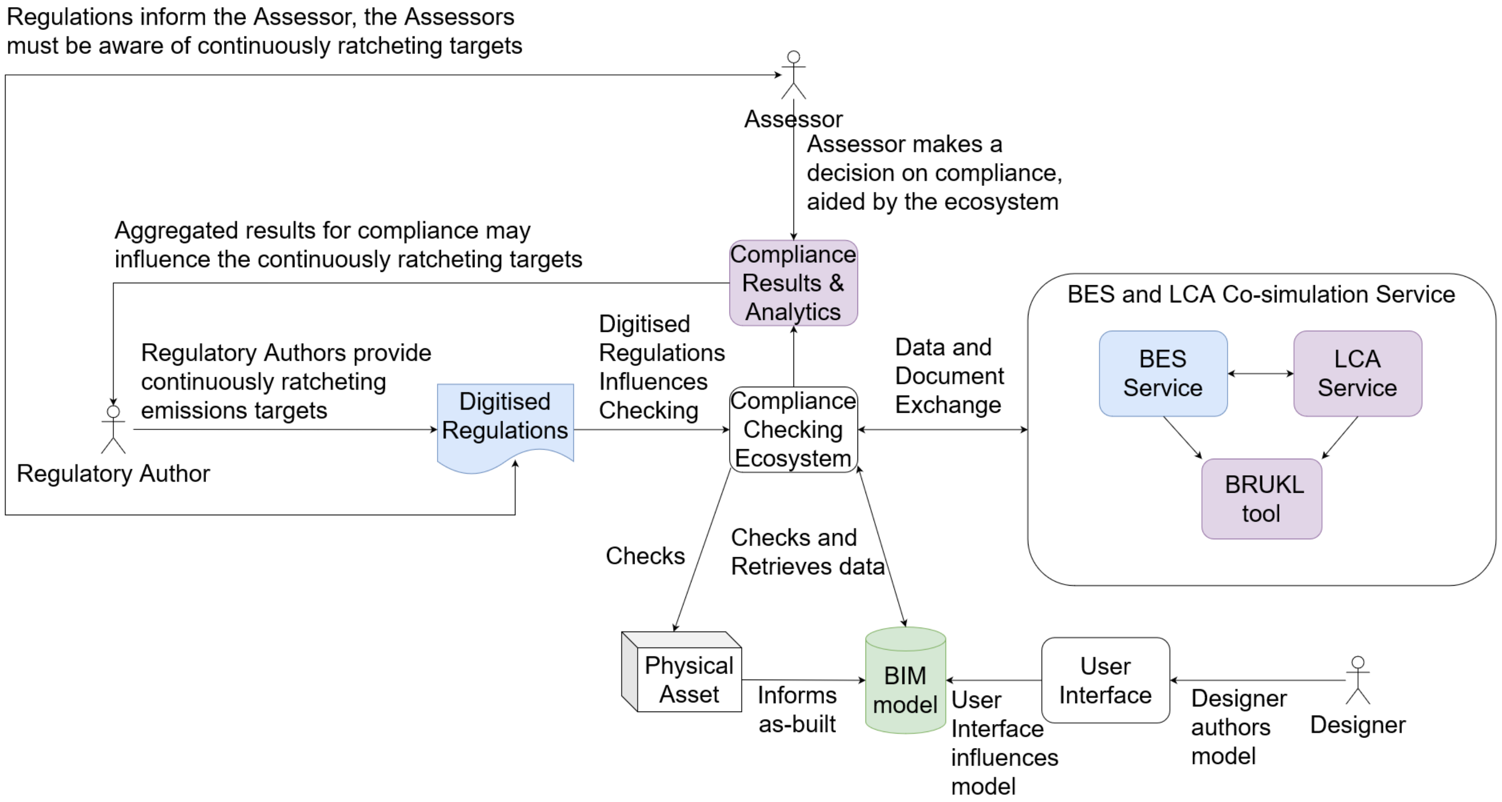


Figure 5.1: Automation and digitisation augmented framework

This augmented framework aligns the framework (developed in Chapter 4) with the vision by Beach et al., and integrates the BES and LCA co-simulation as an additional service within the compliance checking ecosystem. Co-simulation couples two or more domain models and is necessary to achieve innovative and optimal multi-disciplinary solutions as discussed in Chapter 2 [9]. The BES and LCA co-simulation is an automated architecture that accelerates the process of assessing a buildings energy and environmental impact for both design and compliance purposes and will be presented in Chapter 6.

The elements in Figure 5.1 are colour coded as:

1. Components of the ecosystem developed by Beach et al., (no colour)
2. Components of the ecosystem extended in this work (blue)
3. Components of the wider, Design and Regulatory framework for BES and LCA co-simulation (purple)

The first clear change is the centralisation of the Compliance Checking Ecosystem within the framework. The Ecosystem replaces the PDF submission process that current compliance processes follow, instead data is shared through the ecosystem that is accessed through a user interface.

The second augmentation is in relation to the Regulatory Author and Assessor, digitised versions of the regulations replace the previous non-digitised versions and are stored within the ecosystem. This reduces additional time burdens on the Assessor, as the ecosystem provides a navigable system in which the complex body of regulations may be accessed and their interconnecting aspects utilised [10]. Furthermore, the assessor is assisted by the ecosystem, either in; automatically making decisions on the compliance of elements within a building, or aiding the assessor when an automatic check is either not possible or not desired. The uplifts described in Chapter 4 fall into the former category as they are new uplifts based on current requirements that are automatically checked by the existing BRUKL, which the Assessor checks in turn.

For the Regulatory Author, digitisation of regulations means that there is now a mechanism in place to provide progressively ratcheting emissions targets. It is envisaged that targets will be updated without the necessity for issuing a new edition or amendment, though this is subject to the necessary quality assurance and error checking mechanisms being in-place, alternatively, targets could be codified ahead of time, with targets to come in place at a given time. In the new augmented framework, a mechanism is in place for analytics of compliance results, so that Regulatory Authors are enabled to produce informed, realistic and feasible targets. This mechanism has been described to present a holistic view of the developed framework, however, implementation and validation of this mechanism is not within the scope of this Thesis.

For the designer, the augmentation of the framework simplifies the number of tools and models needed to be managed. Now, the Designer authors only one BIM model in a given user interface, which is accessed by the ecosystem. The ecosystem is able to check and retrieve data from the BIM model and share information with services such as the BES and LCA co-simulation service. Whilst, this Chapter has presented the augmented, Digitised, Design and Regulatory Framework, the evolution of the BES and LCA threads of the framework into a co-simulation service is covered in Chapter 6 and consolidates the BES service, LCA service and new BRUKL tool into one co-simulation service.

5.3 Digitisation Process, Approved Document Part L

This Section will firstly discuss the digitisation of the entire Approved Document Part L2A 2016 in Section 5.3.1. Then, in Section 5.3.2 this chapter discusses the digitisation of the key clause (Clause, 2.3 of Part L 2023) with potential to facilitate GHG emission assessment. Finally, in Section 5.3.3, this chapter discusses the digitisation of the extended Clause 2.3, proposed in Chapter 4.

The digitisation exercise was conducted on Approved Document Part L2A 2016. It should be noted that this exercise began in January 2020 and at the time, L2A 2016 was the most recent document with applicability to non-domestic buildings, as the 2018 update only applied to domestic buildings (Part L1A). In recent updates, the document naming was consolidated from Part L1A and L2A into Part L.

This Section will document the digitisation of Approved document Part L2A 2016 and further document the digitisation of particular clauses in the 2023 update that are relevant to the assessment of GHG emissions for the purposes of net zero and WLCA. By updating particularly clauses, this Thesis also illustrates the applicability of this framework to progressively ratcheting emissions targets.

This Section now documents the digitisation exercise, initialised in January 2020, and will introduce and discuss concepts relevant to the digitisation of regulatory documents.

5.3.1 Approved Document Part L 2016

The digitisation exercise began in January 2020 and at the time, L2A 2016 was the most recent document with applicability to non-domestic buildings. This Section, will discuss the digitisation of the entire Approved Document Part L2A 2016.

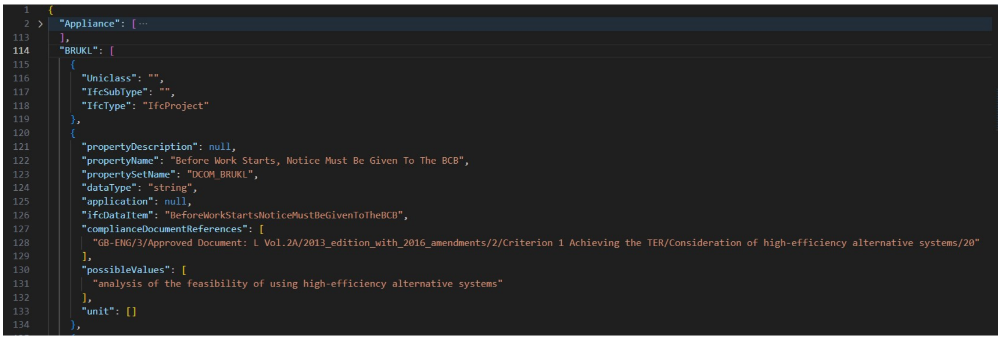
Then, in Section 5.3.2 the digitisation of the key clause (Clause, 2.3 of Part L 2023) with potential to facilitate GHG emission assessment is addressed. Finally, in Section 5.3.3, this chapter discusses the digitisation of the extended Clause 2.3, proposed in Chapter 4.

Table 5.1 recaps the number of Requirements and their associated Classifications and is a shortened version of Table 2.2, presented in Section 2.7.1.

Table 5.1: Approved Document Part L 2016 Clause Classification

Category	**L2A**
BIM Data	62
Product Data	13
Colour Contrast	0
Cross-References	1
Geometric	2
Energy Simulation	30
Other	80
Total	193

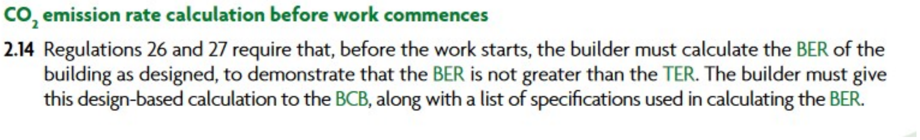
The digitisation of Part L 2016 produced a total of 193 checks which are stored in a JSON dictionary. Of the 193 checks, 30 requirements relate specifically to energy simulations, which are currently assessed through the BRUKL document. Figure 5.2 indicates the structure of this JSON dictionary, illustrated by the 'BRUKL' entry in the JSON.



```
{
  "Appliance": [···
  ],
  "BRUKL": [
    {
      "Uniclass": "",
      "IfcSubType": "",
      "IfcType": "IfcProject"
    },
    {
      "propertyDescription": null,
      "propertyName": "Before Work Starts, Notice Must Be Given To The BCB",
      "propertySetName": "DCOM_BRUKL",
      "dataType": "string",
      "application": null,
      "ifcDataItem": "BeforeWorkStartsNoticeMustBeGivenToTheBCB",
      "complianceDocumentReferences": [
        "GB-ENG/3/Approved Document: L Vol.2A/2013_edition_with_2016_amendments/2/Criterion 1 Achieving the TER/Consideration of high-efficiency alternative systems/20"
      ],
      "possibleValues": [
        "analysis of the feasibility of using high-efficiency alternative systems"
      ],
      "unit": []
    },
```

Figure 5.2: Digitised Part L 2016, 'BRUKL' entry

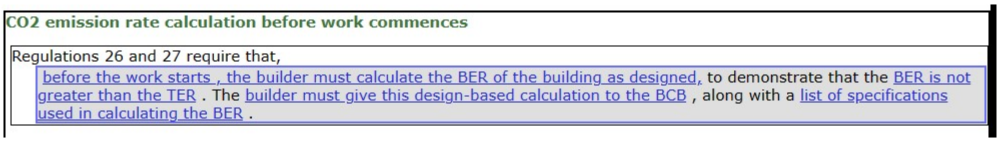
Chapter 4 identified and developed two uplifts to current regulations (2023) and the clause which could facilitate these uplifts, Clause 2.3. Clause 2.14 (of Part L2A 2016) is the predecessor to Clause 2.3 (of Part L 2023) and is illustrated in it's human-readable form in Figure 5.3, it's HTML form with RASE mark up applied in Figure 5.4 and its machine-readable form in Figure 5.5.



CO$_2$ emission rate calculation before work commences

2.14 Regulations 26 and 27 require that, before the work starts, the builder must calculate the BER of the building as designed, to demonstrate that the BER is not greater than the TER. The builder must give this design-based calculation to the BCB, along with a list of specifications used in calculating the BER.

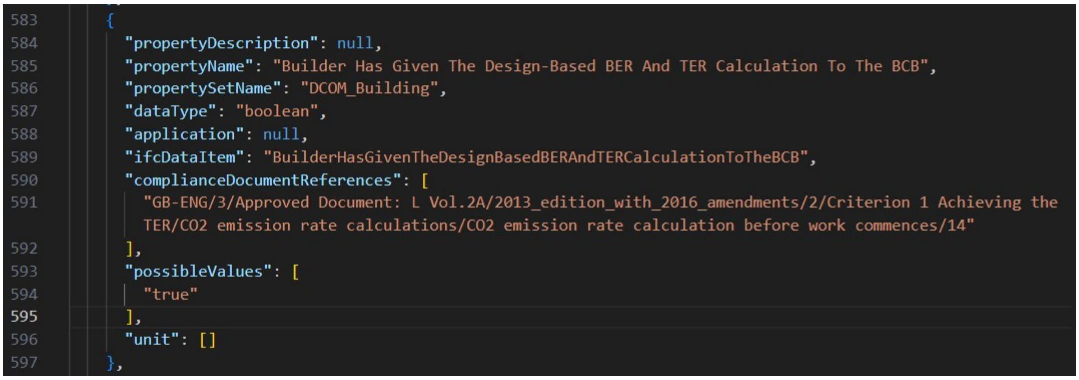
Figure 5.3: Human-readable Clause 2.14



CO2 emission rate calculation before work commences

Regulations 26 and 27 require that, before the work starts , the builder must calculate the BER of the building as designed, to demonstrate that the BER is not greater than the TER . The builder must give this design-based calculation to the BCB , along with a list of specifications used in calculating the BER .

Figure 5.4: HTML with RASE Markup Clause 2.14



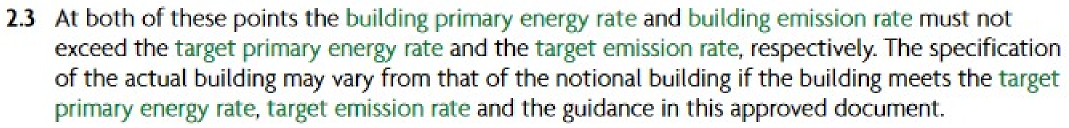
```
    {
      "propertyDescription": null,
      "propertyName": "Builder Has Given The Design-Based BER And TER Calculation To The BCB",
      "propertySetName": "DCOM_Building",
      "dataType": "boolean",
      "application": null,
      "ifcDataItem": "BuilderHasGivenTheDesignBasedBERAndTERCalculationToTheBCB",
      "complianceDocumentReferences": [
        "GB-ENG/3/Approved Document: L Vol.2A/2013_edition_with_2016_amendments/2/Criterion 1 Achieving the
        TER/CO2 emission rate calculations/CO2 emission rate calculation before work commences/14"
      ],
      "possibleValues": [
        "true"
      ],
      "unit": []
    },
```

Figure 5.5: Machine-readable Clause 2.14

5.3.2 Approved Document Part L 2023

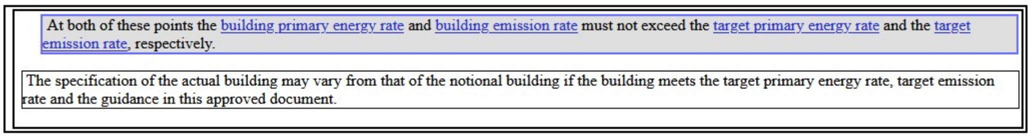
The digitisation exercise described in the previous Section, was conducted in January 2020 on the most up-to-date version of Part L with applicability to non-domestic buildings, which was L2A 2016. For completeness, and also in order to illustrate the applicability of digitisation to the concept of progressively ratcheting emission targets, this Section will now update the appropriate clause from Part L2A 2016 (Clause 2.14) to align with the current requirement from Part L 2023 (Clause 2.3), by digitising the new requirement.

Clause 2.3 of Part L 2023 is illustrated in it's human-readable form in Figure 5.6, it's HTML form with RASE mark up applied in Figure 5.7 and its machine-readable form in Figure 5.8.



2.3 At both of these points the building primary energy rate and building emission rate must not exceed the target primary energy rate and the target emission rate, respectively. The specification of the actual building may vary from that of the notional building if the building meets the target primary energy rate, target emission rate and the guidance in this approved document.

Figure 5.6: Human-readable Clause 2.3



At both of these points the building primary energy rate and building emission rate must not exceed the target primary energy rate and the target emission rate, respectively.

The specification of the actual building may vary from that of the notional building if the building meets the target primary energy rate, target emission rate and the guidance in this approved document.

Figure 5.7: HTML with RASE Markup Clause 2.3

5.3.3 Proposed Amendment to Clause 2.3

This Section will document the process of updating the JSON dictionary to align with the extended Clause 2.3, proposed in Chapter 4, which was:

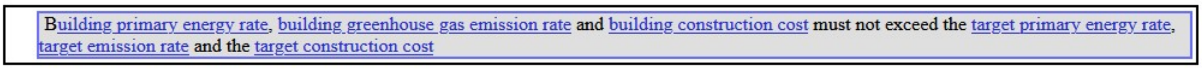
Building primary energy rate (BPER), building greenhouse gas emission rate (BGGER) and building construction cost (BCC) must not exceed the target primary energy rate (TPER), target greenhouse gas emission rate (TGGER) and the target construction cost (TCC).

Similarly to the previous Section, here, a check is being amended, and a new check added. However, unlike the previous Section, there is no existing human-readable version. A human-readable version has been created, solely to illustrate the process of digitisation and so, Figure 5.9 presents the marked up Clause. The new digitised rule

```
      "unit": []
    },
    {
      "propertyDescription": null,
      "propertyName": "The As-Designed BER does not exceed the TER",
      "propertySetName": "DCOM_BRUKL",
      "dataType": "boolean",
      "application": null,
      "ifcDataItem": "AsDesignedBERDoesNotExceedTER",
      "complianceDocumentReferences": [
        "GB-ENG/3/Approved Document: L Vol.2A/2021_edition_with_2023_amendments/2/3"
      ],
      "possibleValues": [
        "true"
      ],
      "unit": []
    },
    {
      "propertyDescription": null,
      "propertyName": "The As-Designed BPER does not exceed the TPER",
      "propertySetName": "DCOM_BRUKL",
      "dataType": "boolean",
      "application": null,
      "ifcDataItem": "AsDesignedBPERDoesNotExceedTPER",
      "complianceDocumentReferences": [
        "GB-ENG/3/Approved Document: L Vol.2A/2021_edition_with_2023_amendments/2/3"
      ],
      "possibleValues": [
        "true"
      ],
      "unit": []
    },
    {
```

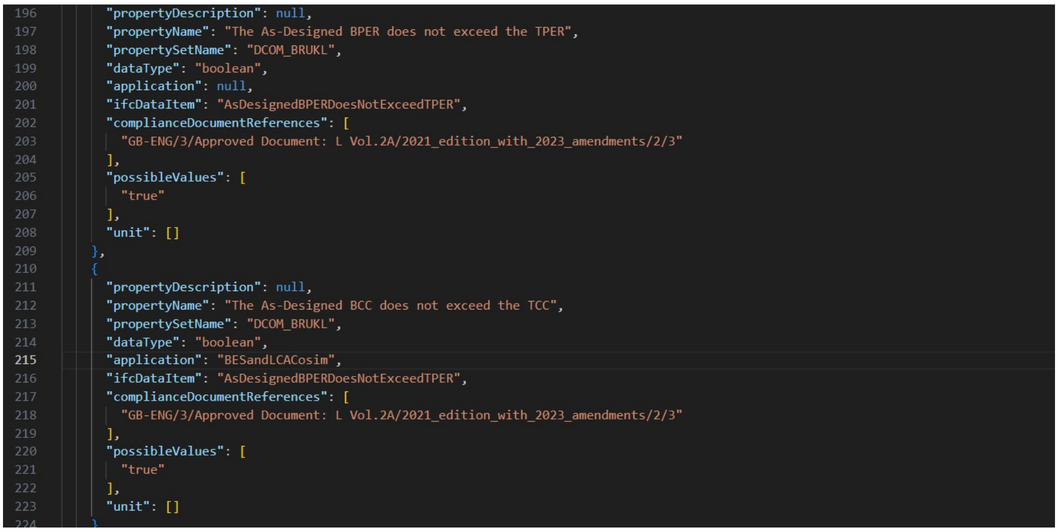
Figure 5.8: Machine-readable Clause 2.3

is illustrated in Figure 5.10, here, two of the five mappings (marked up in Figure 5.9) are shown.



Building primary energy rate, building greenhouse gas emission rate and building construction cost must not exceed the target primary energy rate, target emission rate and the target construction cost

Figure 5.9: Machine-readable extended and proposed Clause 2.3



```
      "propertyDescription": null,
      "propertyName": "The As-Designed BPER does not exceed the TPER",
      "propertySetName": "DCOM_BRUKL",
      "dataType": "boolean",
      "application": null,
      "ifcDataItem": "AsDesignedBPERDoesNotExceedTPER",
      "complianceDocumentReferences": [
        "GB-ENG/3/Approved Document: L Vol.2A/2021_edition_with_2023_amendments/2/3"
      ],
      "possibleValues": [
        "true"
      ],
      "unit": []
    },
    {
      "propertyDescription": null,
      "propertyName": "The As-Designed BCC does not exceed the TCC",
      "propertySetName": "DCOM_BRUKL",
      "dataType": "boolean",
      "application": "BESandLCACosim",
      "ifcDataItem": "AsDesignedBPERDoesNotExceedTPER",
      "complianceDocumentReferences": [
        "GB-ENG/3/Approved Document: L Vol.2A/2021_edition_with_2023_amendments/2/3"
      ],
      "possibleValues": [
        "true"
      ],
      "unit": []
```

Figure 5.10: Machine-readable extended and proposed Clause 2.3

5.4 Conclusion

The purpose of this Chapter was to address Research Question 2, which was:

What are the current accepted approaches for automatic compliance checking within the UK regulatory building sector?

This Chapter will now conclude by addressing this question. As part of the literature review conducted in Chapter 2, Section 2.7 established and described the ACC national adoption efforts conducted through the D-COM Network [80]. The latest advancement in this area from D-COM is the Ecosystem architecture designed as part of the D-COM networks Vision for ACC, developing and releasing a set of prototype software tools.

In Section 5.2, this Chapter has augmented and aligned the wider, Design and Regulatory Framework for BES and LCA Co-simulation with the D-COM Vision for ACC.

Section 5.3 has presented the digitisation of current requirements (with the potential to facilitate GHG assessment) and the uplifts proposed in Chapter 4.

With the augmentation of the framework into a digital framework and the digitisation of requirements and uplifts, this Chapter has applied the principles underpinning the current accepted approaches to ACC and has aligned the framework developed in this work to function within the D-COM ecosystem, therefore addressing Research Question 2.

The following Chapter will present the developed, automated, BIM-based, BES and LCA co-simulation architecture that forms the co-simulation service of the augmented framework. The co-simulation service will be triggered by the ACC Ecosystem via the JSON dictionary, as illustrated in Figure 5.10.

Chapter 6

An Architecture for Automated BES and LCA Co-Simulation

This Chapter will describe the automated, BIM-based, BES and LCA co-simulation architecture that forms the co-simulation service in the Digitised, Design and Regulatory Framework for BES and LCA co-simulation.

This Chapter contains the **Co-simulation Architecture Development** and **Co-simulation Automation and Digitisation Augmentation** tasks, established in Figure 3.2 in Chapter 3.

The co-simulation service in this Chapter, will be implemented within the Digital Framework developed in **Chapter 5** as a proof-of-concept in order to address Research Question 3, which is:

How would a BES and LCA co-simulation architecture be integrated into the wider UK building design and regulatory framework, to enable net zero and WLCA with regards to: (a) building design processes and (b) building regulatory processes

This Research Question will be addressed in Chapter 7.

Section 6.1 will detail the technical architecture for a BES and LCA co-simulation, which will be integrated into the Digitised, Design and Regulatory Framework. Section 6.2 concludes this Chapter.

6.1 An automation framework for BES and LCA co-simulation

In this section, the technical architecture for the co-simulation service (implemented within the digitised, framework) will be specified. Figure 6.1 presents an overview of the technical architecture. In this Figure, tools/software newly developed for this research are coloured purple, existing tools/software are uncoloured. Figure 6.2 presents a sequence diagram and Figure 6.3 illustrates a use-case diagram, both from the perspective of a Designer. The following subsection will describe each component of the Automated and Digitised, Design and Regulatory Framework for BES and LCA Co-simulation.

6.1.1 Designer Workflow

The technical architecture and designer sequence diagram are discussed from the perspective of the Designer only and not the Regulatory Author or Assessor as the Designer is the only actor that interacts directly with the architecture. The Assessor's role is only to oversee automated checking of the BRUKL output, and the Regulatory Author will be able to access high level, aggregated results (BRUKL), neither interface with the Co-simulation Architecture.

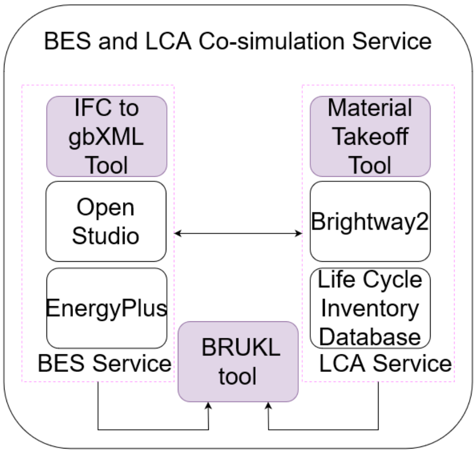


Figure 6.1: BES and LCA Co-simulation architecture, newly developed elements are coloured purple.

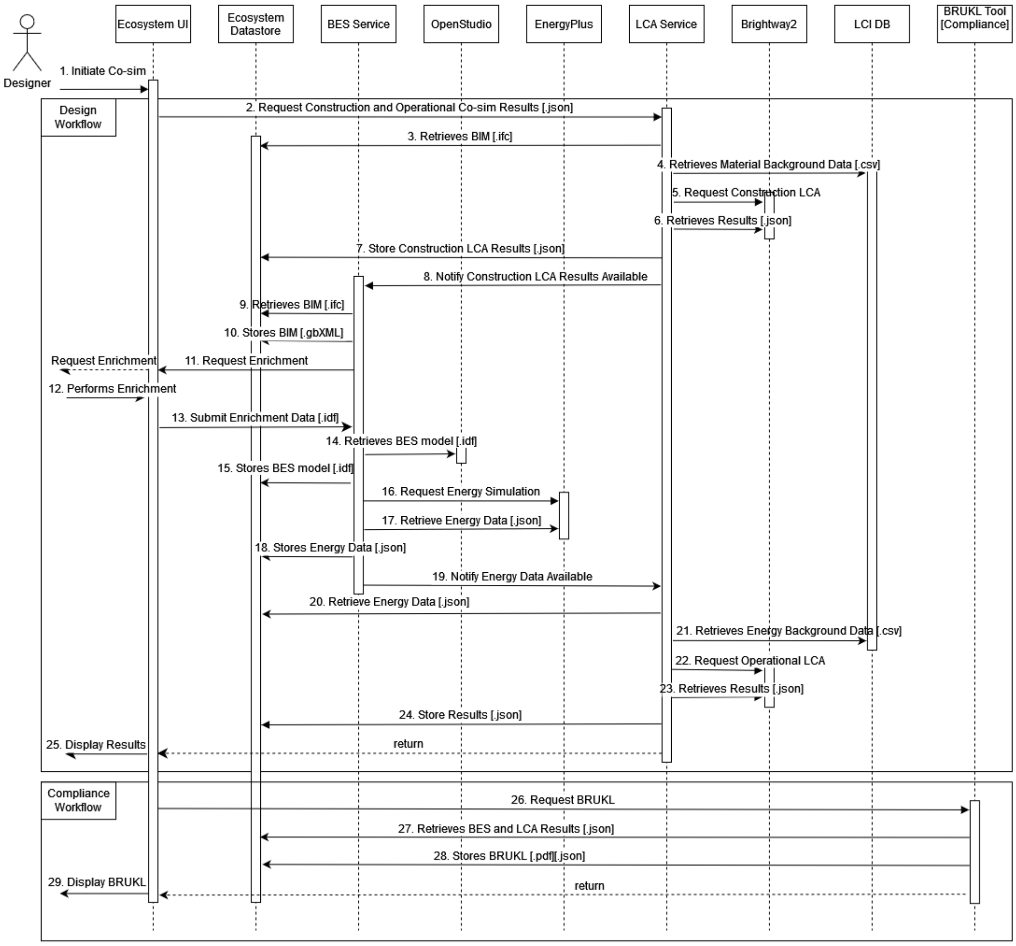


Figure 6.2: Co-simulation Sequence Diagram for the Designer, Arrows Refer to Processes.

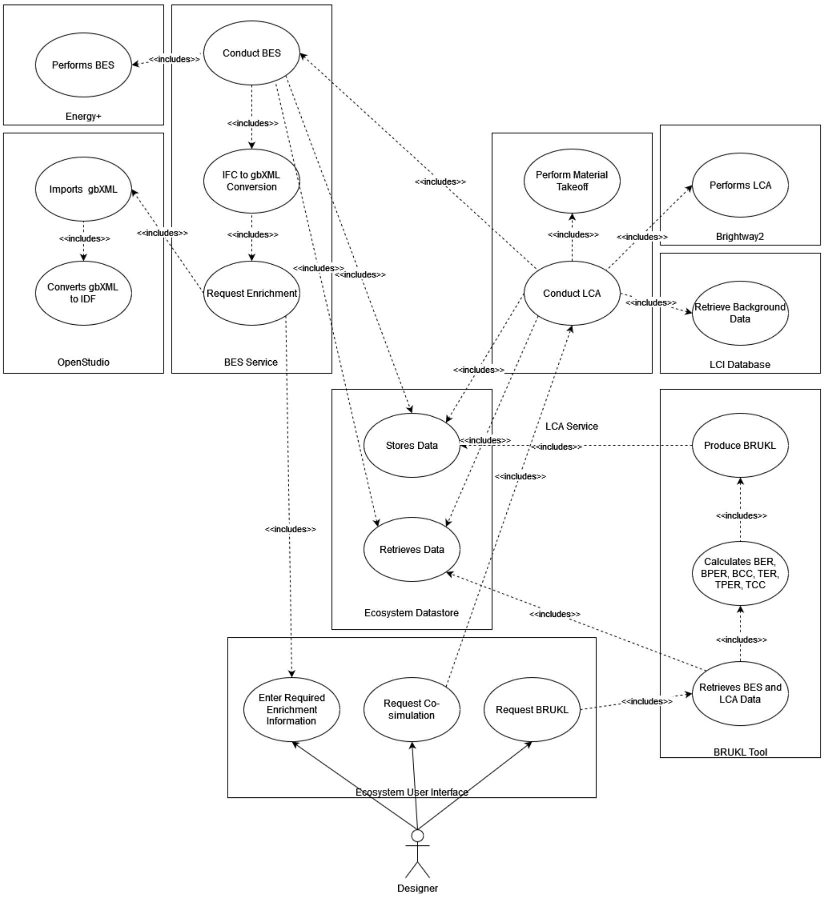


Figure 6.3: Co-simulation Use Case Diagram

In the following sections, arrows in Figure 6.2 will be referred to as processes. A linear traversal through the Co-simulation Sequence Diagram in Figure 6.2 will be described in the following sections. The diagram details two workflows that are typical for a Designer; design activities and compliance activities (or workflows).

Section 6.1.6 describes processes that only need to be performed during a compliance workflow, however processes in the Design Workflow must first be completed in order to do so. A compliance workflow is only conducted when a Designer is about to submit a project for compliance checking. The compliance workflows in today's processes are the 'as-designed' and 'as-built' BRUKL submissions, performed by the Designer. The calculation methodologies behind the metrics assessed in the proposed BRUKL are documented in Section 6.1.6. The compliance workflow covers Regulatory aspects of the framework, namely the ’as-designed’ and ’as-built’ proposed BRUKL’s (presented in Chapter 4). The proposed BRUKL’s submission process reflects the current submission process, in which the ’as-designed’ BRUKL is submitted at the conclusion of early design activities and the ’as-built’ submitted once the building has been constructed, these are submitted by the Designer. The calculation methodologies are the same for the two BRUKL’s, but are submitted in two instances to capture any unforeseen changes to the design during construction. This applicability of this research is the design phase prior to compliance submission, and so focusses explicitly on the ’as-designed’ submission.

6.1.2 Prerequisites and Co-simulation Initialisation: Processes 1 and 2

For a built environment domain user such as a designer, the initial process to initiate this framework is the submission of an IFC model of a given asset, illustrated by Process 1 in Figure 6.2. Therefore, the prerequisite for this workflow is an IFC model of a building.

In general, BIM authoring tools have the capability to export models into an IFC schema, BIM authoring tools capable of IFC export are equally suitable to this architecture.

For clarity, the scope of this research applies only once an IFC has been submitted, for information however, IFC’s can be created through standard export in BIM software, for example REVIT, as is the case of the IFC forming part of the proof-of-concept implementation presented later in Chapter 7.

This co-simulation architecture sets certain data requirements for input BIM’s or IFC’s. BIM’s are typically developed for non-BES purposes, rather their own, and so information required from a BES perspective is not contained within the BIM. Thus, before this architecture can be applied, BIM's should contain a sufficient level of detail. These requirements are outlined below:

1. All spaces defined and types assigned to the spaces - For all rooms in the BIM a 'space' is inserted, space types such as; corridor, closed-office, plant room, WC etc are assigned
2. Definition of thermal zones - thermal zones may be defined to represent room(s) of interest or complex arrangements
3. Define materials and assign constructions - material makeup for all constructions are assigned

Steps 1 and 2 are commonly completed in well specified BIMs produced currently. Step 3, however, may require additional enrichment beyond the standard norms. It should be highlighted that even though exports from some BIM authoring tool into IFC format do not necessarily create a perfect conversion of geometry from all elements, this architecture can overcome this issue through the definition of spaces. Specifically, geometry, thermal zones and material constructions are automatically translated from IFC to gbxml. BES enrichment (conducted via the UI) requires input of building services systems and internal loads. This does not provide additional burden to the designer, as based on current processes, BES designers must manually recreate all inputs.

This architecture elected to define these BIM requirements as a prerequisite to the co-simulation architecture. However, only Step 1 is necessary. Steps 2 and 3 could technically, form part of the BES enrichment process (described in Section 6.1.4) - which does form part of the architecture - however, this study elected to make Steps 2 and 3 prerequisites for two reasons. In the context of the building design process, BES models are created at a later stage than the BIM. Typically, in BIM creation, spaces have already been defined in the BIM to fulfil functions such as floor plan legends. Similarly, BIM's inherently represent the properties of elements so materials and thermal zones are already defined. Therefore, it is logical to represent these steps here, rather than to duplicate or redo later. This may present a minor departure from the sequencing of current processes. In current processes, BES models may be developed in parallel, as soon as geometry is available, in the proposed processes, the BES model is derived from the BIM once Steps 1, 2 and 3 have been complete. It is envisaged that this will reduce unnecessary duplication and re-entry of information, however it may be the case that BES models are created at a later point than in current processes. Whether this sequence change affects the BES model completion point or compliance submission is not apparent.

Upon initialisation, the Ecosystem requests the LCA service to provide Construction and Operational Co-simulation Results, which is represented by Process 2.

6.1.3 LCA Construction Phase: Processes 3 - 8

Once the LCA Service has received the request to start co-simulation (from the digitised, framework developed in Chapter 5) in Process 2, the service (Figure 6.1) conducts Process 3, which is to retrieve the IFC from the datastore. Upon retrieval, the LCA Service parses the file and uses an automated tool to extract material information for the different constructions in the building. The automated tool has been developed specifically for this purpose and is presented in Appendix D. The tool is illustrated in Figure 6.1 as the material takeoff tool. The material takeoff tool parses the IFC to extract the material quantities, in kg's.

Each of the respective material properties are then in turn retrieved from a LCI represented by Process 4. Material markets are not necessarily given in the same units as those extracted by the material takeoff tool, and so, unit conversions are necessary in some cases. The LCA Service then requests construction LCA to be performed by BW2 (Process 5), before retrieving the results of the LCA (Process 6) and storing them in the Datastore (Process 7). Finally, the LCA Service will notify the BES Service that

Construction LCA Results are available (Process 8) as a trigger to begin its activities.

The LCA Service consists of a set of scripts and tools alongside BW2 and a LCI. BW2 is free and open source LCA framework developed in Python [35] and provides the underlying methods that calculate environmental impact. The LCA calculations made with BW2 are driven by background data which is provided by the LCI. This framework uses ecoinvent 3.8 which is a subscription based database. Ecoinvent is used here as it is the largest LCI database worldwide [37], however this Thesis envisages that, if implemented in practice, this framework could implement a UK built environment specific database, maintained in some part by the Regulatory Authors.

6.1.4 BES Operational Phase and Enrichment: Processes 9 - 19

Upon receiving notification from the LCA Service in Process 8, the BES Service retrieves the IFC from the Datastore (Process 9) and performs IFC to gbXML translation. An automated tool was developed for this translation. The tool is based on a previously developed open source code by MGVisschers [117], which has been updated to function with the latest IFC version. A link to the tool is provided in Appendix D

The gbXML is stored within the Datastore in Process 10, as part of this process, a weather file is fetched from an online service [118] and this is linked to the stored gbXML.

The service then requests BES enrichment (Process 11), which is conducted by the Designer (Process 12). The elements to be enriched are building services systems and internal loads. With current processes, this manual enrichment process is necessary as current interoperability processes do not support these elements. This enrichment process is similar to current established workflows, but without geometry duplication and data re-entry. Furthermore, BIM models are not made for BES purposes and so this enrichment is necessary to be able to conduct a BES. The Designer performs BES enrichment through the Ecosystem User Interface and then OpenStudio converts the enriched model into an IDF.

Once enrichment is complete, the data is submitted to the BES Service (Process 13), which in turn, retrieves the IDF (Process 14) and stores it in the Datastore (Process 15). The service then requests energy simulation initiation by E+ (Process 16), before retrieving the data from that simulation and storing it in Processes 17 and 18.

The BES Service consists of two, free and open source energy modelling software technologies and a set of scripts. E+ provides the underlying calculation engine for building energy simulation [119]. OpenStudio is traditionally used as a frontend for E+ and in this service provides the interoperability methods forming part of this service [45].

Finally, the BES Service notifies the LCA Service that Energy Data is available so that it may conduct the Operational LCA (Process 19).

6.1.5 LCA Operational Phase: Processes 20 - 25

In order to conduct the Operational phase LCA, the service retrieves the operational energy data (stored by the BES Service) from the Ecosystem Datastore in Process 20. Again, background data (dictated by the Energy Data) is retrieved from the LCI database, represented in Process 21. The LCA service then requests the Operational LCA before retrieving and storing the results from the co-simulation in the Datastore, Processes 22, 23 and 24.

Finally, the results from co-simulation for both the construction and operational phases are displayed to the user in Process 25. With the co-simulation of whole-building BES and LCA, one can better inform the LCA with energy data that is time-differentiated. By adding this dimension in turn, this architecture is able to represent dynamacity in the operational phase of the building through time-differentiated LCA results.

6.1.6 BRUKL Tool [For Compliance Processes Only]: Processes 26 - 29

Process 26 initiates the Compliance specific Processes in Figure 6.2 by requesting a BRUKL. A compliance workflow is only conducted when a Designer is about to submit a project for compliance checking. A Designer will need to have conducted the Design Workflow Processes and would undertake these processes in order to meet compliance in the digitised, framework presented in Chapter 5. The BRUKL tool retrieves the BES and LCA results stored in the datastore (Process 27), for both construction and operation in order to calculate the BGGER, BPER, BCC and their target equivalents (Chapter 4). The BRUKL tool then produces the BRUKL which is stored in the Ecosystem Datastore (Process 28). Finally, the BRUKL is displayed to the Designer in Process 29. At a later stage, when the Designer or Design team is in a position to submit the project for compliance checking, the produced BRUKL is submitted alongside the rest of the project submission.

This Section now details the calculation methodologies for the individual digitised checks from the extended Clause 2.3, developed in this research. Decomposed into individual digitised checks, the extended Clause requires the following:

1. Building Primary Energy Rate (BPER) < Target Primary Energy Rate (TPER)
2. Building Greenhouse Gas Emission Rate (BGGER) < Target Greenhouse Gas Emission Rate (TGGER)
3. Building Construction Cost (BCC) < Target Construction Cost (TCC)

Where, current standards require only the following [7, p.10]:

1. Building Emission Rate (BER) < Target Emission Rate (TER)
2. Building Primary Energy Rate (BPER) < Target Primary Energy Rate (TPER)

The BPER vs TPER check remains unchanged from current requirements, however the BER vs TER check (which only assessed CO_2 emissions) has been replaced with the two uplifts proposed and digitised in this research, the BGGER vs TGGER check (which assesses GHG emissions with Global Warming Potential) and the BCC vs TCC check (which assess the Global Warming Potential from constructing the building).

Calculation methods for the current, BER vs TER and BPER vs TPER checks from the NCM Modelling Guide will be documented, along with those developed in this research, BGGER vs TGGER and BCC vs TCC.

The core element of all checks (except the BCC vs TCC) is the monthly electrical usage. The BER vs TER and BPER vs TPER methodologies are reproduced from the NCM Modelling Guide [19, p.25,36]. For both the actual building and the target (notional) building, each metric follows the same methodology, with the monthly electrical usage corresponding to the actual (Building) and notional (Target) values.

The **Emission Rate** calculation methodology (BER vs TER), is made up by the summation of 4 elements, each multiplied by the respective CO_2 emission factor from the NCM Modelling Guide Tables [19, pp.59-60]. These Tables are reproduced for completeness in Appendix B. The four elements are; The Monthly Electrical Usage (a_i), Monthly Energy Usage (c_i), Monthly Electricity Generated by PV (e_i) and the Monthly Electricity generated by Non-PV (g_i). The mathematical expression for the **Emission Rate** is documented in Equation 6.1, where, for the actual or notional building:

$$\sum_{i=1}^{n} a_{\mathrm{i}} b_{\mathrm{i}} + \sum_{i=1}^{n} c_{\mathrm{i}} d_{\mathrm{i}} + \sum_{i=1}^{m} e_{\mathrm{i}} f_{\mathrm{i}} + \sum_{i=1}^{m} g_{\mathrm{i}} h_{\mathrm{i}} = EmissionRate \tag{6.1}$$

The respective CO_2 Emission Factors are given as b_i, d_i, f_i and g_i. n and m are dictated by the number of respective consumption or generation assets.

The **Primary Energy Rate** calculation methodology (BPER vs TPER) follows the same methodology as the Emission Rate (Equation 6.1), but substituting the CO_2 emission factors (b_i, d_i, f_i and g_i) for the respective primary energy factors from each table in the NCM Guide [19, pp.59-60].

This Section, now documents the calculation methodologies for the two checks developed and documented in the extended Clause 2.3; BGGER vs TGGER and BCC vs TCC.

The **Greenhouse Gas Emission Rate** calculation methodology (BGGER vs TGGER) is the methodology for the uplift that replaces the Emission Rate check. This check is calculated by the summation of the products of the energy usage (by source) (denoted by a_i) and the respective market (b_i) from an appropriate LCI database (this research used ecoinvent 3.9) and is presented in Equation 6.2. Where n is the number of energy sources:

$$\sum_{i=1}^{n} a_\mathrm{i} b_\mathrm{i} = GreenhouseGasEmissionRate \tag{6.2}$$

The **Construction Cost** calculation methodology (BCC vs TCC) is the methodology for the uplift that enables construction phase GHG emission assessment. This check is calculated by the summation of the products of the material quantities (denoted by a_i) and the respective market (b_i) from an appropriate LCI database, with the total being dividing by an assumed 60-year life span inline with institutional and industry recommendations [5, p.42] and is presented in Equation 6.3. Where n is the number of energy sources:

$$(\sum_{i=1}^{n} a_\mathrm{i} b_\mathrm{i})/60 = ConstructionCost \tag{6.3}$$

6.1.7 Assessor Workflow

With the previous subsections covering the Designers workflows, this subsection discusses the Regulatory Assessor's workflow. A sequence diagram is presented in Figure 6.4 to illustrate this process.

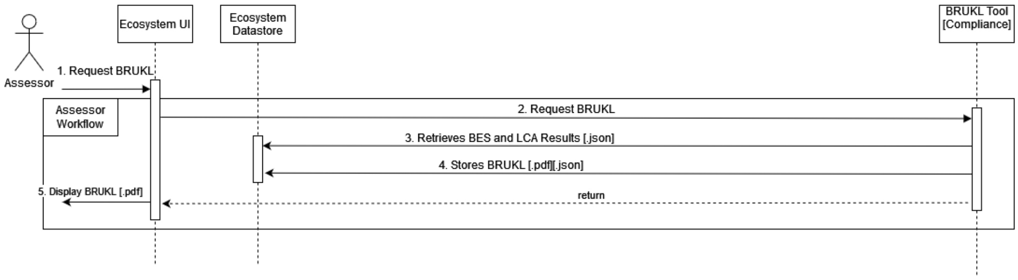


Figure 6.4: Co-simulation Sequence Diagram for the Regulatory Assessor, Arrows Refer to Processes.

In these processes, the assessor requests to view the BRUKL document output. The ecosystem UI will request the .pdf document from the BRUKL Tool, which retrieves the most recently uploaded BES and LCA co-simulation results. A new .pdf is generated by the BRUKL tool, which is then displayed to the assessor.

6.1.8 Author Workflow

This subsection discusses the regulatory author's workflow, Figure 6.5 presents a sequence diagram describing this process.

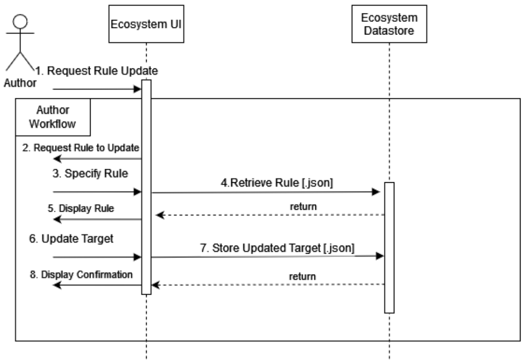


Figure 6.5: Co-simulation Sequence Diagram for the Regulatory Author, Arrows Refer to Processes.

The regulatory author requests to update a rule via the ecosystem UI, the UI will ask the author to specify the rule to update, in this case, the progressively ratcheting emission targets for net zero. The UI will retrieve the specified rule in .json format before displaying this to the author for updating. Once the author has updated the target, the new value is stored in the ecosystem datastore before confirmation is displayed to the author.

6.2 Conclusion

This section has introduced and described each element of the automated co-simulation architecture. With the co-simulation architecture integrated into the digital framework as an additional service, the user is able to access both the BIM and associated functionality for both BES and LCA purposes (derived from E+ and BW2 respectively). The user (Designer) is able to use this architecture for both design and regulatory purposes. For design workflows, the Designer is able to represent dynamacity in the operational phase of the building through time-differentiated LCA results, better informing the building design. For compliance workflows, the Designer is able to check the compliance of their building design and at a later stage, submit the BRUKL output alongside the rest of the project submission. Similarly, the assessor is able to retrieve this output. For the regulatory author, updating rules in line with the progressively ratcheting emissions targets for net zero is facilitated through the ecosystem UI and datastore.

Chapter 6 concludes the development activities of this Thesis, the following Chapter will validate the Digitised, Design and Regulatory Framework for BES and LCA Co-simulation. This will be achieved through the integration of the co-simulation service within the digital framework as a proof-of-concept. This proof-of-concept will be applied and explored against two BIMs following a strategy of simulation research.

Chapter 7

Proof-of-concept and Validation

The wider, design and regulatory framework developed in Chapter 4 was augmented through automation and digitisation and aligned to the D-COM vision for ACC, with Chapter 5 presenting the digitised framework. The technical architecture for the automated, BIM-based, BES and LCA co-simulation was developed and presented in Chapter 6.

The co-simulation architecture is now integrated within the digitised framework as a proof-of-concept for validation and is presented in Figure 7.1. Figure 7.1 is annotated to highlight key elements and indicate particular points for discussion:

1. Purple elements denote elements that have been developed in this research
2. Blue elements denote elements implemented in this work, but developed in other research
3. White elements denote elements not developed nor implemented, but have been identified for future research
4. Orange elements denote open source free software tools that underpin this implementation
5. Red elements denote paid for licensed data
6. Green ticks denote elements of this research that have been completed and validated

7. Red crosses denote elements of the developed framework that are beyond the scope of this research and subsequent validation
8. '!' denote elements of this research that form key reflection points in Section 7.3

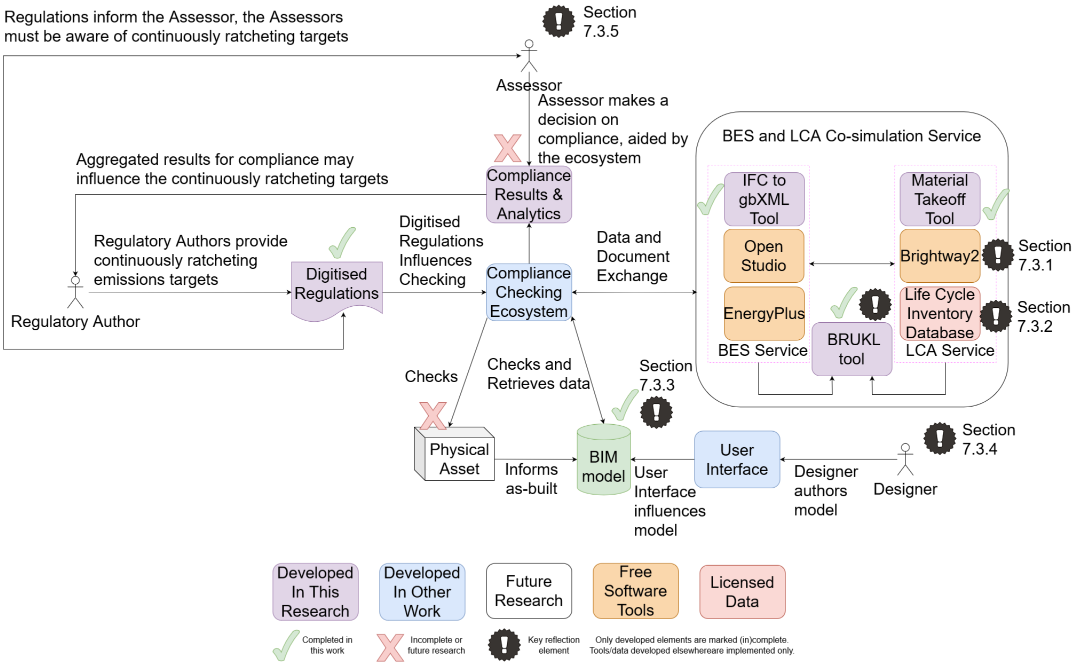


Figure 7.1: Automated and Digitised, Design and Regulatory Framework for BES and LCA Co-simulation.

The proof-of-concept has been implemented to address Research Question 3:

How would a BES and LCA co-simulation architecture be integrated into the wider UK building design and regulatory framework, to enable net zero and WLCA with regards to: (a) building design processes and (b) building regulatory processes

This question will be addressed by adopting a simulation research strategy, in which the framework and regulatory uplifts proposed in this research is demonstrated and contrasted against the existing processes.

This question has been decomposed into individual work and validation elements. With Figure 7.1 presenting the developed digitised framework, the work elements of this decomposition are complete, for reference these were:

1. **Work Element**: Development of a BES and LCA Co-simulation methodology (Chapter 6)
2. **Work Element**: Integration of the developed BES and LCA Co-simulation methodology within the defined Framework as a proof-of-concept (Figure 7.1)

The remainder of this Chapter focusses on the validation elements of the proof-of-concept implementation.

1. **Validation Element**: Validation of the proof-of-concept, by demonstrating the benefits arising from the **Design** aspects of the proposed framework when compared against existing processes
2. **Validation Element**: Validation of the proof-of-concept, by demonstrating the **Regulatory** aspects of the proof-of-concept and comparing existing requirements against those proposed in this work
3. **Validation Element** Reflection and evaluation of the proof-of-concept, focussing on the role automation and digitisation as enablers

Section 7.1 presents the demonstration of the Design aspects of the framework, addressing validation element 1. This is achieved through verification of the framework against a case study building (modelled for the early design stage), that is co-simulated and explored from the perspective of a Designer. The case study explores a University building during the early design stage, to illustrate the applicability to non-domestic buildings. The co-simulation design demonstration investigates three scenarios and compares the sequential results from dynamic co-simulation against current static methods. The impact of dynamic BES and LCA co-simulation results for the Designer and GHG assessment is discussed.

Validation element 2 is addressed in Section 7.2, through the demonstration of the Regulatory aspects of the framework. The Regulatory aspects of the framework concern the submission of the 'as-designed' BRUKL (presented in Chapter 4) by the Designer. The calculation methodologies are the same for the two BRUKL's (as-designed or as-built), however, for the former, the model being checked is as-designed following the early (concept) design stages. The latter model is as has been constructed or as-built, and follows after the construction stage. The suitability of the implementation is later discussed in relation to the 'as-designed' and 'as-built' BRUKL's in Section 7.3.2. The BRUKL (as-designed) is subject to automated compliance checking by the Assessor, aided by the Ecosystem (presented in Chapter 5). The Ecosystem's automated checking are based on metrics, prescribed by the Regulatory Author. This Section will co-simulate and generate a (proposed) BRUKL based on the *Example Building - Complete* model that is provided alongside the iSBEM Compliance Software Tool [120]. The, *Example Building* is a fully specified model of a mixed use building based in London. This model was chosen to provide a comparison using a fully specified model ready for compliance checking under current Part L standards. The selection of the *Example Building* further serves to highlight the high levels of compatibility with current processes by using a model that is an exemplar of current Part L assessment. In doing so, the validation is implicitly compatible with Part L and current processes.

Validation element 3 will be addressed in Section 7.3, This Section will evaluate and reflect upon the implementation of the proof-of-concept and discuss outcomes.

7.1 Demonstrating Design Aspects of the Digitised Co-simulation Framework

The Design Workflow aspects of the digitised, design and regulatory framework for BES and LCA co-simulation (illustrated in Figure 7.1) will be demonstrated in this Section. This validation is achieved through a simulation research strategy, in which this research will *experience* the outcomes of the proof-of-concept implementation of the proposed framework.

In this demonstration, alternative design options (scenarios) are explored for a University building during its early design phase. The modelled detail and complexity of the University building is representative of BIMs during the early design stages, and so, the applicability of this framework to the exploration of multiple design options is explored.

The University building is one of several buildings forming part of Cardiff University's School of Engineering Campus. Located in the centre of Cardiff city with a floor area of 3728 m2, this building is composed of three occupiable floors, containing various room types (laboratories, offices, dining spaces and restrooms).

For this demonstration, 3 scenarios have been co-simulated over an annual period:

1. Scenario 1 'Building Base': baseline scenario with typical occupancy and operation
2. Scenario 2 'Building reduced': with occupancy and operation reflecting the year 2020
3. Scenario 3 'Building reduced 0ht': per scenario 2 with further reduced heating load (where certain spaces have heating load reduced to zero assuming non-occupancy)

These scenarios were designed to capture real but extreme operating variations. By investigating real but highly varied scenarios, this validation will capture and illustrate the greatest impact that dynamic BES and LCA co-simulation results may have on the design process.

Regarding scenarios 2 and 3, these (co-)simulations applied occupancy and operational schedules derived from the year 2020. The year 2020 presented an abnormal operational period for buildings due to the COVID-19 pandemic, and so schedules for occupancy and operation are based on the Institute for Government COVID timeline in tantamount with the experience lived by the authors in their respective buildings [121].

These three scenarios have been explored with the purpose of illustrating the results outputted from the BES and LCA co-simulation architecture. Furthermore, the exploration of these scenarios provide the *experiences* for comparison and identification of the benefits of designing for operational emissions and WLCA. The co-simulation architecture enables dynamic, time-differentiated LCA results, and so, the benefits over traditional static results is explored, alongside implications for the Designer. By contrasting the results derived from the (co-)simulation of varying building operation scenarios, this validation captures the resulting effects on environmental impacts and how designers and managers can use that data. The results from these scenarios will evidence how the integration of BES and LCA in BES and LCA co-simulation can aid the design of the University building.

For each scenario, results obtained from implementation of the proof-of-concept are compared against those obtained from current LCA practices, i.e. the status quo. The aim of this demonstration is to experience and evaluate the outcomes of time-dimensioned results (obtained from the research developed in this Thesis), over static results (obtained from applying current LCA practices)

Figures 7.2 represents the IFC model forming the basis for the University building case-study. Figures 7.3 details the resulting spaces imported into OpenStudio.

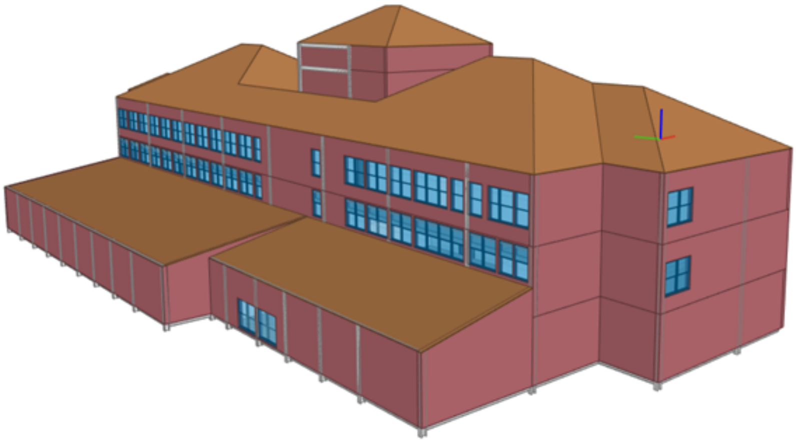


Figure 7.2: IFC representation of the University building

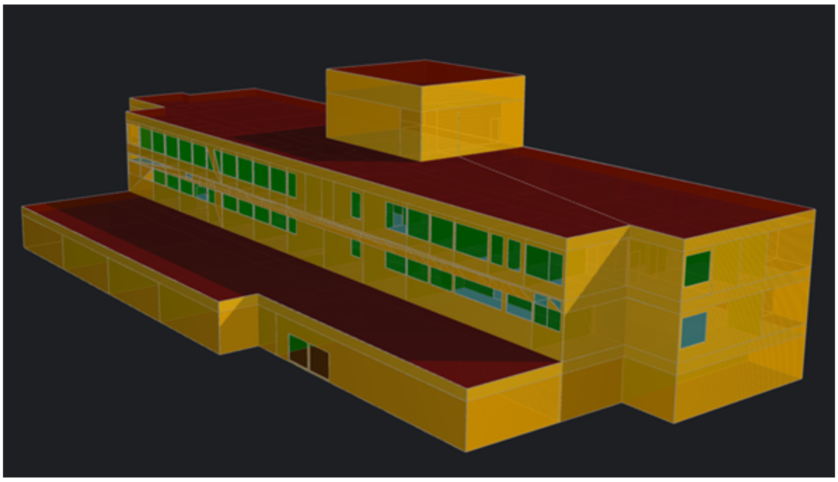


Figure 7.3: OS representation of imported spaces in the University Building

The following subsections will present the results obtained from current static LCA processes (Section 7.1.1) and the dynamic results obtained from the proof-of-concept implementation of the co-simulation framework (Section 7.1.2), before findings from the implementation and comparison are summarised in Section 7.1.3.

7.1.1 Static LCA Results - Current Practices

This subsection presents the results obtained from applying current LCA practices, which result in static results. Figure 7.4 presents LCA results under Scenario 1, for the University building's materials and energy consumption over an annual period. This validation assumed the lifespan of the building to be 60 years, inline with institutional and industry recommendations [5, p.42]. These results provide information on the GWP impact of the building and highlight areas for improvement. Figures 7.4, 7.5 and 7.6 present only relevant results to GHG emissions (GWP) and are normalised to the highest result in each impact category.

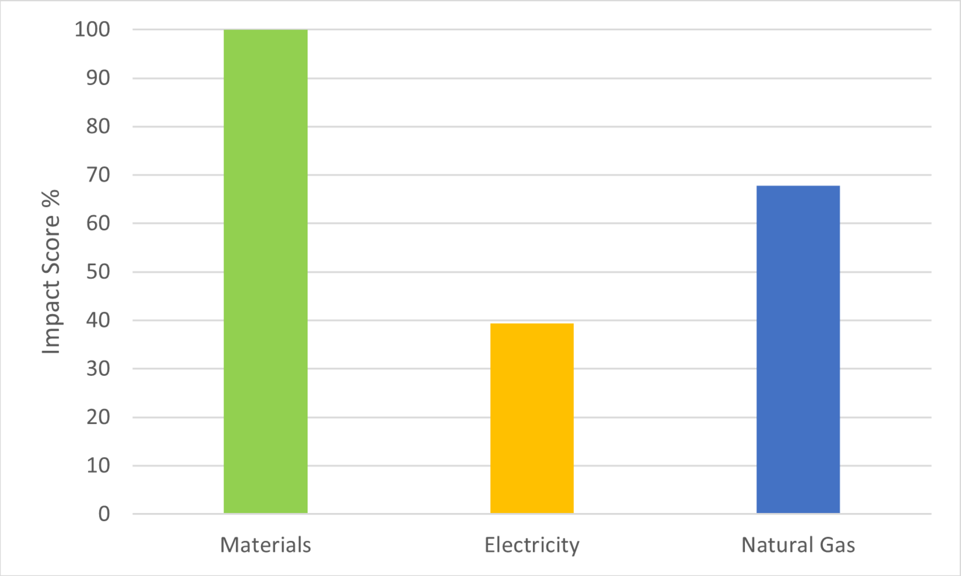


Figure 7.4: Scenario 1: GWP for Materials, Electricity and Natural Gas Over an Annual Period.

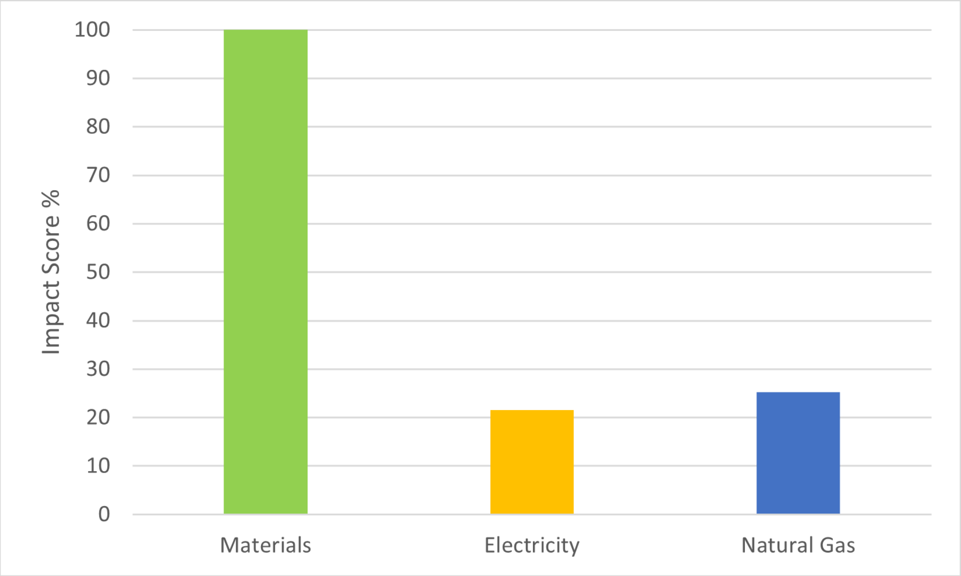


Figure 7.5: Scenario 2: GWP for Materials, Electricity and Natural Gas Over an Annual Period.

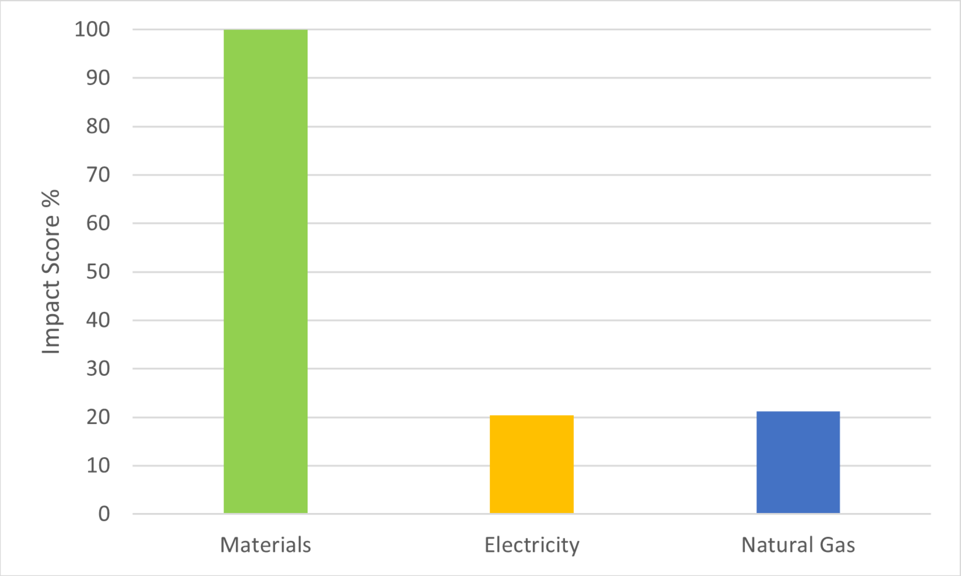


Figure 7.6: Scenario 3: GWP for Materials, Electricity and Natural Gas Over an Annual Period.

Comparing the results across the three scenarios, the material impact remains consistent as no changes have been made to the building fabric. Impacts from electricity and natural gas have been reduced in Scenario 2 and 3 through optimisation, with impacts from natural gas reduced to almost equal that of electricity consumption.

Finally, the material breakdown for the University building is presented in Figure 7.7, which further analyses the environmental impacts linked to the total materials demand, evaluating the weight of the different material types found in the BIM. Concrete dominates, which can be attributed to two factors: the large environmental footprint of concrete production, and the nature of the BIM process. In this BIM, structural elements defining the geometry of the building such as concrete were typically considered first, while other materials such as metal products (piping, cables, etc.) were left for a later stage of the design process.

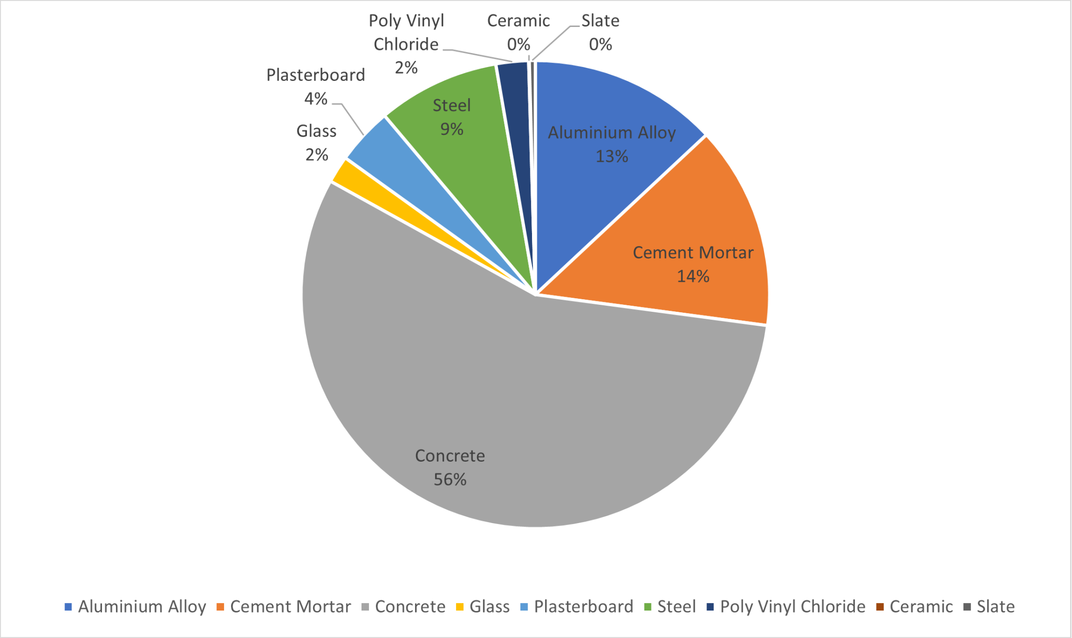


Figure 7.7: University Building Material Breakdown and GWP Percentage

7.1.2 Dynamic LCA Results - Proposed Framework

This subsection presents the dynamic results obtained from implementing the framework developed in this Thesis. Figure 7.8 presents the dynamic impacts on climate change (GWP) from the operation of the University building under the three different scenarios co-simulated. Decreasing occupancy and operation in the 'Reduced' scenario resulted in a 56% reduction of the total environmental impact. This reduction increased to 61% in the 'Reduced 0ht' scenario, where the heating load was reduced compared to the former scenario.

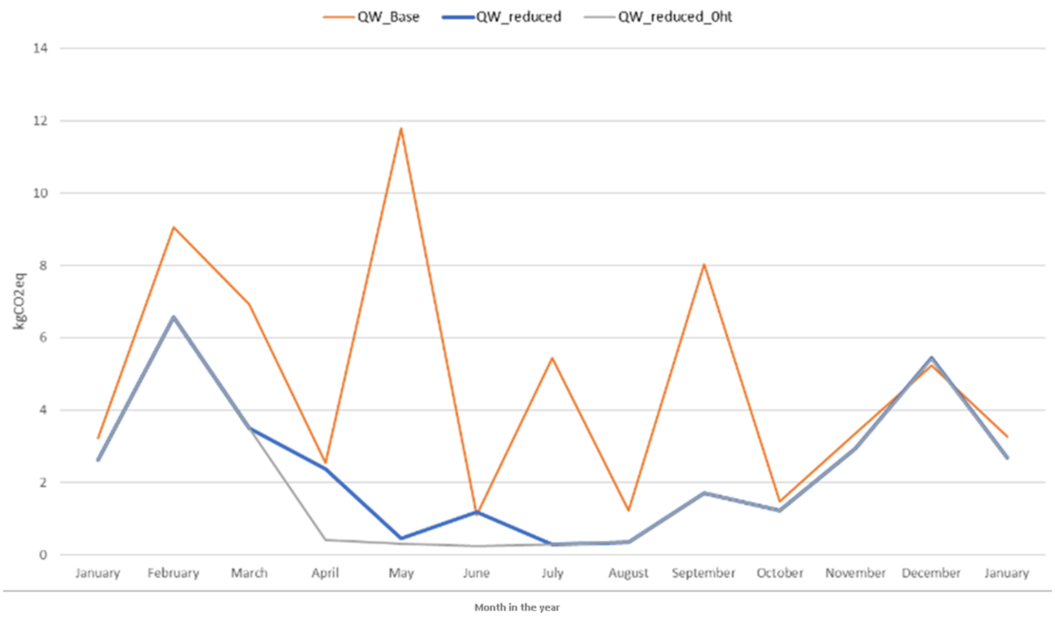


Figure 7.8: GWP Monthly Time Series for the University building

It should be explicitly clarified that the representation of GWP in Figures 7.8 has been abstracted, where a single data point for each month has been plotted for ease of dissemination in paper format, via the UI, these data points can be viewed in full (ten-minute time steps). Figures 7.9 similarly demonstrates an hourly time-series plot over a monthly period.

When analysing the results from Figures 7.4, 7.5 and 7.6 in contrast with Figures 7.8 and 7.9, one can see the value that can be derived from time-differentiated results. Figures 7.4, 7.5 and 7.6, show LCA results from the traditional static LCA perspective. In contrast, Figures 7.8 and 7.9, provide a time dimension to the GWP of the building as a whole.

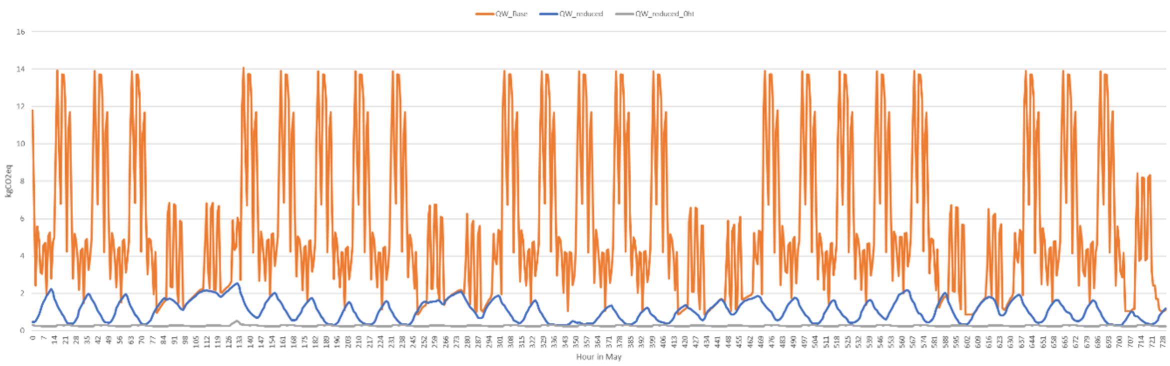


Figure 7.9: GWP Hourly Time Series for the University building

This allows the designer or manager to assess and intervene at a more granular and accessible level. For instance, whilst Figure 7.4 quantifies what element (natural gas, electricity or materials) has the greatest impact Figure 7.8 indicates when that element has a greater or lesser impact. When considering this with the ability to simulate different scenarios one can assess when interventions have the greatest resulting impact. For instance, changes in operation between the scenarios in Figure 7.8 had a great impact on GWP in May but little to no effect in December. Designers and managers are thus able to understand their impact on a much greater level. Dynamic co-simulation results and time-dimensioning of impacts enable a greater understanding of impacts in design evaluation, which in turn allows the simulation of more complex strategies that factor in dynamism.

In summary, the comparison of results obtained from traditional LCA processes and those obtained from the co-simulation framework have demonstrated that the framework provides dynamacity through time-dimensioning. Results in Section 7.1.1 allow for comparison of scenarios at an annual level, results in Section 7.1.2, outputted from the framework, allow for comparisons across the scenarios at a far more granular level (ten-minute timesteps). This allows for strategies and design options to be considered that account for seasonal operational variations and so, enable designers to pursue more specific and complex designs.

This section has demonstrated the processes and results obtained through, traditional and static LCA processes (Section 7.1.1) and dynamic BES and LCA co-simulation through the proof-of-concept implementation (Section 7.1.2). The demonstration of the implementation has validated the correctness of the framework (applied to the design aspects), as the framework has been demonstrated to provide not only that of traditional LCA processes, but also dynamacity (through time-dimensioning).

7.1.3 Summary of Findings

This Section has illustrated the value that can be derived from time-differentiated LCA results and has validated the correctness of the proposed framework, compared against traditional static processes. In simple terms, the benefits of such results over traditional static LCA results for a given period are primarily the dimensioning of environmental impacts over time, which in turn provides capability for the assessment of the whole building at a much more granular level than previously possible. At this granularity, designers and managers can explore and understand the outcomes of their interventions with much better accuracy (being able to capture exactly when the benefits occur as opposed to benefits gained over an aggregated period) and with much better focus on what and when the focus of improvements should be.

With regards to Research Question 3, this Section has demonstrated the early design stage Design aspects of the Digitised, Design and Regulatory Framework for BES and LCA Co-simulation and has identified the key benefits (namely accuracy, granularity and time-dimensioning) for the Designer over current processes. This section has demonstrated the early design stage design aspects of the framework for BES and LCA co-simulation against a simulation of current LCA practices, the key findings resulting from this demonstration are:

1. The proposed framework (and subsequent co-simulation architecture) has enabled GWP (and so GHG) design stage evaluation of BIMs.

2. The co-simulation architecture enables dynamic BES and LCA co-simulation results.
3. Dynamic BES and LCA co-simulation results dimension time in relation to GWP.
4. Time dimensioning of GWP enables designers to assess the impact of scenarios in greater granularity and so, allow for more complex strategies.
5. Time dimensioning is enabled through the co-simulation and required no additional modelling efforts beyond the typical BES enrichment process (discussed in Section 6.1.3).

7.2 Demonstrating Regulatory Aspects of the Digitised Co-simulation Framework

This Section will demonstrate the Regulatory aspects of the Digitised, Design and Regulatory Framework for BES and LCA Co-simulation. The Regulatory aspects of the framework concern the submission of the BRUKL (as-designed) (presented in Chapter 4 and is referenced as the Compliance Workflow in Chapter 6) by the Designer, for automated compliance checking by the Assessor, aided by the Ecosystem (presented in Chapter 5). The Compliance Workflow's covered in this Section apply when early design stage activities are concluded.

This Section will demonstrate the Regulatory Workflow aspects of the framework illustrated in Figure 7.1. Following a simulation research strategy, this Section applies the regulatory aspects of the framework on the *Example Building* (an exemplar compliance model), and compares the outcome against the current BRUKL document for the *Example Building*.

In the following, subsection 7.2.1 presents the relevant BRUKL output under current regulations for the *Example Building*. Subsection 7.2.2 presents the output under the requirements proposed in this Thesis (the uplifts), resulting from the framework co-simulation. Finally, the results of the two are compared in subsection 7.2.3.

The *Example Building* model is provided alongside the iSBEM Compliance Software Tool [120]. The *Example Building* is illustrated in Figure 7.10 and consists of a two-storey building, made up of Retail, Restaurant and Office building type zones, with a total floor area of 2900 m^2 [122, p.148].

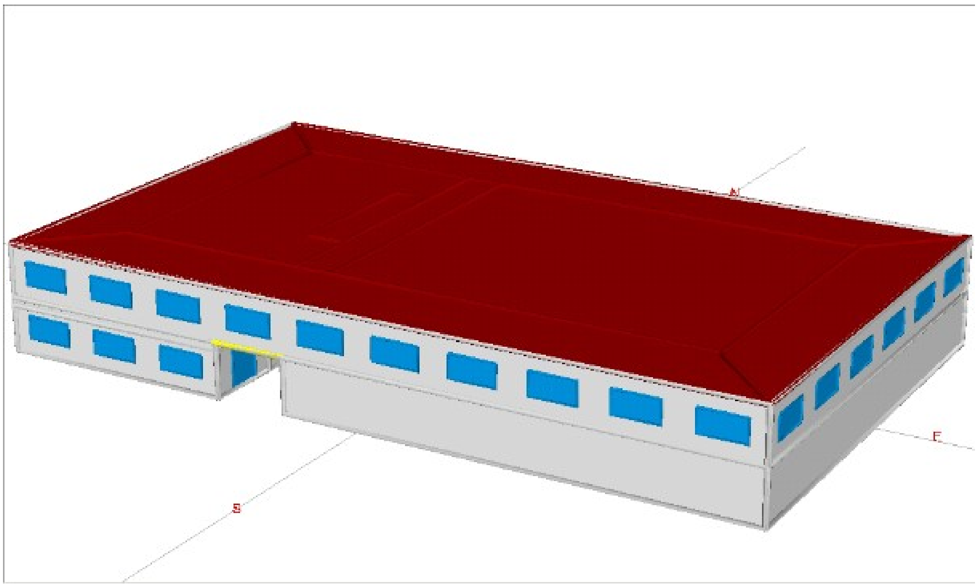


Figure 7.10: ***Example Building*** **[122, p.148]**

This model was chosen to provide a comparison against a fully specified model ready for compliance checking under current Part L standards, it further serves to highlight the high levels of compatibility with current processes.

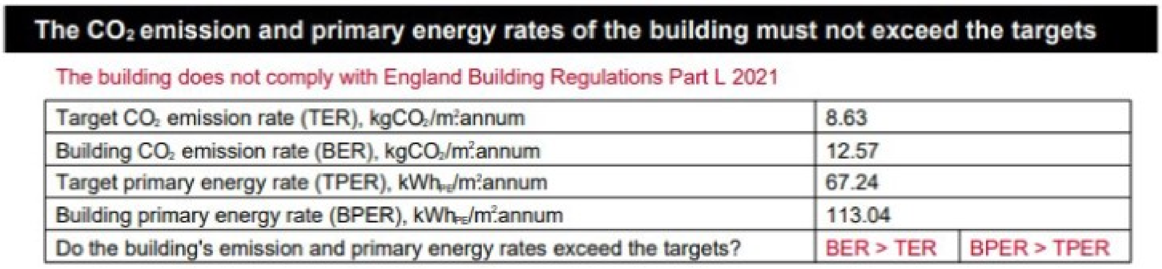
7.2.1 *Example Building* BRUKL Document - Current Requirements

This subsection presents the BRUKL output for the *Example Building*, assessed against current requirements, which are [7, p.10]:

1. Building Emission Rate (BER) < Target Emission Rate (TER)

2. Building Primary Energy Rate (BPER) < Target Primary Energy Rate (TPER)

A sample from the *Example Building's* BRUKL report, based on current standards is presented in Figure 7.11. The Figure indicates the BER, TER, BPER and TPER of the London based building (this Figure was previously used as an example in Chapter 4). The building contains mixed types, including retail, restaurants and offices.



The CO_2 emission and primary energy rates of the building must not exceed the targets

The building does not comply with England Building Regulations Part L 2021

Target CO_2 emission rate (TER), $kgCO_2/m^2annum$	8.63	
Building CO_2 emission rate (BER), $kgCO_2/m^2annum$	12.57	
Target primary energy rate (TPER), kWh_{PE}/m^2annum	67.24	
Building primary energy rate (BPER), kWh_{PE}/m^2annum	113.04	
Do the building's emission and primary energy rates exceed the targets?	BER > TER	BPER > TPER

Figure 7.11: ***Example Building*** **BRUKL report under current standards (2023)**

7.2.2 *Example Building* BRUKL Document - Proposed Requirements

A new proposed BRUKL section (presented in Chapter 4) has been generated for the *Example Building* model with the tool developed in Chapter 6, this is presented in Figure 7.12.

The proposed and developed BRUKL tool (Chapter 6), checks the extended Clause 2.3 (proposed in Chapter 4), through it's digitised form (Chapter 5). The proposed and extended Clause 2.3 requires that:

Building primary energy rate (BPER), building greenhouse gas emission rate (BGGER) and building construction cost (BCC) must not exceed the target primary energy rate (TPER), target greenhouse gas emission rate (TGGER) and the target construction cost (TCC).

As in the case of the current Clause 2.3, the extended Clause 2.3 must be adhered to at two stages (post detailed design and construction) and are referred to as, 'as-designed' and 'as-built' BRUKL's [7, p.10]. This research is limited to the 'as-designed' BRUKL.

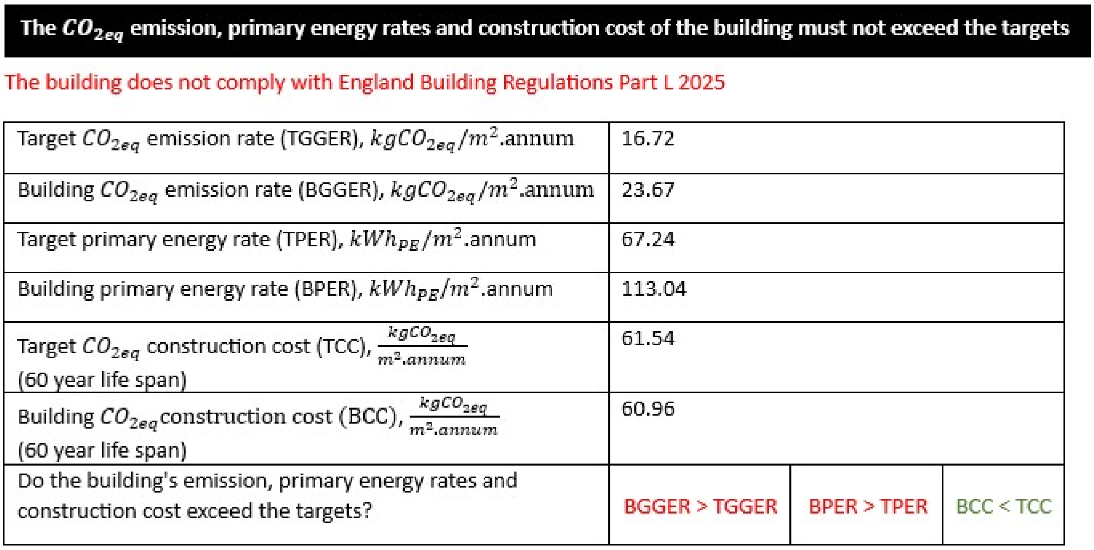
Figure 7.12 illustrates a sample of the 'as-designed' BRUKL generated based on the requirements proposed in this thesis, the extended Clause 2.3. Decomposed into individual digitised checks, the extended Clause requires the following:

1. Building Primary Energy Rate (BPER) < Target Primary Energy Rate (TPER)
2. Building Greenhouse Gas Emission Rate (BGGER) < Target Greenhouse Gas Emission Rate (TGGER)
3. Building Construction Cost (BCC) < Target Construction Cost (TCC)

The BPER vs TPER check remains unchanged from current requirements, however the BER vs TER check (which only assessed CO_2 emissions) has been replaced with the two uplifts proposed and digitised in this research, the BGGER vs TGGER check (which assesses GHG emissions with GWP) and the BCC vs TCC check (which assesses the GWP from constructing the building).

When validated, the BRUKL tool was successfully able to generate all the metrics (BPER, TPER, BGGER, TGGER, BCC and TCC) required by the extended Clause 2.3 (Figure 7.12). Similarly to the current BRUKL document (Figure 7.11), the metrics are presented as a fraction of the building total floor area.

An IFC model with equivalent geometry was authored to assess the proposed BCC vs TCC check for the *Example Building*, as the iSBEM model is not provided in IFC format and so the material quantities required for LCA could not be retrieved. The IFC model is presented in Figure 7.13.



The CO_{2eq} emission, primary energy rates and construction cost of the building must not exceed the targets

The building does not comply with England Building Regulations Part L 2025

Target CO_{2eq} emission rate (TGGER), $kgCO_{2eq}/m^2$.annum	16.72		
Building CO_{2eq} emission rate (BGGER), $kgCO_{2eq}/m^2$.annum	23.67		
Target primary energy rate (TPER), kWh_{PE}/m^2.annum	67.24		
Building primary energy rate (BPER), kWh_{PE}/m^2.annum	113.04		
Target CO_{2eq} construction cost (TCC), $\frac{kgCO_{2eq}}{m^2.annum}$ (60 year life span)	61.54		
Building CO_{2eq}construction cost (BCC), $\frac{kgCO_{2eq}}{m^2.annum}$ (60 year life span)	60.96		
Do the building's emission, primary energy rates and construction cost exceed the targets?	BGGER > TGGER	BPER > TPER	BCC < TCC

Figure 7.12: Proposed BRUKL targets section

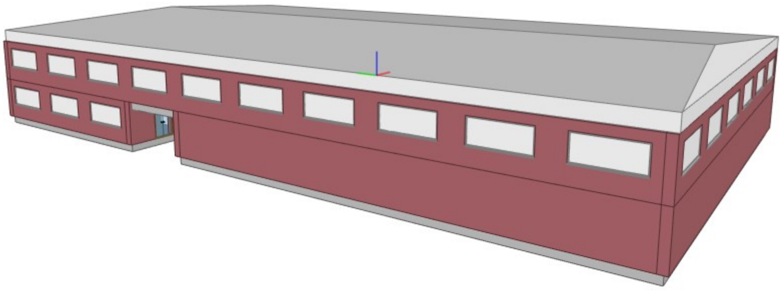


Figure 7.13: *Example Building* IFC

It was necessary to assume fabric constructions as the iSBEM model only contains data on the thermal performance (U-value) of the constructions and not the fabric that they consist of. Therefore, this research assumed fabric constructions for the notional building that achieve the U-value performance in the *Example Building* (illustrated in Table 7.1).

Table 7.1: *Example Building* Notional Constructions and Thermal Performance [122, p.149]

Construction	**U-value W/m^{2}K**
Roof	0.15
Ground	0.18
Internal Floor/Ceiling	0.25
Internal Walls	1.7
External Walls	0.16
Glazing	1.5
Doors	2

These fabric constructions were assumed, utilising standardised data from the Tables of U-values and thermal conductivity document by the Scottish Building Standards Agency [123]. This document provides tabular thermal performance data for typical performance with typical fabric constructions, there is no equivalent document published by England or Wales. A breakdown of the materials in the notional *Example Building* IFC and their associated portion of the Global Warming Potential is presented in Figure 7.14.

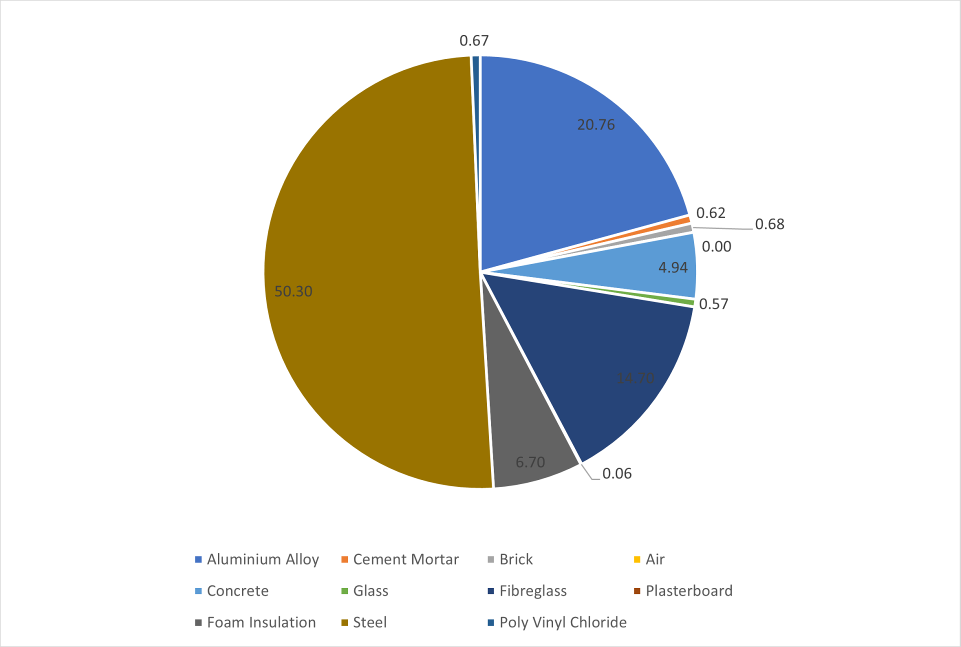


Figure 7.14: Notional *Example Building* Material Breakdown and GWP percentage.

Similarly, in order to illustrate the BCC element of the check, the IFC model assumed fabric constructions for the ’actual’ *Example Building*, this time achieving the limiting U-value performance prescribed in the current, Approved Document Part L 2023 [7, p.25], described in Table 7.2. This document does not stipulate internal constructions and so the values from the NCM Guide have been retained.

Table 7.2: *Example Building* Actual Constructions and Thermal Performance

Construction	**U-value W/m^{2}K**
Roof	0.16
Ground	0.18
Internal Floor/Ceiling	0.25
Internal Walls	1.7
External Walls	0.26

Continued on next page

Table 7.2: *Example Building* Actual Constructions and Thermal Performance (Continued)

Construction	**U-value W/m^{2}K**
Glazing	1.6
Doors	3

A breakdown of the materials in the actual *Example Building* IFC and their associated portion of GWP is presented in Figure 7.15.

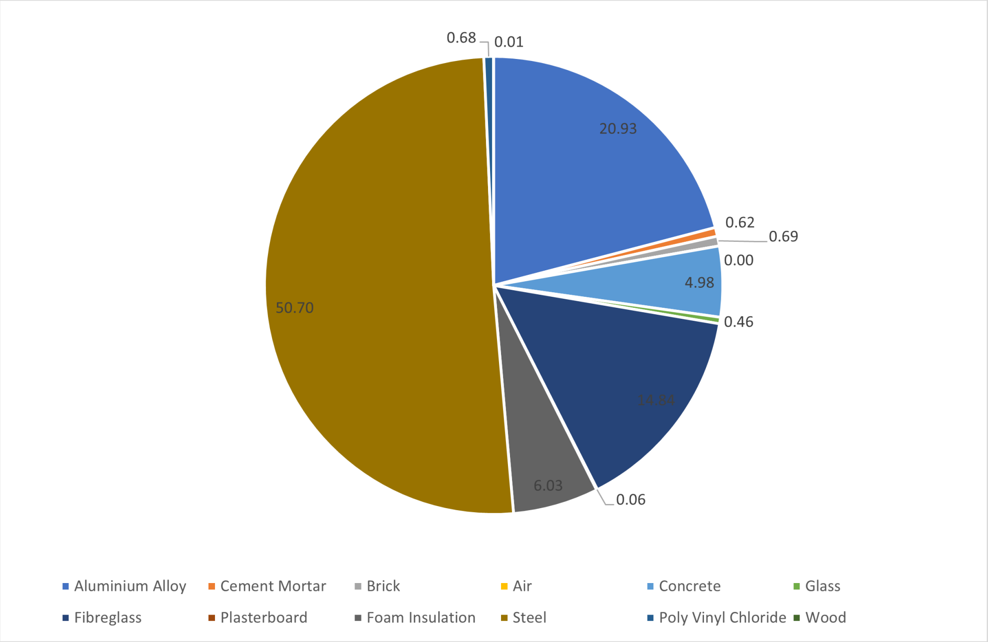


Figure 7.15: Actual *Example Building* Material Breakdown and GWP percentage.

The *Example Building* fails the first two checks (BPER vs TPER and BGGER vs TGGER) but passes the BCC vs TCC check. Regarding the BPER vs TPER results from the proposed BRUKL (Figure 7.12), these values remained the same as the *Example Building* BRUKL under current requirements (Figure 7.11). This is expected as the calculation methodology and model is consistent across the two comparisons. The equivalence of the two, validates the correctness of the calculation methodology of the proposed BRUKL. The *Example Building* fails this check under both current and proposed standards as the notional building contains specifications for renewable energy.

Regarding the BGGER vs TGGER results from the proposed BRUKL (Figure 7.12), these values have no direct equal under current requirements (Figure 7.11). It is however, derived from the BER and TER check and differs by the inclusion of CO_2 equivalenced GHG. Whilst this check failed for the *Example Building* under proposed requirements, it is logical as the *Example Building* failed under current requirements. Again, this validates the consistency of the checks in the proposed BRUKL as it would be illogical for the *Example Building* to pass this metric (BGGER vs TGGER) when it did not pass the BER vs TER check.

The *Example Building* did however, pass the new proposed BCC vs TCC check. The U-values used in the actual building are less onerous than those of the notional, meaning the thermal performance is less. This also means however, that the amount of insulating materials is less, and so the environmental impact from construction is less. This finding, brings forth an interesting point regarding GHG emissions (and thus environmental performance), in that assessing lifecycle phases of a building in isolation illustrates a limited picture. If only operational checks were considered (BGGER vs TGGER and BPER vs TPER), the *Example Building* unanimously fails. If only construction checks were considered (BCC vs TCC), the *Example Building* would pass.

The time required to digitise Approved Document L2A was 83 hours, which involved the digitisation of the entire human-readable regulatory document. This is a one-off process and is not envisaged to take place with every update to regulations, rather, once existing documents are digitised, updating regulations may be performed on the digitised, machine-readable versions. This has been explored in Sections 5.3.2 and 5.3.3. The time taken to digitise a single Clause was 26 minutes.

A comparison was conducted to compare the time taken to perform a manual vs an automated compliance check, this is presented in Table 7.3.

Table 7.3: Compliance Checking Manual vs Automatic Comparison

Document	**L2A *and regulatory uplifts**
Example Building (manual)	2 hours
Example Building (automatic)	13 minutes*

The 13 minutes described in Table 7.3, is the time taken for the D-COM ecosystem to complete the automatic compliance checking of Approved Document Part L2A, with the regulatory uplifts.

The 2 hours described in Table 7.3, is the time taken for a real building compliance officer to conduct a compliance check of Approved Document Part L2A.

In both instances, the time taken to check is based not only the regulatory uplifts, proposed in this work, but the entire Approved Document Part L2A.

These figures, quantify the benefit for the Assessor in reducing the time required to complete checking of a building design. For the comparisons against Part L, the time taken to check the *Example Building* was reduced by 89%, compared to the current (manual) counterpart.

These quantifications of time and comparisons of time taken to perform compliance checking, illustrate how automation and digitisation may save time and the associated costs with regards to Regulatory Authors and Assessors.

7.2.3 Summary of Findings

In summary, this section has demonstrated the new BRUKL tool and the resulting BRUKL output (Section 7.2.2), this is presented in contrast to the existing BRUKL output (Section 7.2.1.). The demonstration has shown that the new BRUKL tool is correct in its representation of the BPER VS TPER check (as compared against the existing counterpart). This provides confidence that the formation of the newly developed metric checks are correct in there representation. Furthermore, it has demonstrated a manner in which current requirements are adapted to assess GWP in the construction and operational phase, aligning (within the scope of this Thesis) recommendations for WLCA to enable the net zero vision.

The proof-of-concept implementation has illustrated the GWP assessment of the requirements proposed in this Thesis (TGGER vs BGGER and TCC vs BCC requirements) and the correctness and logical rationale behind them has been discussed. This discussion highlights the importance of implementing the end-of-life stage, as the implementation of the construction and operational stages each conclude opposing results when viewed in isolation (*Example Building* fails the operational stage but passes the construction).

This has verified the applicability of this framework in terms of Regulatory aspects and through demonstration has illustrated the viability of this framework for the 'as-designed' BRUKL stage.

In summary, the key findings resulting from the demonstration of this proof-of-concept implementation are:

1. Regulatory uplifts proposed in this research are able to assess GHG emissions in the construction and operation stage
2. BRUKL output from existing requirements aligns with those from the proposed requirements (and BRUKL tool), where they overlap (TPER vs BPER)
3. Exemplar compliance models (*Example Building*) fail both existing requirements and the associated ones proposed here.
4. Under the proposed requirements, low amounts of insulating materials mean that a BIM can pass the BCC vs TCC check, but fail the other two metrics.
5. Assessment of GHG emissions for a given stage, in isolation of others paints a very limited picture.

6. ACC of Part L with the proposed regulatory uplifts results in a 89% reduction in checking time.

The remaining sections in this Chapter will reflect further upon the proof-of-concept implementation of the framework for BES and LCA co-simulation. Outcomes and findings are discussed and evaluated in the following section.

7.3 Reflection and Evaluation of the Proof-of-concept

Thus far, this Chapter has demonstrated the Design and Regulatory Workflow aspects of the framework proof-of-concept implementation. The ’correctness’ of the representations of the proposed design aspects (Section 7.1) and the regulatory aspects (Section 7.2) of the framework have been validated against representations of existing design and regulatory processes This Section now reflects upon the proof-of-concept implementation and demonstration, in relation to the reflection points denoted in Figure 7.1. The reflection points discussed in the following subsections are key points that have developed through this authors experience of implementing the proof-of-concept for the purposes of design and regulation. The following subsections reflect on each of these topics: WLCA modules, LCI databases, BIM design and data and reflections directly from the implementation of the design and regulatory aspects of the framework.

7.3.1 WLCA Modules

This subsection refers to the ’!’ related to Brightway2 in Figure 7.1. Brightway2 is the underlying open source software package that facilitates LCA’s. This software is the LCA half of the BES and LCA co-simulation. The scope of this Thesis and the proof-of-concept is the construction and operational stages of a building’s life cycle, with a view to laying the foundations to implement WLCA in future work. In order to provide a first implementation this research integrated the developed BES and LCA co-simulation methodology within the ACC Ecosystem (developed by D-COM).

Industry and institutional recommendations for WLCA are underpinned by the EN 15978 modular LCA structure [5, p.10]. The modular structure allows for impacts to be assigned to the lifecycle stage they occur in.

To prove the concept, this research implemented Modules A1, A2, A3 and B6. This is not exhaustive, as modules; A4 and A5 (necessary information was unavailable from the LCI database), have not been implemented whilst, B1-5, B7 and C1-4 are out of scope. The following list indicates the modules implemented (or not):

1. Product Stage: **A1** - raw material supply, **Implemented**
2. Product Stage: **A2** - transport, **Implemented**
3. Product Stage: **A3** - manufacturing, **Implemented**
4. Construction Process Stage: **A4** - transport, **Not implemented**
5. Construction Process Stage: **A5** - installation process, **Not implemented**
6. Use Stage: **B1** - use, **Out of scope**
7. Use Stage: **B2** - maintenance, **Out of scope**
8. Use Stage: **B3** - repair, **Out of scope**
9. Use Stage: **B4** - replacement, **Out of scope**
10. Use Stage: **B5** - refurbishment, **Out of scope**
11. Use Stage: **B6** - operational energy, **Implemented**
12. Use Stage: **B7** - operational water, **Out of scope**
13. End of Life Stage: **C1** - de-construction, **Out of scope**

14. End of Life Stage: **C2** - transport, **Out of scope**
15. End of Life Stage: **C3** - waste processing, **Out of scope**
16. End of Life Stage: **C4** - disposal, **Out of scope**

This research validates the underpinning framework and architecture to facilitate these assessments. C1-4 concern the end-of-life stage which is beyond the scope of this research (along with B7), whilst B1-5 concern maintenance, repair, replacement and refurbishment, and so, not applicable to the early design stage. The remaining modules from the construction phase (A4, A5) have not been implemented and so not validated, this point for discussion is covered in the following Section, which elaborates on the role of the LCI database in relation to these modules and Section 7.3.3 does so similarly, with regards to BIM design.

Regarding those modules not implemented or out of scope, to ’complete’ the embodied phase, modules A4 and A5 should be implemented. The proposed framework is technically capable of this, however is dependent on the necessary data from installation to do so. A4 is easily calculated or measured, module A5 is more difficult as it would require an on-site record of demolition, this could be replicated in simulation research.

Module B1 refers to direct emissions from construction products, this was not suitable for modelling due to the scope of this research being limited to the ’as-designed’ BRUKL, however could be investigated as part of future ’as-built’ research, again specific selections should be made before implementing this step. Modules B2, B3, B5 were beyond the scope of this research as they regard maintenance and refurbishment. This research has demonstrated how embodied stage impacts can be designed and assessed, to enable these refurbishment modules, a refurbished BIM model could be produced and assessed, with the difference indicating the impact from refurbishment. B7 covers water use, this could be readily implemented within the current framework, approximations for water consumption could be made by the designer.

Modules C1-C4 regard the end-of-life stage and were beyond the scope of this research. This module represents the greatest difficulty in implementation and requires background information in the domain of circularity and knowledge of what happens to component at end-of-life. Furthermore, this research has used a 60-year RSP inline with industry and institutional recommendations for WLCA, however, the recommendations (and this author) agree that this period is arbitrary and implemented only for comparative purposes [5, p.42]. There are many questions to be answered in this area of research, should buildings be designed for a particular length of time? What happens if the buildings fails to achieve that lifespan? What happens if it stands longer than its lifespan? These questions should be addressed alongside completion of the remaining modules of the WLCA modular structure, through real-world testing.

7.3.2 LCI Database

This subsection refers to the '!' related to the LCI database in Figure 7.1. LCI databases provide the fundamental information that LCA's are based on, however, provides only generic data. This research used the ecoinvent database as it is the largest database available [37].

The scope of this Thesis is parallel to the 'as-designed' BRUKL, which covers the early design stages prior to attaining planning permission. At this stage in the UK building construction process, specific selection information is not available, for example, it is standard practice for BIM's to use generic models instead of specific models from manufacturers. Selections often change later on in the construction process. For this reason, this research implemented only modules A1, A2 and A3 using material base quantities and transport and manufacturing data available in ecoinvent.

Furthermore, the inventory built from ecoinvent was assumed to be scientifically valid. It is this authors opinion that it would be preferable for the inventory to be derived from a database managed in some part by the government in a more transparent manner. An 'as-built' version of this research could directly use Environmental Product Declarations (EPD), however there is no equivalent generic database suitable for the 'as-designed' counterpart. EPD's are declarations of a specific products environmental impact, which have not been discussed prior in this Thesis due to the scope being limited to the 'as-designed' BRUKL, however, is mentioned here to enable discussion on potential difficulties and solutions for real-world implementation.

In either instance, future work in this area is needed, areas to investigate before the framework can be applied in the real world to truly provide WLCA are; research into applying this framework at the 'as-built' stage and development a of UK building LCI database.

7.3.3 BIM Design and Data Suitability

This subsection refers to the '!' related to the BIM model in Figure 7.1. This research previously mentioned 'as-designed' and 'as-built' BRUKL's, which this author suggests is a possible solution to the generic vs specific data debate (Section 7.3.2). For 'as-designed' submissions, generic data will be used. For 'as-built' submissions specific information from EPD's will be used. Selections change often throughout the design, procurement and construction process and so generic models are more suitable than specific EPD information for the design stage. However, the inventory built through ecoinvent still lacked the information necessary to complete other modules of the construction stage, A4 (transport) and A5 (installation process).

In either instance, the implementation has proven that the framework facilitates the processes required for GHG design and assessment of buildings for BIM's. This has been validated in this research for the 'as-designed' BRUKL only. Whilst the 'as-built' BRUKL implementation should be covered in future work, this framework presents the means to do so, with an appropriate substitution of the LCI database (Figure 7.1). It is envisaged by the author of this research that the 'as-built' implementation may be more readily implemented than the 'as-designed'. At the 'as-built' stage, specific selections are finalised, and assuming that EPD's for those selections are available from an appropriate source, may be handled directly by the BRUKL tool instead of being calculated first through Brightway2, though this requires the necessary development activities.

7.3.4 Reflections from Implementation of the Design Aspect of the Framework

This subsection refers to the '!' related to the designer in Figure 7.1. Whilst benefits from the implementation of the proof-of-concept are demonstrable, it is of importance to this Research to explore and reflect upon other outcomes of the implementation.

Literature presented in Chapter 2 established that standard LCA's are estimated to consume 60% more time [116]. The proof-of-concept implementation presented little time burden for the simulations 'designer', information is automatically extracted from the IFC/BES and passed to Brightway2, however, this does not necessarily mean that there is no extra time requirement for the designer, at the very least, some time must be allowed to the designer to evaluate these results, with time-dimensioned results assumed to consume more time in evaluation due to there more granular nature.

In terms of balancing simplicity and complexity, this framework and co-simulation architecture was implemented in this Thesis by an author with experience in building design, BES and LCA and programming competency. For any lone researcher or designer, a similar skill set would be necessary to replicate this approach, however, assuming the use case of a typical designer within a larger organisation, the framework simplifies the designer's workflow. The Designer now needs only to manage one software tool (ecosystem) and model (BIM), whereas previously, the Designer was required to manage a BIM and recreate this in both BES and LCA tools. This is enabled through improved interoperability between BIM, BES and LCA tools, which avoids the manual re-entry of data. This enables the Designer to integrate GHG emission assessment from the early design stages.

7.3.5 Reflections from Implementation of the Regulatory Aspect of the Framework

This subsection refers to the '!' related to the assessor and the BRUKL tool. Aligning the framework developed in this work against the D-COM vision and integrating the BES and LCA co-simulation as a proof-of-concept means that there is little extra burden resulting from this Thesis beyond those already accepted with D-COM. Furthermore, whilst the proposals in this Research change the processes and outcomes of the regulatory aspects of the framework, no deviations from existing concepts are introduced, this Thesis has only extended and aligned existing concepts (for example; notional building), requirements (Part L, BRUKL) and industry and institutional recommendations (WLCA, RSP).

By extending and altering existing processes, it is envisaged that the transition and extra burden placed on the regulatory aspect is reduced. For example, whilst the individual metric checks are different, the process of compliance checking and approval for the regulatory assessor is not, fundamentally they still only need to refer to the submitted BRUKL document, which states whether the building complies, or not.

For the regulatory author, an outcome of this research is a mechanism to implement the recommended progressively ratcheting emission targets. It is important to stress, that progressively ratcheting emission targets is not an out outcome of this framework, only a mechanism to manifest it, rather it is a direct outcome of the net zero strategy and recommendations for WLCA.

7.4 Conclusion

The Digitised, Design and Regulatory Framework for BES and LCA Co-simulation has been developed and analysed with the purpose of answering the validation elements of Research Question 3. These validation elements were:

1. **Validation Element**: Validation of the proof-of-concept, demonstrating the **Design** aspects of the Framework
2. **Validation Element**: Validation of the proof-of-concept, demonstrating the **Regulatory** aspects of the Framework
3. **Validation Element** Reflection and evaluation of the proof-of-concept, focussing on the role automation and digitisation as enablers

Research Question 3 was:

How would a BES and LCA co-simulation architecture be integrated into the wider UK building design and regulatory framework, to enable net zero and WLCA with regards to: (a) building design processes and (b) building regulatory processes

Research Question 3 has been addressed by the development of the digitised framework (Figure 7.1) and digitisation of current and proposed requirements. Validation has been conducted through exploration of the design and regulatory aspects of the proof-of-concept implementation.

Thus, a BES and LCA co-simulation architecture can be integrated into the UK building Design and Regulatory Framework, aligning government requirements with industry and institutional recommendations for net zero and WLCA, using automation and digitisation technologies.

In this Chapter, Section 7.1 addressed validation element 1 through demonstrating the early stage Design aspects of the Digitised, Design and Regulatory Framework for BES and LCA Co-simulation (Section 7.1.2) Key findings from the design demonstration were:

1. The proposed framework (and subsequent co-simulation architecture) has enabled GWP (and so GHG) design stage evaluation of BIMs.
2. The co-simulation architecture enables dynamic BES and LCA co-simulation results.
3. Dynamic BES and LCA co-simulation results dimension time in relation to GWP.
4. Time dimensioning of GWP enables designers to assess the impact of scenarios in greater granularity and so, allow for more complex strategies.
5. Time dimensioning is enabled through the co-simulation and required no additional modelling efforts beyond the typical BES enrichment process (discussed in Section 6.1.3).

Section 7.2 addressed validation element 2 through demonstrating the post-design, 'as-designed' compliance submission stage of the Digitised, Design and Regulatory Framework for BES and LCA. In this Section, a proof-of-concept implementation of the framework and regulatory uplifts was implemented for validation, assessing against the proposed BRUKL requirements (Section 7.2.2) and the results discussed comparatively with an assessment against current requirements (Section 7.2.1). Key findings from the regulatory demonstration were:

1. Regulatory uplifts proposed in this work are able to assess GHG emissions in the construction and operation stage
2. BRUKL output from existing requirements aligns with those from the proposed requirements (and BRUKL tool), where they overlap (TPER vs BPER)

3. Exemplar compliance models (*Example Building*) fail both existing requirements and the ones proposed here.
4. Under the proposed requirements, low amounts of insulating materials mean that a BIM can pass the BCC vs TCC check, but fail the other two metrics.
5. Assessment of GHG emissions for a given stage, in isolation of others paints a very limited picture.
6. ACC of Part L with the proposed regulatory uplifts results in a 89% reduction in checking time.

Finally, validation element 3 was addressed in Section 7.3, which reflected upon the findings and experience of implementing the proof-of-concept implementation. The key reflection points discussed in this Section were:

1. A implementation has been conducted (the proof-of-concept) to check the correctness of the proposed framework and regulatory uplifts, against a simulation of the existing processes and requirements.
2. The proof-of-concept implemented WLCA modules A1, A2, A3 and B6, the remaining modules in the two phases within scope of this Thesis should not bear any specific technical challenge, though the data required for them requires future work.
3. An important question in the development of end-of-life stages is the appropriateness of the 60-year RSP recommended by industry and institutions, it is necessary for comparative assessment, however the question remains as to how reflective this is of the actual building.
4. The use of generic data from the LCI database is appropriate to the 'as-designed' BRUKL submission due to the use and specification of generic models and data, however it is assumed that this is not appropriate for the 'as-built' BRUKL which is out of scope for this research

5. To implement this framework across all lifecycles, there is need for a UK specific construction LCI database, for both generic models and those submitted by manufacturers (EPD's).

6. The proof-of-concept implementation was able to produce BES and LCA co-simulation results without any extra modelling effort or time beyond the typical design and modelling requirements. Furthermore, the designer similarly now manages only one software tool and so, the demands of incorporating dynamic LCA in early design is reduced.

The summary of findings and reflections concludes this Chapter, in which Research Question 3 has been addressed. The remaining Chapter, concludes this Thesis, in which this research will be summarised and future research is discussed at length.

Chapter 8

Conclusion

This Chapter will conclude this Thesis by re-visiting key elements of the research methodology and summarising the research conducted to address them. The following Section will revisit the research gaps identified in Chapter 2 and will re-introduce the hypothesis that dictated this research.

Sections 8.1 will summarise the research conducted to answer each research question. Section 8.2 will summarise the key contributions of this research. Limitations of this work are discussed in Section 8.3, before this Chapter outlines avenues for future research in Section 8.4.

8.1 Revisiting Research Gaps, Hypotheses and Research Questions

Chapter 2 identified a number of research gaps surrounding the UK government's net zero targets, which this Thesis has aimed to address. The research gaps were:

1. Net Zero targets have been established by the UK Government, however there is no clear methodology for how this can be achieved for buildings [3, p.3]., nor is there consensus with institutions and industry on the life cycles that should be assessed.

2. Calculation methodologies for LCA and WLCA exist, however there is no technical methodology/architecture integrating this with BES in a co-simulation necessary to design and regulate for progressively ratcheting emission targets [11]
3. No work exists that has enabled such a WLCA and BES co-simulation through BIM and ACC.

A hypothesis was formed to address this gap:

The integration of BIM, ACC and (BES and LCA) co-simulation within a digital, design and regulatory building framework will provide a pathway to net zero buildings and whole life carbon assessment that aligns governmental strategy with industry and institutional recommendations.

The following paragraphs will now summarise the Research Questions which were formulated to test these hypotheses.

Research Question 1 was: *What are the requirements in the UK regulatory landscape in terms net zero and how can they be aligned with recommendations for WLCA to deliver GHG assessment of UK buildings?*

In answer to this Research Question, Table 2.1 summarises the requirements and recommendations surrounding net zero and WLCA. Chapter 4 has documented the proposal and definition of a framework, which encapsulates the design and regulatory aspects of GHG emission assessment of buildings which addresses the *how?* element of this question. Furthermore, Chapter 4 identified that Clause 2.3 of Part L 2023 held the potential to facilitate GHG assessment, based on this clause, Chapter 4 proposed two regulatory uplifts to facilitate net zero and GHG in the construction and operational stages (as a proof-of-concept for) WLCA. These two uplifts, align the requirements for net zero with the recommendations made for WLCA.

Research Question 2 was: *What are the current accepted approaches for ACC within the UK regulatory building sector?*

Section 2.7, established that national adoption efforts for UK ACC has been conducted through the D-COM network, with the latest development being the ecosystem architecture for ACC.

Chapter 5 has augmented and aligned the framework for BES and LCA co-simulation with the D-COM ecosystem architecture. Furthermore, following the D-COM digitisation approach, Chapter 5 presented the digitisation of Approved Document Part L and the regulatory uplifts proposed in Chapter 4. This has been done to facilitate the proof-of-concept exploration of current processes with those proposed in this Thesis, presented in Chapter 7.

By augmenting the framework in alignment with D-COM and applying the digitisation process on relevant requirements, Research Question 2 has been addressed.

Research Question 3 was: *How would a BES and LCA co-simulation architecture be integrated into the wider UK building design and regulatory framework, to enable net zero and WLCA with regards to: (a) building design processes and (b) building regulatory processes*

This question was decomposed into individual work and validation elements, the work elements were completed in Chapter 6 and Chapter 7 respectively, and were:

1. **Work Element**: Development of a BES and LCA Co-simulation methodology (Chapter 6)
2. **Work Element**: Integration of the developed BES and LCA Co-simulation methodology within the defined Framework as a proof-of-concept (Figure 7.1)

The validation elements of the proof-of-concept implementation were:

1. **Validation Element**: Validation of the proof-of-concept, by demonstrating the benefits arising from the **Design** aspects of the proposed framework when compared against existing processes

2. **Validation Element**: Validation of the proof-of-concept, by demonstrating the **Regulatory** aspects of the proof-of-concept and comparing existing requirements against those proposed in this work
3. **Validation Element** Reflection and evaluation of the proof-of-concept, focussing on the role automation and digitisation as enablers

Validation element 1, which demonstrated the design aspects of the framework, concluded the following findings:

1. The proposed framework (and subsequent co-simulation architecture) has enabled GWP (and so GHG) design stage evaluation of BIMs.
2. The co-simulation architecture enables dynamic BES and LCA co-simulation results.
3. Dynamic BES and LCA co-simulation results dimension time in relation to GWP.
4. Time dimensioning of GWP enables designers to assess the impact of scenarios in greater granularity and so, allow for more complex strategies.
5. Time dimensioning is enabled through the co-simulation and required no additional modelling efforts beyond the typical BES enrichment process (discussed in Section 6.1.3).

With validation element 2, concluding:

1. Regulatory uplifts proposed in this work are able to assess GHG emissions in the construction and operation stage
2. BRUKL output from existing requirements aligns with those from the proposed requirements (and BRUKL tool), where they overlap (TPER vs BPER)

3. Exemplar compliance models (*Example Building*) fail both existing requirements and the associated ones proposed here.
4. Under the proposed requirements, low amounts of insulating materials mean that a BIM can pass the BCC vs TCC check, but fail the other two metrics.
5. Assessment of GHG emissions for a given stage, in isolation of others paints a very limited picture.
6. ACC of Part L with the proposed regulatory uplifts results in a 89% reduction in checking time.

Finally, validation element 3, reflected upon the following key points:

1. A simulation has been conducted (the proof-of-concept) to check the correctness of the proposed framework and regulatory uplifts, against a simulation of the existing processes and requirements.
2. The proof-of-concept implemented WLCA modules A1, A2, A3 and B6, the remaining modules in the two phases within scope of this Thesis should not bear any specific technical challenge, though the data required for them requires future work.
3. An important question in the development of end-of-life stages is the appropriateness of the 60-year RSP recommended by industry and institutions.
4. The use of generic data from the LCI database is appropriate to the ’as-designed’ BRUKL submission due to the use and specification of generic models and data, however it is assumed that this is not appropriate for the ’as-built’ BRUKL which is out of scope for this research
5. To implement this framework across all lifecycles, there is need for a UK specific construction LCI database, for both generic models and those submitted by manufacturers (EPD’s).

6. The proof-of-concept implementation was able to produce BES and LCA co-simulation results without any extra modelling effort or time beyond the typical design and modelling requirements. Furthermore, the designer similarly now manages only one software tool and so, the demands of incorporating dynamic LCA in early design is reduced.

Therefore, Research Question 3 has been addressed, the proof-of-concept implementation and Figure 7.1 detail the *How?* element of the question by integrating the co-simulation architecture into the framework. The framework proof-of-concept implementation has demonstrated how the framework will enable net zero and WLCA for UK buildings, with regards to the design and regulatory processes. The findings and reflections identified are the key outcomes of the simulation research implemented to address this question. The above reflection points provide the basis for future work, discussed in the following section.

Revisiting the hypothesis, this research can conclude that the following hypothesis is correct:

The integration of BIM, ACC and (BES and LCA) co-simulation within a digital, design and regulatory building framework will provide a pathway to net zero buildings and whole life cycle assessment that aligns governmental strategy with industry and institutional recommendations.

Chapter 7 has shown through demonstration that the use of BIM, ACC and BES and LCA co-simulation within a framework encompassing the design and regulatory elements necessary for GHG emission design and assessment can indeed provide a pathway that aligns the governments net zero strategy with recommendations from industry and institutions for WLCA.

This is however, only a pathway, and at the conclusion of this Thesis, is not yet ready for general use. What this Thesis has achieved is the implementation of WLCA modules A1, A2, A3 and B6 and the validation of the framework and co-simulation architecture, this was achieved through implementation and a comparison and reflection of the outcomes against current processes and requirements.

This outcome is valuable as; no previous research has enabled dynamic BES and LCA co-simulation results, furthermore no previous research has demonstrated methods for enabling GHG emission design and assessment of UK buildings, in particular in a manner aligning government, industry and institutional requirements and recommendations. Finally, the reflections culminating from this Thesis present insight (derived from experiencing the outcomes of this simulation research), which will guide future research in completing the necessary work to implement this framework in the real-world.

8.2 Key Contributions

This Section, will now summarise the key contributions of this Thesis before discussing them further. The key contributions are:

1. Digitisation of Approved Document Part L 2016, alongside updated relevant key clauses from the current Part L
2. Development and digitisation of the newly proposed regulatory uplifts that enable GHG emission assessment across construction and operational lifecycle stages through the proposed, extended Clause 2.3 and their associated calculation methodologies
3. Development of the newly proposed BRUKL tool to generate the new BRUKL metric tests resulting from the extended Clause 2.3
4. Development of the BES and LCA co-simulation architecture
5. Development of the Digitised, Design and Regulatory Framework for BES and LCA Co-simulation

6. Establishment of key findings resulting from the implementation of the research proposed in this research
7. Establishment of reflections which will guide future research in delivering WLCA for UK buildings

The first key contribution of this research is the **digitisation of Approved Document Part L 2016** in its entirety, **alongside updated (and digitised) relevant key clauses from the current Part L (2023)**.

The digitised Part L 2016 resulted in 193 compliance checks with 30 specifically relating to energy simulation. The time taken to digitise Part L 2016 was 83 hours, with the updating and digitisation of individual clauses requiring 26 minutes only. A comparison simulating the implementation of the proof-of-concept was compared against a simulation of the manual checking process which resulted in a reduction in time taken to check compliance of 89%.

Key contribution 2 is the **development and digitisation of the proposed extended Clause 2.3, alongside their respective calculation methodologies**. The extended Clause 2.3 is:

Building primary energy rate (BPER), building greenhouse gas emission rate (BGGER) and building construction cost (BCC) must not exceed the target primary energy rate (TPER), target greenhouse gas emission rate (TGGER) and the target construction cost (TCC).

Decomposed into individual digitised checks, the extended Clause requires the following:

1. Building Primary Energy Rate (BPER) < Target Primary Energy Rate (TPER)
2. Building Greenhouse Gas Emission Rate (BGGER) < Target Greenhouse Gas Emission Rate (TGGER)

3. Building Construction Cost (BCC) < Target Construction Cost (TCC)

These digitised checks were validated in the proof-of-concept implementation and simulation comparison, applied to the (the *Example Building*), with all proposed checks successfully being calculated by the developed BRUKL Tool, which forms key contribution 3.

Key contribution 3 comprises the **development of the newly proposed BRUKL tool** to generate the new BRUKL document that forms the basis for compliance assessment of the metric tests resulting from the extended Clause 2.3. When validated, the BRUKL Tool generated all required metric checks for the *Example Building*.

The *Example Building* fails the first two checks (BPER vs TPER and BGGER vs TGGER) but passes the BCC vs TCC check. It is worthwhile highlighting that the *Example Building* similarly failed in compliance with current metric tests (BER vs TER and BPER vs TPER).

Regarding the BGGER vs TGGER results from the proposed BRUKL (Figure 7.12), these values have no direct equal under current requirements (Figure 7.11). It is however, derived from the BER and TER check and differs by the inclusion of CO_2 equivalenced GHG. Whilst this check failed for the *Example Building* under proposed requirements, it is logical as the *Example Building* failed under current requirements. Along with BPER vs TPER check, this validates the consistency of the checks in the proposed BRUKL as it would be illogical for the *Example Building* to pass this metric (BGGER vs TGGER) when it did not pass the BER vs TER check.

The *Example Building* did however, pass the new proposed BCC vs TCC check. The U-values used in the actual building are less onerous than those of the notional, meaning the thermal performance is less. This also means however, that the amount of insulating materials is less, and so the environmental impact from construction is less. This finding, brings forth an interesting point regarding GHG emissions (and thus environmental performance), in that assessing lifecycle phases of a building in isolation illustrates a limited picture. If only operational checks were considered (BGGER vs TGGER and BPER vs TPER), the *Example Building* unanimously fails. If only construction checks were considered (BCC vs TCC), the *Example Building* would pass.

Key contribution 4 comprises the **developed and validated, open BIM based co-simulation architecture for BES and LCA**, applicable to whole buildings across both construction and operational phases. The developed architecture is the first to integrate E+ and BW2, both fully-fledged simulation software tools for BES and LCA respectively. It is also the first to integrate LCA and a nationally (UK) approved software program for BES [44].

Regarding electricity and heating consumption, the user interface enabled the execution of the LCA functionality via BW2, allowing for the integration of LCA results with a BES. Any changes made within the BES could then be injected back into the BIM. Thus, the LCA results were effectively integrated into the BIM, improving the comprehensive representation of the building's operational environmental impact.

The integration of E+ and BW2 has allowed this research to maintain a dynamic foreground inventory for electricity, heating and water. This approach provides more accurate estimates and time differentiated results, enabling analysis at a more granular level, allowing for investigations at particular points in time.

The co-simulation architecture can provide a fully-fledged assessment of building energy and life cycle impact from the early design stage. Application at the point of BIM creation reduces labour, time, and cost, in particular, removing the need to recreate geometry in multiple software applications.

The most time-consuming task in energy modelling is the creation of geometry alongside assignment of inputs such as constructions, internal gains and schedules [11]. This study makes a step forward by circumventing geometric problems with spaces and successfully converting the material properties.

Finally, this study demonstrates three different scenarios, representing variations in the building usage across the COVID-19 year. In terms of outcomes, this demonstration resulted in findings aligned with other studies [83], such as the ease of rapid test performance, ease of sub-system modelling distributed amongst a parallel team and a scalable approach. Regarding practical implications, this study has developed a clear and repeatable architecture for the co-simulation of BES and LCA - making a step forward in the co-simulation state of the art - which will enable and encourage further works in the co-simulation area. For industry professionals, this study presents a guide to provide time-differentiated/dynamic LCA results from BIM, addressing the demand to move beyond static LCA data.

Key contribution 5 in this Thesis is the **development of the Digitised, Design and Regulatory Framework for BES and LCA Co-simulation**. This contribution culminates and encompasses the previous key contributions and results in a holistic framework for the application of BES and LCA Co-simulation for both design and regulation workflows in the UK building industry.

This framework has been verified and validated in its applicability to the design and regulation of buildings through GHG emission assessment. This Thesis has assessed the outcomes from implementation of the proposed framework, against the outcomes resulting from a simulation of current practices.

Key contribution 6 of this research is the **establishment of key findings, resulting from the implementation of both current practices, and those proposed in this research**. These key findings have been summarised in Section 8.1.

Finally, key contribution 7 are the establishment of **key reflections which resulted from the comparison and reflection upon the implementation of the proposed framework and uplifts, compared against a simulation of current processes.** The key findings have been presented in Section 8.1.

8.3 Limitations

This section now discusses the key limitations of this research, with the first limitation identified from key contribution 5 of the previous section, the development of the Digitised, Design and Regulatory Framework for BES and LCA Co-simulation. The design, regulatory and validation workflows explicitly described in this Thesis have focussed on the construction and operational building lifecycles. Whilst the applicability to refurbishment is implicit through design, **this research has omitted the exploration of the deconstruction and demolition lifecycle**.

This is most relevant in considering the value of the Construction Cost check. For the case study *Example Building*, the building failed the GHG Emission Rate and Primary Energy Rate checks but passed the Construction Cost check. This calls into question the value of these checks when considered in isolation of each other, i.e. that assessing lifecycle phases of a building in isolation illustrates a limited picture. If only operational checks were considered (BGGER vs TGGER and BPER vs TPER), the *Example Building* unanimously fails. If only construction checks were considered (BCC vs TCC), the *Example Building* would pass. This implies that the 'true' assessment of a building and its environmental performance can be achieved only when considering all lifecycles.

Regarding the co-simulation architecture, this study has developed an 'open' approach, however, **dependency on proprietary tools/databases is not eliminated**. In both case-studies, the open co-simulation architecture was applied to BIM models authored in proprietary tools due to the lack of developed free and open source BIM authoring tools and the associated expertise in using them. Whilst the authoring of models in proprietary tools mirrors current processes and illustrates the compatibility and application to real world models, it does still form a cost barrier (though it may already be accounted for). Secondly, the co-simulation architecture is dependent upon a subscription based LCI Database.

In relation to the LCI Database, the integration of E+ and BW2 has allowed this study to maintain a dynamic foreground inventory for electricity, heating and water. However, the foreground activities are only linked to static background processes from the LCI database ecoinvent and so **further dynamacity may be developed**.

8.4 Future Research

This section now identifies future research based on this Thesis.

Future research, should complete the remaining WLCA modules not implemented in this research, those are, **Modules: A4, A5, B1-5 and B7.** Furthermore, research should extend and complete the inclusion of building lifecycle phases in this research by extended the BRUKL proposed in this research to **cover the end-of-life stage of a building**, only then can the buildings impact be fully assessed. In particular, the **correctness of the 60-year RSP, should be assessed**.

The co-simulation architecture enables dynamic and time differentiated results for environmental impact, however this **dynamacity is still derived from static data from the LCI Database**. Future research around the concept of a UK building sector specific database should also explore dynamic inventory data, which is particularly applicable to electricity consumption.

Similarly, this research has found proven that dynamacity is possible on the design side of the proposed framework, however the regulatory side remains static, the **appeal and feasibility of dynamic compliance checking should be explored.**

For a truly **free and open framework**, future research should explore the validation of BIM's authored in free and open authoring software. Similarly, the concept of a UK building sector specific database should be explored, with the intention of replacing the proprietary LCI database used in this research with an open, transparent and publicly available source, with some overarching governance by the Regulatory Author.

Regarding BIM design and modelling, research should be conducted to **analyse the impact of the inclusion of different building elements in the BES and LCA Co-simulation assessment**. This research included those elements dictated by current Part L requirements in order to validate the technical application of this Framework, however the question of what should be included in future applications of the Digitised, Design and Regulatory Framework for BES and LCA Co-simulation has not been explored, this would aid in the implementation of the remaining WLCA modules.

Finally, the research presented in this Thesis, is the result of simulation research, therefore, before the work developed in this research can be deemed ready for general use, the application of **this research should be applied to real-world case studies, and ideally, real-world users should be sought for testing.** Results from real-world implementation would be comparatively useful in identifying further areas of development and areas of conflict. Furthermore, the proof-of-concept implementation has not validated the robustness of the framework deployed at scale and so, prior to national adoption, **error management, quality assurance and scalability should be investigated.** Similarly, validation of the regulatory authors use of the framework to provide ratcheting emissions targets should be performed.

8.5 Conclusion

This Thesis now concludes having developed, documented and validated the Digitised, Design and Regulatory Framework for BES and LCA Co-simulation. This framework has been validated through demonstration on non-domestic buildings and the applicability from early design through to compliance submission has been verified.

This framework has been developed with the purposes of addressing the research gaps identified at the genesis of this research work:

1. Net Zero targets have been established by the UK Government, however there is

no clear methodology for how this can be achieved for buildings [3, p.3], nor is there consensus with institutions and industry on the life cycles that should be assessed.

2. Calculation methodologies for LCA and WLCA exist, however there is no technical methodology/architecture integrating this with BES in a co-simulation necessary to design and regulate for progressively ratcheting emission targets [11]
3. No work exists that has enabled such a WLCA and BES co-simulation through BIM and ACC.

Research Gap 1 has been addressed for UK buildings by the development of the framework, which incorporates BES and LCA co-simulation architecture and the new BRUKL tool that provides the calculation methodologies to enable the assessment of GHG emission of buildings. Furthermore, a proposed BRUKL document has been developed and generated for a case study building illustrating a clear and viable process for assessing buildings based on progressively ratcheting emission targets.

Research Gap 2 has been addressed through the development and specification of the BES and LCA Co-simulation Architecture. This architecture has been developed to function as a service within the ecosystem architecture developed by D-COM.

Finally, Research Gap 3 has been addressed by the implementation of the Digitised, Design and Regulatory Framework for BES and LCA Co-simulation as a proof-of-concept. Validation has been achieved through simulation research, which compared the application and outcomes of the processes and practices proposed in this Thesis, and those of current practices. In both the design and regulatory cases, the proof-of-concept was able to achieve what traditional processes are capable of and beyond. On the design side, the framework provided dynamacity through time-dimensioning, affording greater insight into building design. On the regulatory side, the framework was successful in calculating the proposed requirements, and when comparing against the existing requirements, outcomes were logical.

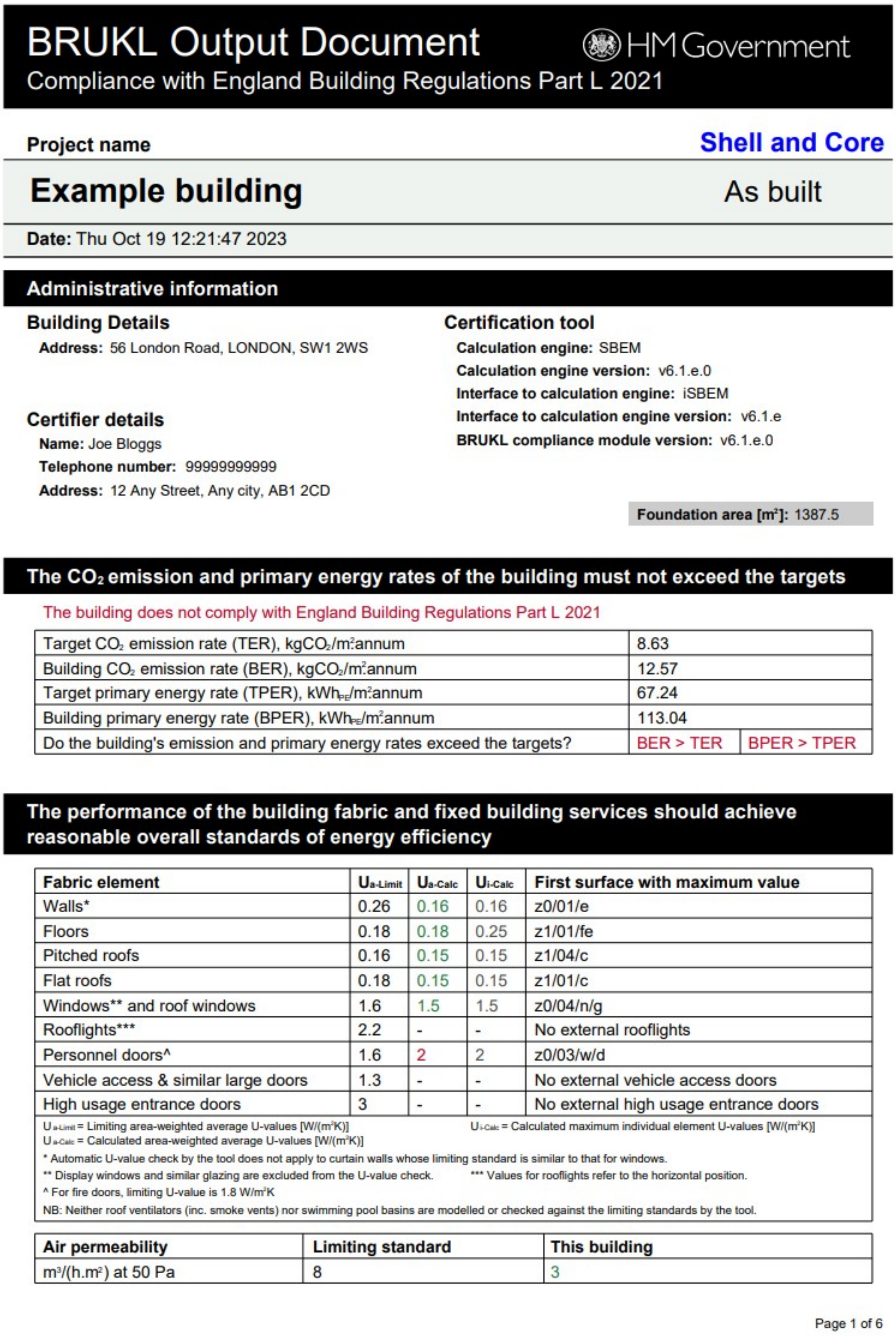
The Hypothesis has been judged to be correct, with Chapter 7 validating the the Digitised, Design and Regulatory Framework for BES and LCA Co-simulation.

To conclude, at the onset of this Thesis, the question was posed as to whether the ’C’ in WLCA should refer to *carbon* as it currently does, or to *cycle* as it does in LCA. Either way, in comparison to the technical concepts discussed in this Thesis, nominal issues are of little importance, however this issue is representative of the greater disparity between government requirements and recommendations from industry and institutions. The author of this Thesis concludes that whilst not the most important issue in this domain, the use of *carbon* in *WLCA* is inherently wrong, though not unacceptable. The use of *cycle* would better align with the underlying calculation methodology that is LCA, and would provide better consistency and clarity for governmental bodies, institutions and industry to achieve net zero. Better alignment would facilitate greater understanding and discussion across the UK construction sector, which is important as there are still many elements of future research to resolve before this framework can be implemented at a national level.

Appendices

Appendix A: Sample BRUKL Document

For brevity only key pages (1 and 5) of the BRUKL document are provided here for illustration



BRUKL Output Document

HM Government

Compliance with England Building Regulations Part L 2021

Project name **Shell and Core**

Example building As built

Date: Thu Oct 19 12:21:47 2023

Administrative information

Building Details

Address: 56 London Road, LONDON, SW1 2WS

Certifier details

Name: Joe Bloggs

Telephone number: 99999999999

Address: 12 Any Street, Any city, AB1 2CD

Certification tool

Calculation engine: SBEM

Calculation engine version: v6.1.e.0

Interface to calculation engine: iSBEM

Interface to calculation engine version: v6.1.e

BRUKL compliance module version: v6.1.e.0

Foundation area [m²]: 1387.5

The CO₂ emission and primary energy rates of the building must not exceed the targets

The building does not comply with England Building Regulations Part L 2021

Target CO₂ emission rate (TER), kgCO₂/m².annum	8.63	
Building CO₂ emission rate (BER), kgCO₂/m².annum	12.57	
Target primary energy rate (TPER), kWh$_{PE}$/m².annum	67.24	
Building primary energy rate (BPER), kWh$_{PE}$/m².annum	113.04	
Do the building's emission and primary energy rates exceed the targets?	BER > TER	BPER > TPER

The performance of the building fabric and fixed building services should achieve reasonable overall standards of energy efficiency

Fabric element	$U_{a\text{-}Limit}$	$U_{a\text{-}Calc}$	$U_{i\text{-}Calc}$	First surface with maximum value
Walls*	0.26	0.16	0.16	z0/01/e
Floors	0.18	0.18	0.25	z1/01/fe
Pitched roofs	0.16	0.15	0.15	z1/04/c
Flat roofs	0.18	0.15	0.15	z1/01/c
Windows** and roof windows	1.6	1.5	1.5	z0/04/n/g
Rooflights***	2.2	-	-	No external rooflights
Personnel doors^	1.6	2	2	z0/03/w/d
Vehicle access & similar large doors	1.3	-	-	No external vehicle access doors
High usage entrance doors	3	-	-	No external high usage entrance doors

$U_{a\text{-}Limit}$ = Limiting area-weighted average U-values [W/(m²K)]
$U_{i\text{-}Calc}$ = Calculated maximum individual element U-values [W/(m²K)]
$U_{a\text{-}Calc}$ = Calculated area-weighted average U-values [W/(m²K)]

* Automatic U-value check by the tool does not apply to curtain walls whose limiting standard is similar to that for windows.

** Display windows and similar glazing are excluded from the U-value check. *** Values for rooflights refer to the horizontal position.

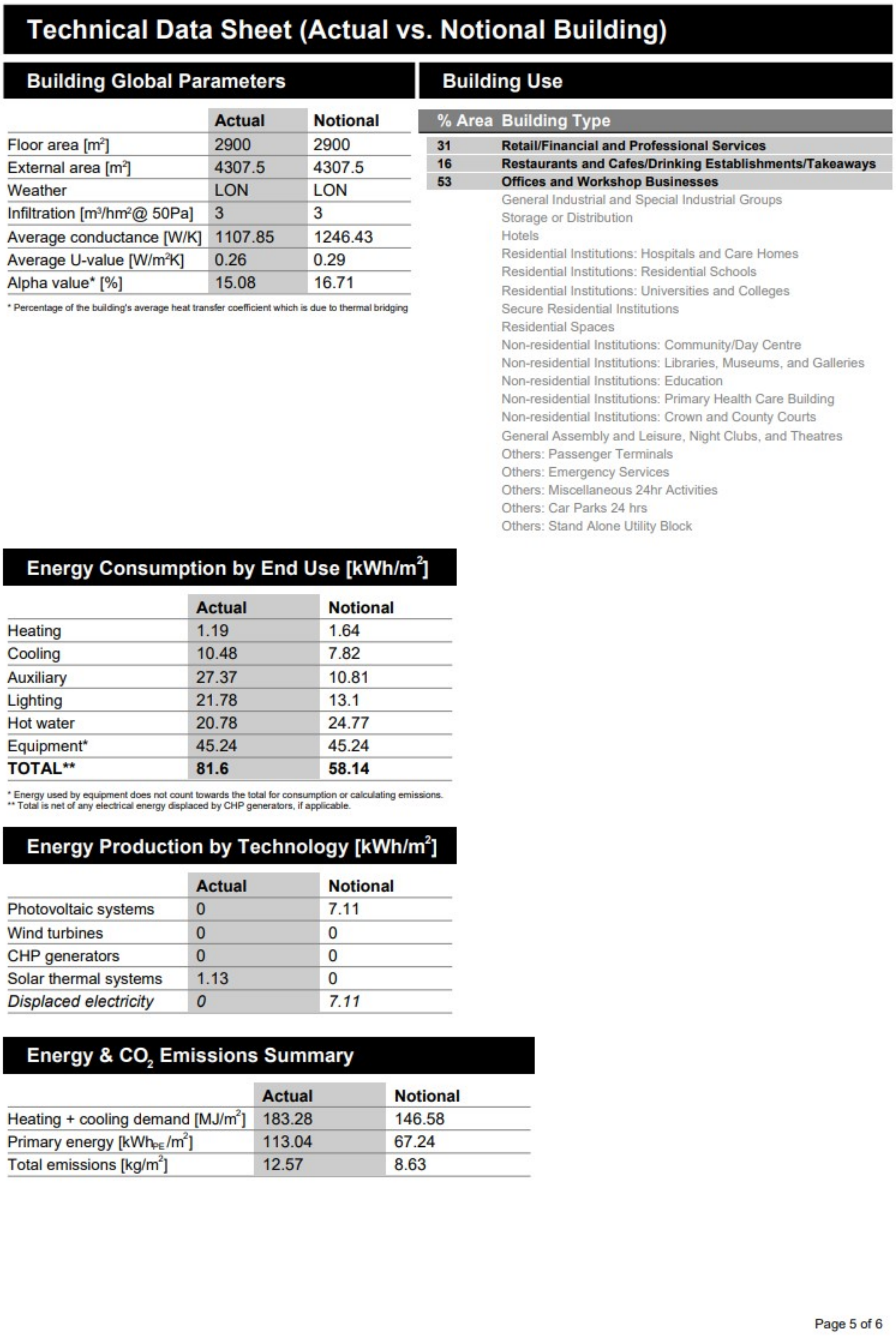
^ For fire doors, limiting U-value is 1.8 W/m²K

NB: Neither roof ventilators (inc. smoke vents) nor swimming pool basins are modelled or checked against the limiting standards by the tool.

Air permeability	Limiting standard	This building
m³/(h.m²) at 50 Pa	8	3

Page 1 of 6

Example BRUKL: Page One



Technical Data Sheet (Actual vs. Notional Building)

Building Global Parameters

	Actual	Notional
Floor area [m^2]	2900	2900
External area [m^2]	4307.5	4307.5
Weather	LON	LON
Infiltration [m^3/hm^2@ 50Pa]	3	3
Average conductance [W/K]	1107.85	1246.43
Average U-value [W/m^2K]	0.26	0.29
Alpha value* [%]	15.08	16.71

* Percentage of the building's average heat transfer coefficient which is due to thermal bridging

Building Use

% Area	Building Type
31	**Retail/Financial and Professional Services**
16	**Restaurants and Cafes/Drinking Establishments/Takeaways**
53	**Offices and Workshop Businesses**
	General Industrial and Special Industrial Groups
	Storage or Distribution
	Hotels
	Residential Institutions: Hospitals and Care Homes
	Residential Institutions: Residential Schools
	Residential Institutions: Universities and Colleges
	Secure Residential Institutions
	Residential Spaces
	Non-residential Institutions: Community/Day Centre
	Non-residential Institutions: Libraries, Museums, and Galleries
	Non-residential Institutions: Education
	Non-residential Institutions: Primary Health Care Building
	Non-residential Institutions: Crown and County Courts
	General Assembly and Leisure, Night Clubs, and Theatres
	Others: Passenger Terminals
	Others: Emergency Services
	Others: Miscellaneous 24hr Activities
	Others: Car Parks 24 hrs
	Others: Stand Alone Utility Block

Energy Consumption by End Use [kWh/m^2]

	Actual	Notional
Heating	1.19	1.64
Cooling	10.48	7.82
Auxiliary	27.37	10.81
Lighting	21.78	13.1
Hot water	20.78	24.77
Equipment*	45.24	45.24
TOTAL**	**81.6**	**58.14**

* Energy used by equipment does not count towards the total for consumption or calculating emissions.
** Total is net of any electrical energy displaced by CHP generators, if applicable.

Energy Production by Technology [kWh/m^2]

	Actual	Notional
Photovoltaic systems	0	7.11
Wind turbines	0	0
CHP generators	0	0
Solar thermal systems	1.13	0
Displaced electricity	*0*	*7.11*

Energy & CO_2 Emissions Summary

	Actual	Notional
Heating + cooling demand [MJ/m^2]	183.28	146.58
Primary energy [kWh_{PE}/m^2]	113.04	67.24
Total emissions [kg/m^2]	12.57	8.63

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Example BRUKL: Page Five

Appendix B: NCM Modelling Guide Tables

Fuel CO_2 emission and primary energy factors for buildings other than dwellings [19].

Fuel Type	**$kgCO_2/kWh$**	**kWh_{PE}/kWh**
Natural gas	0.210	1.126
LPG	0.241	1.141
Biogas	0.024	1.286
Fuel oil	0.319	1.180
Coal	0.375	1.064
Anthracite	0.395	1.064
Manufactured smokeless fuel (inc. Coke)	0.366	1.261
Dual fuel (mineral + wood)	0.087	1.049
Biomass	0.029	1.037
Waste heat	0.015	1.063

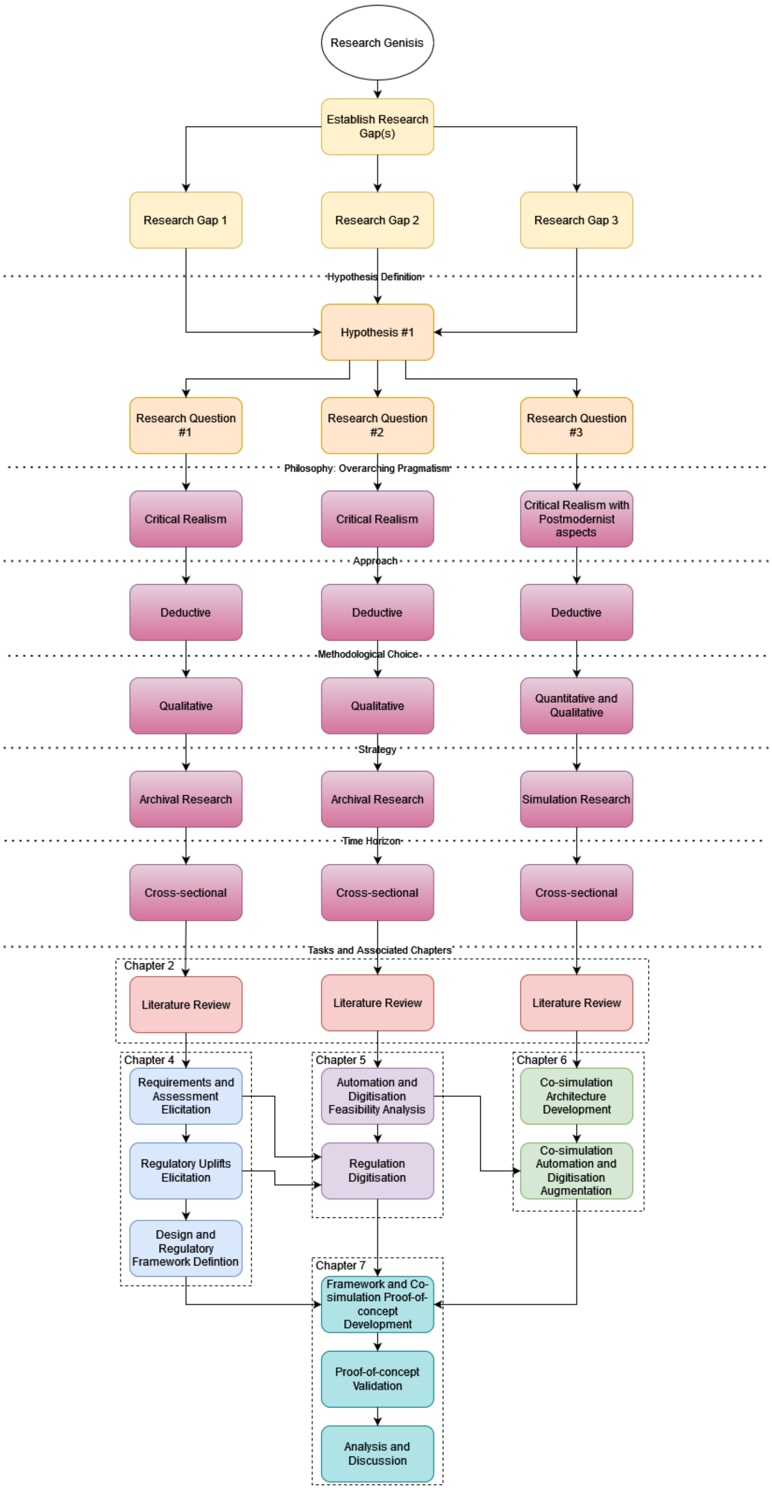
CO_2 emission and primary energy factors for grid-supplied electricity and grid-displaced electricity except that generated by PV systems [19].

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
$kgCO_2/kWh$	0.163	0.160	0.153	0.143	0.132	0.120	0.111	0.112	0.122	0.136	0.151	0.163
kWh_{PE}/kWh	1.602	1.593	1.568	1.530	1.487	1.441	1.410	1.413	1.449	1.504	1.558	1.604

CO_2 emission and primary energy factors for grid-displaced electricity by generation from PV systems [19]

Month	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
$kgCO_2/kWh$	0.196	0.190	0.175	0.153	0.129	0.106	0.092	0.093	0.110	0.138	0.169	0.197
kWh_{PE}/kWh	1.715	1.697	1.645	1.567	1.478	1.389	1.330	1.336	1.405	1.513	1.623	1.718

Appendix C: Thesis Flowchart



Overall Research Methodology Flowchart

Appendix D: Developed Tool Repositories

`https://github.com/jy-cu/BES_and_LCA_Co-simulation_Framework_Tool`

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