Methods to understand the whole life carbon implications of school retrofit at scale

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Declaration

All work presented within this thesis is the author's own work except where specific reference has been made to the work of others.

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Date: 14th May 2025

Statement of conjoined work

The candidate further confirms that all the work submitted is their own, except where work has formed part of a jointly authored publication. The candidate confirms that appropriate credit has been given within the thesis where reference has been made to the work of others. The body of work contained within the thesis has resulted in the following work which is published, under review or in preparation for submission:

1. **Chapter 1 and 2:** Abbey, D., Arbabi, H., Gillott, C., Ward, W., and Densley Tingley, D. (2022) Demolish or reuse? – The balance between operational and embodied emissions in the retrofit of commercial buildings. IOP Conf. Series: Earth and Environmental Science, 1078.

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In all publications I, the candidate, planned, completed analysis for and wrote the manuscript. Co-authors reviewed and provided feedback on the manuscript.

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Abstract

The built environment directly accounts for 25% of UK emissions, the majority of which are caused by energy consumption from existing buildings. Mass intervention is required, including replacement of existing fossil fuel heating systems and improvements to fabric efficiency. In fact, 97% of stock within Europe needs upgrading to meet 2050 emissions targets.

As operational emissions are reduced, the embodied impact of building materials will account for a larger proportion of future emissions. As such, whole life carbon retrofit assessments are advocated to improve our understanding of how to meet carbon targets. A large proportion of current work focuses on residential properties and fabric retrofit measures. When applied at scale, studies often use an archetype approach with buildings grouped into specific age and form categories.

Non-residential buildings often have an increased geometric complexity. This work demonstrates a parametric approach, linking building form to retrofit decision making from a whole life carbon perspective. The results illustrate how building form influences different intervention decisions. The comparison of retrofit to demolition and new construction shows only the most inefficient building forms would benefit from replacement.

A study of English school stock demonstrates the impact of refurbishment on total emissions compared to a devised carbon budget. Results show pathways in which the carbon budget can be met, highlighting the impact of including building form in retrofit decision making.

This thesis shows that retrofit of schools must increase, 10 - 50 times from current practice, to meet the 2050 Climate Change Committee (CCC) carbon budget. The retrofit rate is reduced by 20% by prioritising the least thermally efficient buildings in both fabric and form. The high embodied carbon cost of refurbishment, especially heat pumps, prevents school stock meeting its most stringent, Tyndall centre derived, budget even if all buildings are retrofit in 2025.

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Nomenclature

Building geometry and related factors

Symbol	Description	Unit
A_{floor}	Total floor area	m^2
A_{plan}	Plan area	m^2
$A_{surface}$	Total surface area	m^2
A_{wall}	Wall area	m^2
A_{window}	Window area	m^2
d_f	Floor thickness	m
g	Glazing ratio	
H	Height	m
H_{f_f}	Floor to floor height	m
H_{f_c}	Floor to ceiling height	m
k	Slenderness	
L	Length	m
P_f	Exposed perimeter	m
r	Aspect ratio	
R_c	Typical roof to surface area ratio	
S_c	Typical surface area to volume ratio	$\frac{1}{m}$
w	Wall ratio ($w \equiv 1 - g$)	
W	Width	m
W_c	Typical wall to surface area ratio	
V	Internal volume	m^3
x	Number of floors	

α	Window frame factor	
$\gamma(k, r)$	Compactness	
ζ	Gross internal area ratio	

Carbon emissions and related factors

Symbol	Description	Unit
B	Remaining carbon budget	$kgCO_2e$
$C_{oc,n}$	Constant to define operational carbon within the developed analytical expression	$kgCO_2e/m^2$
$C_{ec,n}$	Constant to define embodied carbon within the developed analytical expression	$kgCO_2e/m^2$
E_e	Embodied emissions	$kgCO_2e$
E_o	Operational emissions	$kgCO_2e$
E_{ob}	Baseline operational emissions	$kgCO_2e$
E_{or}	Post retrofit operational emissions	$kgCO_2e$
E_r	Embodied replacement emissions	$kgCO_2e$
E_{WLC}	Whole life carbon emissions	$kgCO_2e$
e_e	Embodied carbon intensity	$kgCO_2e/m^2$
e_o	Operational carbon intensity	$kgCO_2e/m^2$
e_{WLC}	Whole life carbon intensity	$kgCO_2e/m^2$
m	Material decarbonisation factor	
ξ_{boiler}	Boiler embodied carbon	$kgCO_2e/kW$
ξ_{floor}	Floor embodied carbon	$kgCO_2e/m^2$
ξ_{MVHR}	MVHR embodied carbon	$kgCO_2e/Ls^{-1}$
ξ_{roof}	Roof embodied carbon	$kgCO_2e/m^2$
ξ_{wall}	Wall embodied carbon	$kgCO_2e/m^2$
ξ_{window}	Window embodied carbon	$kgCO_2e/m^2$
σ_{fuel}	Operational carbon factor of modelled fuel	$kgCO_2e/kWh$
$\sigma_{electricity}$	Operational carbon factor of electricity	$KgCO_2e/kWh$

Energy consumption and related factors

Symbol	Description	Unit
C_n	Constant to define energy consumption within the developed analytical expression	kWh/m^2
$F_{electricity}$	Electricity consumption	kWh
F_{DEC}	Metered energy consumption	kWh
F_{DHW}	Hot water consumption	kWh
$F_{heating}$	Heating consumption	kWh
$F_{kitchen}$	Kitchen consumption	kWh
F_{total}	Total energy consumption	kWh
$f_{electricity}$	Electricity consumption intensity	kWh/m^2
$f_{heating}$	Heating consumption intensity	kWh/m^2
$f_{thermal}$	Thermal energy consumption intensity	kWh/m^2
f_{total}	Total energy consumption intensity	kWh/m^2
P_{solar}	Solar energy production	$kWh/m^2.yr$
ϵ	Electricity consumption benchmark	kWh/m^2
κ	Kitchen consumption benchmark	$kWh/meal$

External conditions and related factors

Symbol	Description	Unit
θ_o	Outdoor temperature	$^\circ C$
θ_{winter}	Minimum winter temperature	$^\circ C$
σ_θ	Standard deviation of temperature variation	$^\circ C$
q_{sol}	Solar incident heat gains	kW/m^2
q_s	Solar gains to a space	kW/m^2

Fabric efficiency and related factors

Symbol	Description	Unit
N	Air exchange rate	hr^{-1}

Q_{loss}	Heat losses	kW
U_{av}	Area weighted average U-Value	W/m^2K
U_{floor}	Floor U-Value	W/m^2K
U_{roof}	Roof U-Value	W/m^2K
U_{wall}	Wall U-Value	W/m^2K
U_{window}	Window U-Value	W/m^2K
U'	Heat loss coefficient	kW/K
U'_{fabric}	Heat loss coefficient of building fabric	kW/K
$U'_{ventilation}$	Heat loss coefficient of ventilation losses	kW/K
Z	$\frac{U'}{L^2}$	kW/Km^2
Ψ	Preheat period	hr
Ω	Switch off period	hr

Material properties and related factors

Symbol	Description	Unit
c_{av}	Area weighted average thermal capacitance	kJ/m^2K
c_{floor}	Thermal capacitance of floor	kJ/m^2K
$c_{ceiling}$	Thermal capacitance of ceiling	kJ/m^2K
c_{wall}	Thermal capacitance of wall	kJ/m^2K
c_{window}	Thermal capacitance of window	kJ/m^2K
cp	Specific heat capacity	$kJ/kg.K$
d	Material exposed thickness	m
d_{ins}	Insulation thickness	m
ι	Lifespan of building retrofit element	$year$
s_g	Solar gain factor	
R_{ins}	Thermal resistance of insulation	m^2K/W
λ	Thermal conductivity	W/mK
ρ	Density	kg/m^3
τ	Thermal time constant	hr

Mechanical systems efficiency and related factors

Symbol	Description	Unit
Q_{DHW}	Hot water plant size	kW
Q_p	Heating plant size	kW
Q_{vent}	Ventilation system size	Ls^{-1}/m^2
v	Air provision per person	$Ls^{-1}/people$
Y	$\frac{Q_p}{ZL^2}$	$°C$
β	Heating plant oversize factor	
δ	Heating distribution losses	
$\eta_{heating}$	Heating system efficiency	
η_{DHW}	Hot water system efficiency	

Occupancy parameters and related factors

Symbol	Description	Unit
$\Delta\theta_m$	Temperature difference between hot and cold water	$°C$
l	Hot water consumption	L/m^2
$n_{(h)}$	Occupied and heated period	$days$
n_{meals}	Occupied period with meals served	$days$
$n_{(o)}$	Occupied period	$days$
o_d	Occupancy density	$people/m^2$
t_o	Occupied hours	hr
t_u	Unoccupied hours	hr
q_e	Equipment heat gains	kW/m^2
q_g	$\frac{Q_g}{L^2}$	kW/m^2
q_l	Lighting heat gains	kW/m^2
q_{oc}	Occupant heat gains	kW/m^2
q_o	Internal heat gains	kW/m^2
Q_g	Total internal heat gains	kW
η'	Internal gains factor	
θ_b	Baseline temperature	$°C$

$\overline{\theta_i}$	Mean internal temperature	$^\circ C$
θ_{sp}	Set point temperature	$^\circ C$
$\theta_{typical}$	Typical temperature	$^\circ C$
μ	Meal/Occupancy ratio	
χ_e	Equipment gains fraction	
χ_l	Lighting gains fraction	
χ_{oc}	Occupant gains fraction	
y	Year building is retrofit	$year$

Chapter 1

Introduction

Temperatures in 2011 - 2020 were 1.1°C warmer than pre-industrial levels [40]. The Intergovernmental Panel on Climate Change [40] shows that if we do not mitigate greenhouse gas emissions then these rising temperatures will threaten many aspects of human existence in areas such as human health, food production and loss of existing species. In fact, we are already beginning to experience the impacts of climate change with an increase in concurrent heatwaves and droughts compared to 1950 levels, as well as yearly rising sea levels [40].

The IPCC show a reduction of greenhouse gas emissions by 84 or 64% by 2050 is required to meet 1.5 or 2°C levels of warming respectively [40]. 2°C warming is seen as the critical threshold for dangerous and escalating threats to human life [41]. Therefore, the need for urgent action within all sectors to limit emissions is clear. Further, the predicted growth in population [42] will force targets to be met despite rising demand for resources.

In the UK, buildings and infrastructure directly account for 25% of total emissions [1], demonstrating requirements for large reductions in this sector if we are to meet IPCC targets to reduce greenhouse gas emissions.

1.1 Decarbonising our existing buildings

Buildings emit greenhouse gases in two key ways. The first being operational carbon, which refers to the emissions from energy consumed within buildings. This ranges from heating and cooling to ventilation as well as hot water and electricity consumption. The second is embodied carbon, which refers the emissions related to a construction material's production, transportation, repair, maintenance and disposal throughout that material's lifespan. To reduce these whole life carbon emissions, the energy efficiency of our buildings needs to be improved, while limiting the impacts of additional material consumption.

1.1.1 Operational emissions

Operational energy consumption accounts for 75% of total built environment emissions [1]. In a cold nation like the UK, heating and hot water consumption is a major cause of emissions, especially considering that over 85% of our homes [43] and over 80% of non-residential heating and hot water energy consumption [44] are fuelled by gas or oil boilers. These systems have limited capacity for decarbonisation as they directly release emissions at the source, e.g. burning gas within the boiler, and a managed phase out of fossil fuel systems is therefore necessary. In fact, the UK is planning to phase out both new installations and the replacement of gas boilers beyond 2035 [45].

In the UK, building regulations were first introduced in 1965 [46]. These regulations stipulate a required thermal performance to try and reduce heating needs within buildings. Improving thermal performance, by insulating the building fabric and increasing airtightness, reduces heat losses to a space and therefore should reduce the total required heating energy. Over 50% of our housing stock within the UK was built pre 1965 [43], before any building regulations were in place. In fact, approximately half of all homes have uninsulated walls and are highly thermally inefficient [43].

Reducing heating demand is important because replacement of fossil fuel systems with low carbon alternatives such as heat pumps poses a challenge in other ways. For example, predictions show a 35% and 93% increase in UK annual and peak demand respectively due to the electrification of heat and transport systems [47], which pose a risk to the sustainable and uninterrupted provision of electricity [48]. Without decarbonisation of electricity, heat pumps will not be a sustainable alternative to fossil fuel systems, but this decarbonisation will be more challenging as electricity usage increases. Therefore, minimising heating loads can help to reduce the additional demand on the national grid.

1.1.2 Embodied emissions

The second key cause of emissions within the built environment is embodied carbon. Figure 1.1 demonstrates the UKGBC plan for net zero by 2050 where a large range of different decarbonisation strategies are modelled [1].

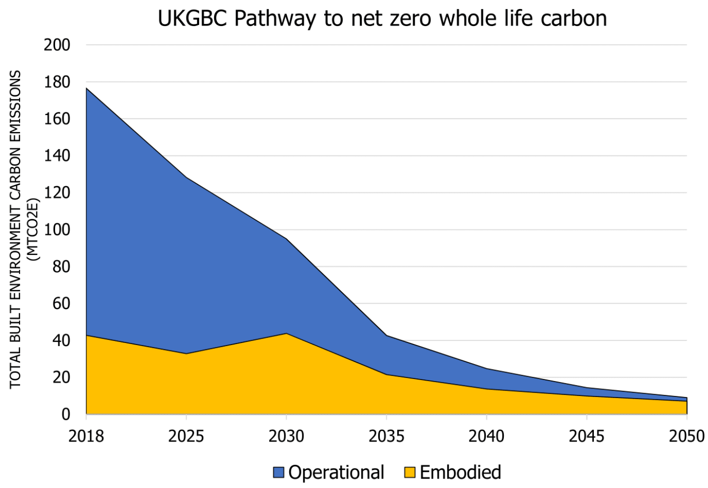

Figure 1.1: The UKGBC whole life carbon pathway more meeting yearly net zero emissions [1]. Emissions are split between predicted operational and embodied carbon.

Despite a 99% modelled reduction in operational emissions, embodied carbon is much slower and harder to decarbonise due to several technical challenges such the decarbonisation of highly carbon intensive materials [49]. In fact, several key construction materials, e.g. steel and glass, are predicted to still emit net-positive emissions by 2050 [1]. As we manage to reduce operational carbon nearly to zero, embodied carbon is shown to take up a much larger proportion of total emissions.

Therefore, while our existing buildings are inefficient and need to be improved upon, making best use of already deployed materials where carbon has already been emitted, in the form of our existing stock, could be highly useful. Intervention to our existing stock would mean retrofit at scale, including replacement of existing fossil fuel systems and fabric measures such as insulation and improved airtightness. Retrofit itself is also shown to have considerable embodied emissions when applied at scale [50], making the comparison of different material and retrofit strategies necessary.

1.2 Demolition and rebuild versus refurbishment

Considering both embodied and operational emissions means that replacing our existing stock holds a lot of significance due to the increased embodied impacts that come from new construction [51]. However, new construction can have potential for lower operational emissions as it is not constrained by factors, such as form and orientation, which impact the efficacy of different retrofit measures [52, 53]. It can also be less complex within new construction to reach better efficiency standards such as improved airtightness levels [54]. This means that yearly energy consumption and therefore carbon emissions could be lower than an equivalent refurbishment project.

There will likely be some buildings whose material lifespan dictate whether they would be demolished. However, the majority of existing buildings are capable of being retained with 85-95% of EU [55] and 80% of UK buildings [56] currently in use, predicted to still be standing by 2050. As the majority of stock is capable of retention, discussions regarding the pros and cons of demolition versus refurbishment are highly relevant, with several high profile cases, shown in Figure 1.2.

One example is the former John Lewis Building in Sheffield. After the store's closure, the council considered multiple options for its future, including refurbishment or demolition and replacement with a different structure, until the building was given listed status and retained [57]. Another debate took place at 485 Oxford Street, London, where points were raised by different stakeholders on the reusability of the existing structure, and the sustainability of demolition versus refurbishment [58].

The John Lewis building and 485 Oxford Street are just two high profile examples of demolition versus retrofit decision making, something that is likely occurring at scale in the UK as currently 50,000 buildings are demolished each year [59].

1.3 Whole life carbon assessments

While there are several potential reasons for demolition which must be considered, such as structural lifespan, the importance of considering carbon emissions is clear due to sustainability targets and the imminent threat of climate change [40].

(a) John Lewis building, Sheffield [57].

(b) 485 Oxford Street, London [60].

Figure 1.2: Two high profile examples of buildings where both demolition and refurbishment have been argued for.

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Whole life carbon assessments are a useful tool for making this comparison as they consider a building's emissions over the entirety of its future lifespan from construction or refurbishment to demolition.

When used in the case studies highlighted above they reveal the importance of considering embodied carbon within future assessments. For the John Lewis building, a study by Arup shows that retaining the building leads to considerably lower emissions than rebuild but that the lowest carbon scenario would be to replace the building with a park [61]. However, this is an unbalanced viewpoint as in this scenario useful floor area is lost. In the UK there is a need for more buildings due to an increasing population and life expectancy [62]. Therefore, losing a building that could be retained or converted into residential space may be less sustainable as the equivalent floor area might then need to be constructed elsewhere. To replace the equivalent floor area of the John Lewis building was found to lead to overall higher whole life emissions despite considerable operational savings from the rebuild option [63].

In the case of 485 Oxford Street different undertakers of whole life carbon assessments reached opposing conclusions on whether demolition or refurbishment was preferable [58]. Within the Sturgis report it is claimed that while contractors compared new construction to a light touch refurbishment which justified demolition, if one was to comprehensively refurbish the building it would lead to considerably lower emissions over the proposed lifespan than the new design [58]. This debate demonstrates the importance of making fair comparisons when undertaking whole life assessments, such as modelling scenarios which meet the best attainable performance level for both retrofit and new construction.

1.4 Research aims and objectives

The sections above highlight the importance of understanding whole life carbon impacts, particularly when considering the required reduction in emissions of the built environment. With emission reduction targets to limit global warming to 2°C [40], there is a need to understand what the best whole life carbon solutions are. Potential solutions include a host of different refurbishment measures, as well as the option of demolition and replacement with a more efficient building.

This body of work aims to **develop an understanding, at scale, of the implications of accounting for whole life carbon within different future retrofit decisions and interventions.**

Motivated by several gaps in understanding, two research questions are asked:

1. ***What influence does building form have on the lowest whole life carbon intervention for existing buildings?***
2. ***What intervention is required to the existing building stock when considering a stock's carbon budget?***

Chapter 2 explores the current knowledge within the field of whole life assessments and retrofit. This section highlights the limited scope of current whole life retrofit studies, across different typologies, retrofit measures, modelling boundaries and spatial scales. It highlights that the large differences in system boundaries do not allow for fair comparisons between different case studies - see Section 2.4 for further discussion of identified research gaps.

Compared to higher educational buildings, Chapter 2 demonstrates that research into primary, secondary schools and colleges is limited. It is also evidenced in Section 2.4 that retrofit of this stock type provides a practical starting point to begin to scale-up the non-residential retrofit sector, due to the drivers of retrofit for schools [64]. By understanding the whole life carbon impacts of retrofit on schools at scale, it is hoped that the key characteristics, e.g. building shape and size, which motivate different potential interventions, e.g. the comparison between retrofit scenarios and demolition and new construction, can be understood for a wide range of different buildings. For these reasons the following research focuses on school buildings.

By answering these research questions, this thesis aims to provide not only a theoretical understanding of the influence of key building characteristics, such as building form, on energy consumption and whole life carbon, but also a practical assessment of how these characteristics influence key whole life carbon decision making in the future. Following this, through assessment of the entire English school stock, pathways in which government carbon targets can be met are modelled. This will include discussion of potential barriers toward meeting these targets, and a comparison between retrofit and the option of demolition and new construction.

To answer the research questions, the following research objectives will be completed:

1. Develop a method to assess building energy consumption at scale and validate this using a range of case studies.
2. Quantify the parametric contribution of building form to both energy consumption and whole life carbon.
3. Assess the impact of building form on typical interventions to the existing school stock.
4. Quantify the whole life carbon impact of retrofit on the English school stock.
5. Identify pathways by which carbon reduction targets devised for the English school stock can be met.

1.5 Thesis structure

Figure 1.3 demonstrates an outline of the work completed within this thesis and a mapping of where each research objective will be answered. For a chart of how all thesis input parameters and modelling methodologies flow into one another, see Appendix E.

The following chapter, **Chapter 2**, provides a systematic review of current relevant literature, beginning with an overview of existing building case study characteristics aiming to highlight gaps within current research. This is followed by analysis of existing methods and key findings within current work, which are used to highlight research gaps in the field. Key research questions are developed from this piece of work which are answered across Chapters 3 - 5, each chapter using the previous chapter's findings to complete the developed research objectives.

Following this, in **Chapter 3** a method is developed which can be used to quantify energy consumption of existing school buildings at scale. This is validated against a set of 234 real building case studies, comparing modelled energy consumption results to metered data. Comparing metered to modelled energy consumption for all case studies shows that currently available data contains systematic errors and missing data points which cause high percentage error in results. If this erroneous data is replaced with an archetype value, e.g. using a typical number of storeys in lieu of available height data, results for both thermal and electrical energy are modelled with a very low average percentage error. However, there remains individual properties with high error between metered and modelled results, implying that, the available data is only sufficient for understanding the aggregated impacts of the school stock, and not on an individual level.

Chapter 4 parametrically links the energy modelling approach used in Chapter 3 and embodied carbon emissions of retrofit to key measures which describe building form. First, different factors of building form are explored, including an assessment of their applicability, as they assume rectangular form, to the actual UK school stock. An analytical expression is then developed which links form factors to whole life carbon emissions of a refurbished building. It is shown that form influences the level of energy saving from retrofit, as well as the required level of intervention to achieve the lowest whole life carbon emissions. As new construction is not constrained by building form, this parametric model provides a computationally time-efficient graphical tool to compare refurbishment strategies to different demolition and new construction standards. Finally, by applying the developed analytical expression to the 234 case study schools also used in Chapter 3, it is shown that whole life carbon retrofit decisions do not change for vast majority of schools if using either metered or modelled baseline data, which demonstrates that modelled energy consumption is sufficient to make whole life carbon retrofit decisions.

Chapter 5 tackles the challenge of quantifying the whole life impact of retrofit at scale. Whole life carbon retrofit modelling is applied to the English school stock, including all primary, secondary schools and colleges, approximately 20,000 schools. Following from Chapter 4, the influence of building form on retrofit decisions at scale is assessed, alongside other key sensitivities such as post retrofit occupancy patterns, electricity and material decarbonisation. This chapter shows that decarbonisation in other sectors is required alongside retrofit if the devised carbon budgets are to be met. Even with wider sector decarbonisation, retrofit rates need to increase markedly, by 10 - 50 times from current predicted rates. Prioritising the least thermally efficient buildings, both in fabric and form, can help reduce these rates. The high embodied carbon cost of retrofit, especially heat pump installations, prevents the school stock from being able to meet the most stringent devised carbon budget. By 2050, retrofit would lead to the lowest emissions compared to demolition unless highly ambitious embodied carbon construction targets are met, e.g. $260kgCO_2e/m^2$. In this case, demolition of those buildings with highly inefficient form would be preferable.

Finally, **Chapter 6** provides a discussion of key findings and wider implications, suggested future work and limitations of this piece of work. This chapter also includes an outline of the key industrial and policy implications in this thesis. This is followed by concluding remarks in **Chapter 7**.

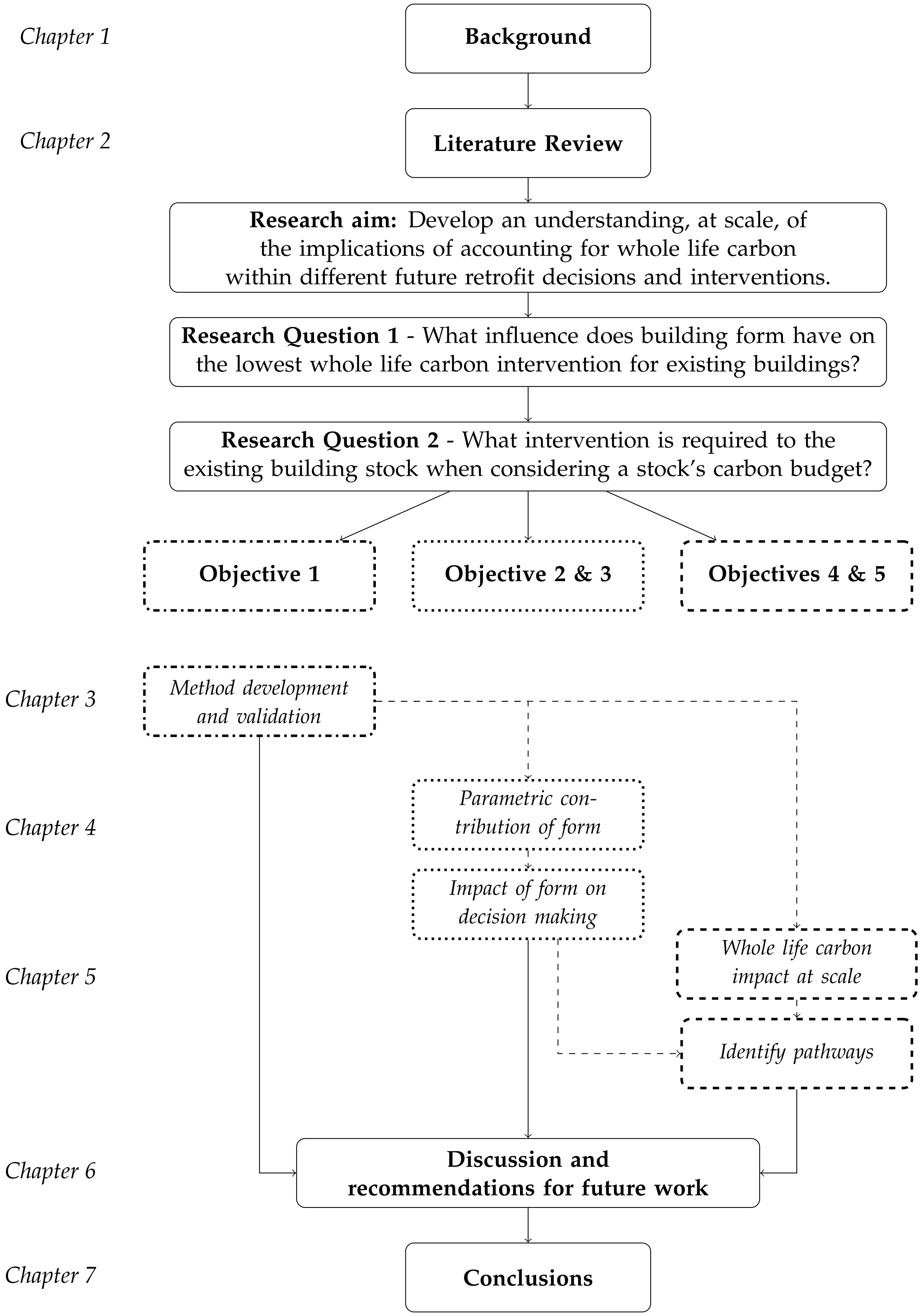


Figure 1.3: Flow chart of thesis structure, providing an outline as to how each chapter is connected to meet the overall research aim. Dashed arrows demonstrates how research objectives are connected, with those previously met used to help meet the following objectives.

Chapter 2

Literature Review

In this chapter, an initial understanding of the impacts of retrofit from a whole life perspective is presented, through reviewing the current literature, identifying research gaps, and assessing the scope of current understanding in the field.

In Section 2.1, studies which contain a whole life retrofit case study are focused upon to provide an assessment of the key characteristics of the current research base. This aims to provide a broad overview of the literature, highlighting wide research gaps and patterns within it.

Secondly, Section 2.2 provides an overview of the key methods used within current research, including methods used to assess embodied and operational emissions as well as different methods where these principles are applied at scale. The inclusion of economic modelling within methods and the use of optimisation is also outlined.

Finally in Section 2.3, in depth analysis of whole life impacts of building retrofit is undertaken. This section focuses on studies which will provide potentially useful information for future intervention of our stock, something which will be required on a large scale [65]. This includes an assessment of why and how embodied emissions should be included in future assessments, the question of demolition versus refurbishment, and an assessment of those studies which aim to understand what needs to be done to meet carbon and energy targets.

The chapter concludes with an outline of research needs within the field and highlights how this body of work will help fill gaps in understanding by answering key research questions.

2.1 Whole life impacts of retrofit - an overview of the field

To begin to understand the progress and limitations of this topic, a systematic literature search is undertaken. Results from the literature search are used to identify key characteristics of the field and inform further analysis.

First, both Scopus [66] and Web of Science [67] were used to retrieve literature published in English - based on the following key word search:

(Retrofit OR renovation OR Refurbishment or renovate or refurbish) AND (building OR dwelling OR office OR school OR hotel OR house OR property OR 'non-residential' OR residential) AND ('embodied impact' OR 'embodied carbon' OR 'embodied energy' OR 'whole life impact' OR 'LCA' OR Life-cycle assessment').

All data was collected on the 15th of April 2024. Only publications from international peer-reviewed journals were analysed. A full methodology is outlined in Appendix A, Section A.1.

The body of work relating to **whole life impacts of retrofit** has grown rapidly with Figure 2.1 showing 55% of publications published since 2020. This creates a new pool of evidence to either support or oppose the importance of embodied emissions within retrofit design as well as inform our understanding on best practices that should be translated to industry.

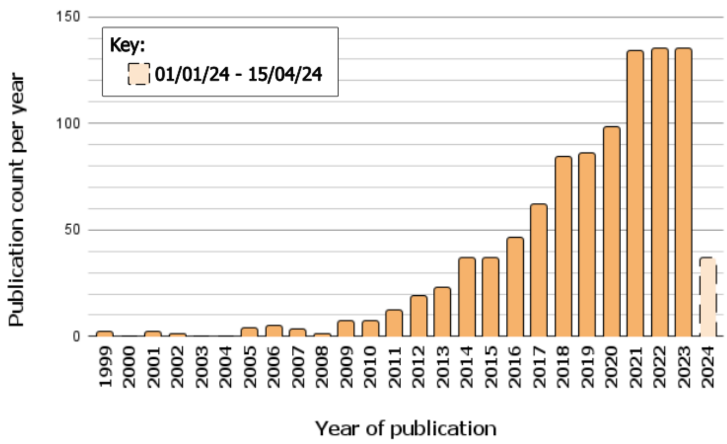


Figure 2.1: Yearly publication count for the literature review database, from the oldest publication in 1999 up to the 15th of April 2024.

Widespread retrofit has been advocated to increase the energy efficiency of building stock with initiatives such as the European Commission's Renovation Wave Strategy aiming to increase Europe's renovation rate from 0.2 to 3% per year [68] . Case studies can potentially provide insight and understanding into the practical challenges associated with this increased retrofit uptake and the implications of accounting for whole life impacts. Therefore, whole life case studies are explored in more detail to identify these challenges. Understanding the key characteristics of these case studies allows for an assessment of the broader research gaps within the field.

To be classified as a whole life retrofit case study the publication must meet the following criteria:

- Assess the environmental impacts of retrofit for an existing building. The building must be occupied and analysis of only new constructions were not included.
- Assess the impacts of both material and energy consumption. A minimum of upfront material impacts (production emissions, cradle-to-gate, stages A1-A3) and building energy use (stage B6) must be included [2].
- Assess energy retrofit, defined here as any form of intervention on an existing building which is designed to reduce the operational environmental impact of the building.

A total of 288 different publications were found to contain whole life retrofit case studies. By isolating the key characteristics of available studies, findings and research gaps with real world applications can be identified to help address this challenge. See Appendix A.1 for further detail on the data collection process.

2.1.1 Whole life retrofit case studies

Existing studies using a whole life approach are distributed extremely unevenly internationally, as highlighted in Figure 2.2. The vast majority of publications, 77%, are European studies, with only three located in South America [69, 70, 71] and one which has analysed impacts of refurbishment for a set of three neighbourhoods in each countries' capital city, worldwide [72]. This is mirrored by findings in existing reviews for whole buildings where there was a focus on more developed countries [73, 74] and a focus on cold countries, where space heating dominates [75]. Case study locations being concentrated in certain countries is not unexpected, as knowledge production in general has been shown to be overwhelmingly skewed towards certain locations such as the USA, Europe and East Asia [76].

It is also likely that the varying requirements of different countries for the future building stock is driving each country's priorities in research. For example, China's floor space nearly doubled in 15 years from 2000 - 2015 with an average annual growth rate of 4% [77], demonstrating a large proportion of its stock is relatively new. This is in comparison with the European Union, where more than 40% of residential buildings were built before 1960 and growth rates in this sector ranged from just 0.1-2.1% between European nations [78]. The age of European stock highlights why retrofit may be a larger focus within these countries' research bases.

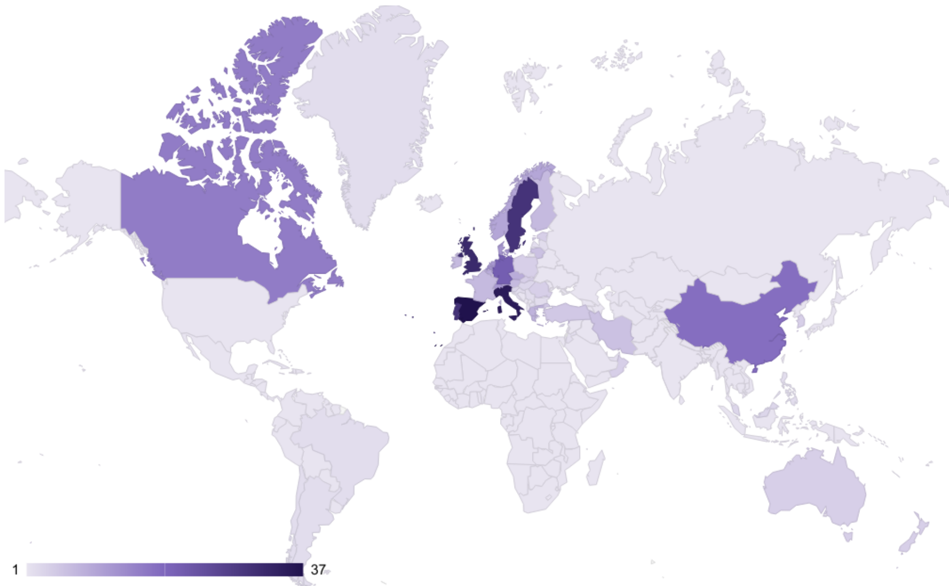


Figure 2.2: Publication count of the location of whole life retrofit studies. Purple highlights where studies are located with the darker the colour indicating more studies within a country.

The three most frequently used locations for building studies are Spain, Italy and the United Kingdom. Italy provides an example of a nation where both energy and seismic retrofit assessments are being conducted [79, 80, 81], in contrast to wider European assessments which typically focus on only energy retrofits. It is shown that the risks from seismic activity can increase the embodied impacts of energy retrofit in comparison to simultaneous seismic and energy retrofit [79]. Seismic activity is therefore an example of an additional challenge which existing stock would ideally also be designed to withstand and impacts both the efficacy of energy refurbishment as well as the total whole life carbon impacts of a refurbishment project [70].

The areas of the world that are frequently overlooked by retrofit research also face additional challenges such as residential quality standards, which would need to be improved alongside decarbonisation of stock [70]. The whole life impacts of these additional needs pose an added challenge to building retrofit, something which is not reflected in the current literature. It has been demonstrated that as emerging economies increase their use of fossil fuels within the built environment, the global energy demand of buildings has risen by 1% from 2021 to 2022 [82]. This further demonstrates the importance of understanding the impacts of retrofit across a wider range of countries.

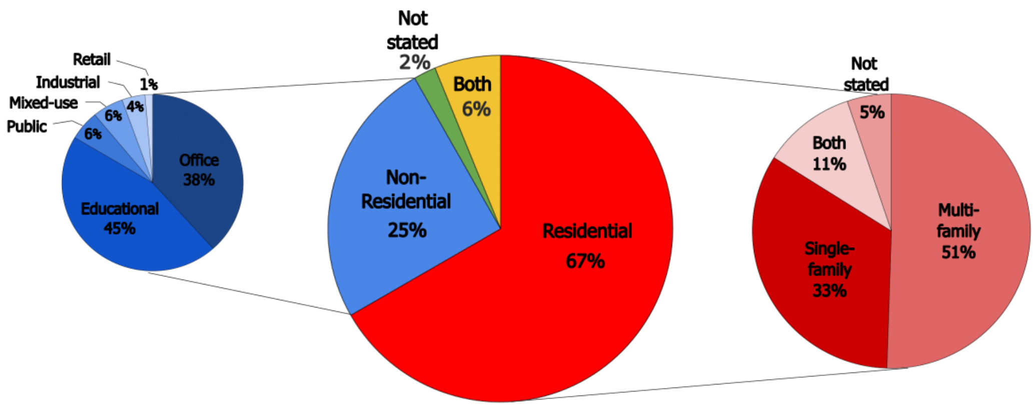


Figure 2.3: Pie charts to show publication count of the building typology of whole life retrofit case studies.

As the operation of residential buildings accounts for over double the carbon emissions of non-residential [82] it is logical that they are the most commonly assessed building typology within literature, as shown in Figure 2.3. In fact in the UK, 65% of building emissions are attributed to residential and 36% to commercial and public buildings, and this proportional split is reflected relatively well by existing case studies [83]. However, diversity in the assessment of non residential typologies is shown to be lacking. Office and educational buildings account for the majority of non-residential typologies, with only two retail studies [84, 85].

Data availability is one potential reason for this lack of diversity; with educational buildings being the most frequently studied non-residential building, it is possible that researchers are able to more easily attain information about buildings within their University. This is agreed upon in Figure 2.4 as the majority of educational cases are university buildings. From a UK context this is not representative of the existing stock, as there is approximately $80km^2$ [15] of school internal floor area compared to 30 km^2 of university space [26, 27, 28, 29, 30, 31] (when accounting for 141/168 universities - including all 50 most populated universities in the UK [86].).

The differences in occupancy and energy use patterns between different non-residential ty-

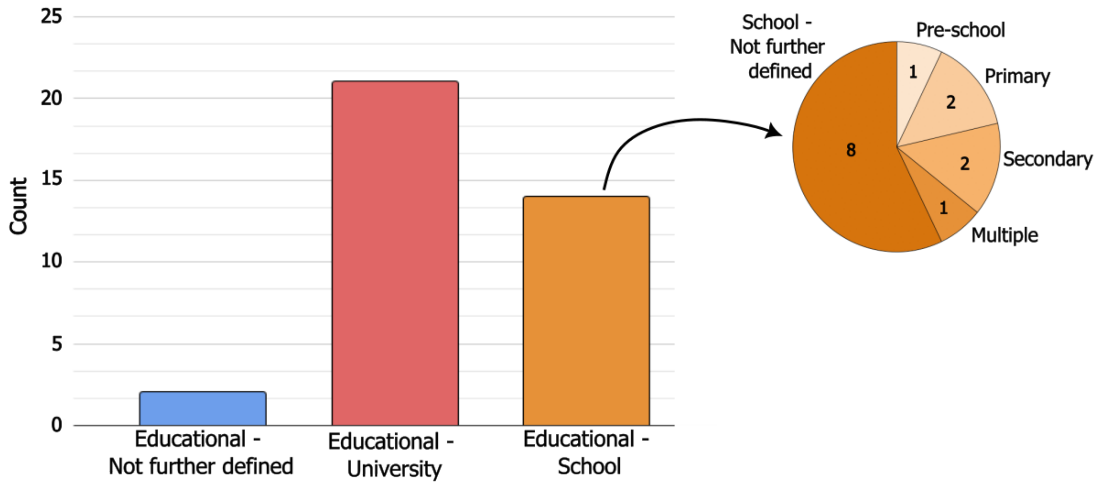


Figure 2.4: Bar chart to show the exact breakdown of educational building typologies, measures as the total count of papers.

pologies can vary widely [87], demonstrating why a full understanding of all typologies is required. Energy benchmarks show health, hospitality, leisure and retail spaces to have the highest energy use intensities [88], showing why it is important to explore how best to reduce the whole life impacts of these buildings further. As there is an immediate need to reduce emissions, successfully refurbishing those buildings which provide the highest energy savings has been shown to assist meeting carbon reduction targets for residential buildings [89] and could also be further translated to the non-residential stock.

Different typologies also face additional challenges when being retrofitted. For example, some healthcare buildings require the internal environment to be designed to prevent disease transmission, with evidence showing that a mechanical ventilation strategy controls the transmission of infectious diseases [90]. Reducing disease transmission, alongside energy efficiency improvements, may give a potential embodied carbon hotspot that is currently being overlooked by literature due to the lack of case studies.

Figure 2.5 demonstrates that of the assessed studies, the vast majority are at the individual building scale. The largest application at scale is at a continental level, with both studies assessing residential buildings in Europe [91, 92]. More studies with a larger geographical scope and larger range of building typologies would be useful to help provide comparison of the differences in whole life impacts of retrofit that occur in different locations and types of buildings.

When Schwartz et al. [93] compared the whole life carbon footprint of new buildings to re-

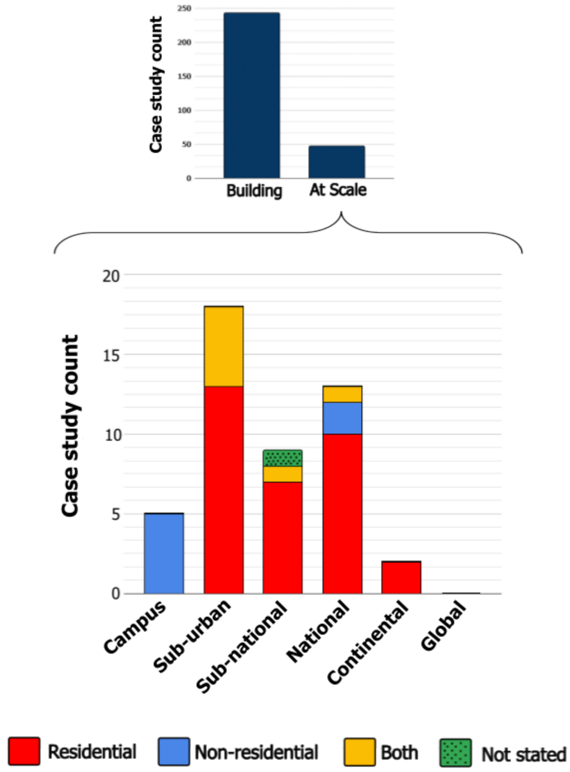


Figure 2.5: Publication count of at scale studies, including building typology of at scale studies. To be classified as an 'at scale' the case study must investigate the impact of multiple buildings within a defined geographical scope while also demonstrating the level of representation of those buildings (See Appendix A.1 for further details on categorisation).

furbishments, it was found that on average refurbishment cases had a lower carbon footprint. However, there were new buildings which had a lower life-cycle carbon footprint than refurbishment cases, causing uncertainty when answering the question of whether buildings should be demolished and replaced or refurbished. There was further uncertainty as to whether this was caused by differences in performance or as a result of different protocols and methods used in studies [93]. This result highlights a benefit of case studies which assess retrofit across multiple buildings and building typologies, such as at neighbourhood, city or national scale, to allow for a fair comparison using the same methods (See Figures 2.8 -2.9 for further exploration of this topic).

Figure 2.6 demonstrates which types of refurbishment have been included in each case study. It is shown that fabric retrofit (additional insulation, new glazing and increased airtightness) is included in nearly all of the refurbishment case studies, with less than half also including an assessment of Mechanical, Electrical and Plumbing systems (MEP) or renewable energy measures. MEP and renewable's contain materials, such as metals, of high embodied carbon cost

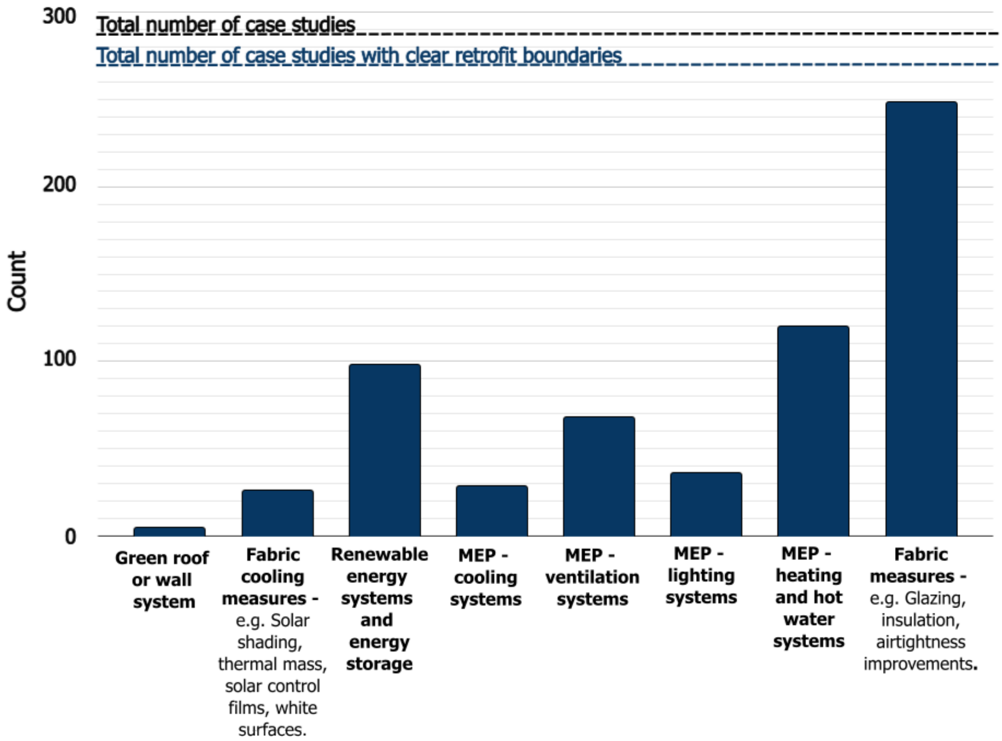


Figure 2.6: Different categories of refurbishment measures included in each case study. MEP stands for mechanical, electrical and plumbing systems.

and Hamot and George [94] state that mechanical systems could account for up to 75% of the total embodied carbon emissions within retrofit projects. In fact, Opher et al. [95] found that mechanical systems were the single biggest contributor to embodied carbon emissions within their retrofit case study. This shows the importance of considering the effects of MEP systems within an embodied carbon assessment. This is especially important due to immediate need for MEP improvements within our existing stock as many different countries such as EU nations, UK and Canada, require the replacement of fossil fuel systems at scale, e.g. replacement of gas boilers [96, 97, 98], to successfully decarbonize the built environment.

Also, as previously discussed, different building typologies have varying needs which can lead to very different MEP requirements. For example, school buildings have been shown to suffer from poor ventilation, impacting student performance and health [99, 100]. Therefore, the whole life impact of mechanical ventilation strategies, which have been shown to improve these factors [101] is an important consideration. This review has demonstrated, residential studies are more commonplace than non-residential. This, alongside fewer MEP assessments, suggests that studies into the impacts of large scale building systems improvements are less frequent.

Vilches et al. [102] found, during a review, that refurbishment reduced the operational energy use of buildings from 30-80%, due to large differences in the level of intervention by each case. This demonstrates why a whole building retrofit approach to modelling, including both MEP and insulation, would be very useful to provide a more comprehensive view of the best refurbishment strategies.

Figure 2.6 shows a lack of case studies which include assessment of cooling energy systems or fabric measures such as shading. This may be due to the research bases focus on Europe which due to its climate, space heating energy accounts for 64% of average total building energy consumption and space cooling accounts for just 0.5% [103]. It is demonstrated for a University campus that additional external shading had a carbon payback period above the lifespan of a typical building [104], showing that the limited geographical boundaries in the research base may impact our overall understanding of retrofit effectiveness. Cooling systems typically run off electricity which is able to be decarbonised at the point of the electric grid without building level systems replacement. However, the high embodied carbon cost of electricity supply decarbonisation [105] alongside potential supply issues from increased electricity consumption due to electrification of transport and heating sectors [48, 47], demonstrates the benefits of also reducing cooling energy consumption. Therefore, being able to understand how best to reduce cooling energy from a whole life perspective is highly important and currently underrepresented within existing case studies.

Ventilation improvements are also shown to be considerably less researched in this field than other MEP such as replacement heating and renewable energy systems. This highlights a potential gap with assessments in colder countries, as relatively new technologies such as Mechanical Ventilation and Heat Recovery (MVHR), which now can recover up to 95% of waste heat [106], has potential to significantly reduce heating energy load. Not only this, but mechanical ventilation is shown to improve key measures of air quality within buildings such as particulate matter concentration [101]. However, Figure 2.6 shows their whole life impacts are under researched in comparison to other measures. There is a need for assessment of these relatively newly developed or increased efficiency systems to understand how they will impact our ability to meet carbon budgets and targets.

Overall, the case study analysis suggests a lack of diversity in location and climate, typology and the retrofit measures modelled during whole life retrofit analysis. The vast majority of studies are taken at the single building level, with the system boundaries of each case study explored further in Section 2.2.1.

2.2 Methods

2.2.1 Whole life assessments

A Life-Cycle Assessment (LCA) is a systematic method for calculating the environmental impact of a building over the entire period of its life [107]. Figure 2.7 shows the different stages that can be potentially included in an LCA. This has been defined by British Standards [2] and splits a material's life into several key stages. These stages are often used to define the system boundaries of a case study, making it important to fully understand this method and its limitations if it is to be included in future work. The majority of limitations for existing studies are caused by the lack of a standardised method, which creates difficulties when comparing two or more case studies.

Stages B1 - B7 are the in-use stages of a building's life-cycle, such as maintenance and repair, and are therefore dependant on the lifespan of a building. Figure 2.8 shows the choice of lifespan or study period within retrofit case studies ranges from 9 - 100 years. This range is also highlighted in previous reviews [73] but perhaps more concerning is that 9% of publications did not stipulate any lifespan or study period within their work. The choice of lifespan has been shown to impact the total emission estimates and the conclusions drawn when comparing different intervention scenarios [108]. It is therefore important that future publications clearly state assumed building and component lifespans or the length of study period. Longer lifespans can also allow for the yearly benefits of retrofit to payback from upfront impacts where shorter lifespans would not [109], therefore changing the conclusion as to whether retrofit has a positive or negative environmental impact.

Further to this, within whole life retrofit case studies, arbitrary lifespans are often used, with the most frequently adopted building lifespans being 50 and 60 years which is the theoretical lifespan of a new build, not retrofit [12]. Being able to accurately determine the remaining potential service life of an existing building is a challenge that requires further research as the behaviour and condition of a building's structural materials must be understood. In fact,

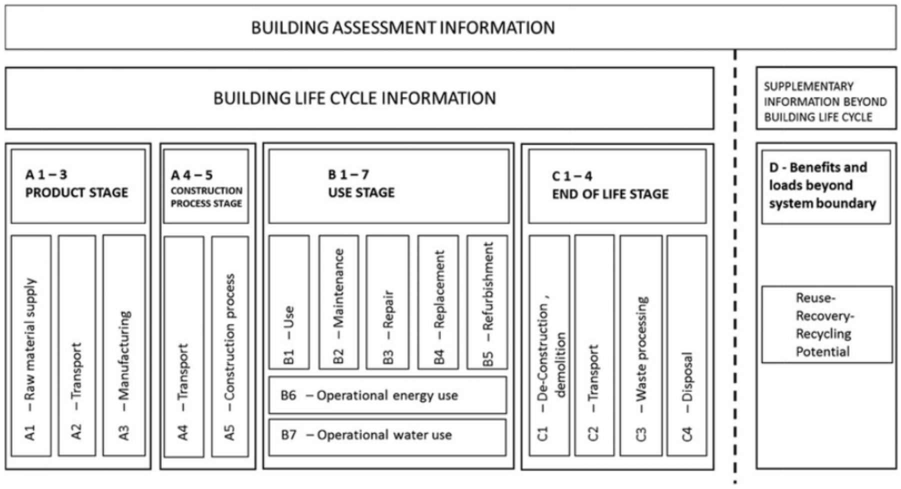


Figure 2.7: The stages included in a Life-Cycle Assessment (LCA) [2]

Dias [110] shows that in tropical climates, concrete structures exposed to Chloride sources can require major repair due to carbonation after just 30 years. This demonstrates that building location is another influencing factor on service life of a building.

The potentially shorter lifespan of retrofit buildings causes further uncertainties when comparing refurbishment with demolition and replacement. If an existing building will reach the end of its service life in the near future it may not be worth adding additional material to refurbish it, when considering life-cycle emissions. Palacios-Munoz [108] calculated the durability based service life of a reinforced concrete existing and new building. It was found that the new building would have a 6 times longer service life than the refurbished building. Using durability based service lives rather than a constant value of 100 years also caused a cumulative difference of 14 - 15% in the whole life carbon comparison [108]. Figure 2.8 shows that the majority of studies do not explore multiple lifespans, but sensitivity analysis is advocated for future work to assess the impact of altering buildings lifespan.

Figure 2.9 demonstrates that there is large variation in the scope of whole life assessment undertaken within each study. There are a number of stated reasons for different life cycle stages being excluded within publications, these include: assumptions of negligible impact [111, 112, 113, 114, 115, 116] or uncertainty [117], inaccuracy [118] and limitations [113] with the data available.

In a study of the refurbishment of a large industrial building, Opher et al. [95] found that construction/installation, stage A5 which is often excluded within existing case studies, would account for 0.6 - 1.8% of carbon emissions over a 60 year lifespan depending on the fuel type

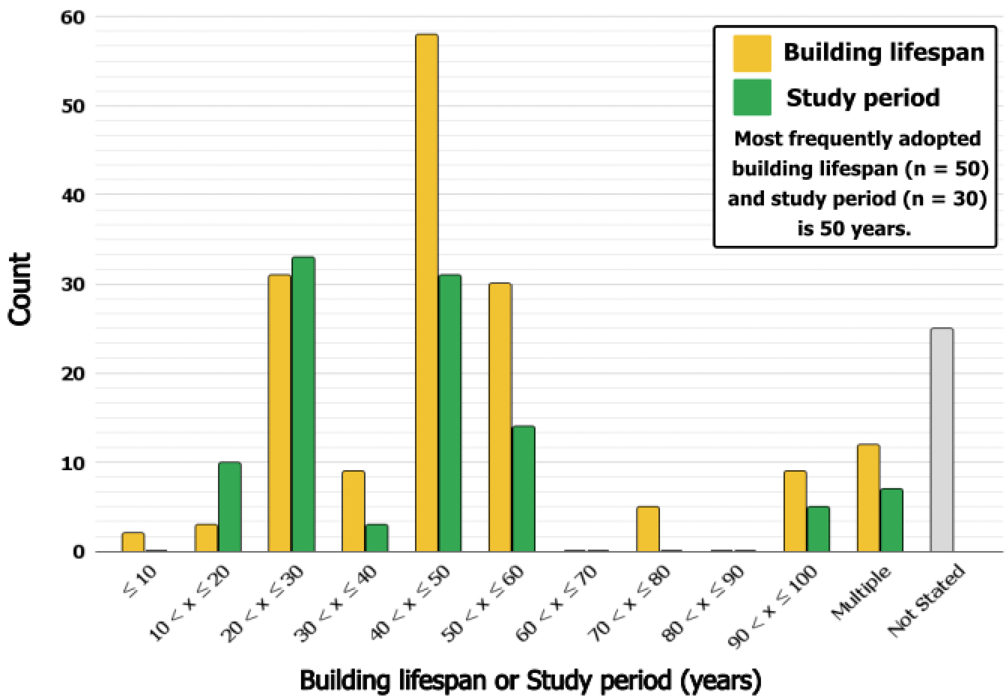


Figure 2.8: Stipulated building lifespan or study period of retrofitted buildings. **Building lifespan** is defined as the remaining modelled lifespan or service life of the refurbished building. **Study period** is the assessment period of the whole life impact assessment when building lifespan is not provided. **Not stated** refers to studies where no building lifespan or study period is provided with enough clarity to be counted.

adopted. Though a relatively small percentage, this would cause the emission of 60tC02e, equivalent to approximately 63 flights from London to New York [119] which is significant, especially if scaled up to the level in which we require retrofit.

The lack of standardisation indicates that results from different case studies cannot be easily compared with each other. The large number of studies with incomplete system boundaries, also implies that many may be underestimating the whole life carbon of building refurbishment.

Comparisons are made even harder between studies when these boundary conditions are not stipulated clearly within a paper. There are 36 cases where the boundary conditions were not clear enough to be included in this study, despite both embodied and operational emissions being stipulated. Further, though it is common for publications to use similar terminology outlined in BS EN 15978:2011 [2], some papers adopt very different phrasing making it difficult to define the boundaries of their study. Consistency and transparency between future studies (e.g. continued use of BS EN 15978:2011 terminology) would prevent this problem in

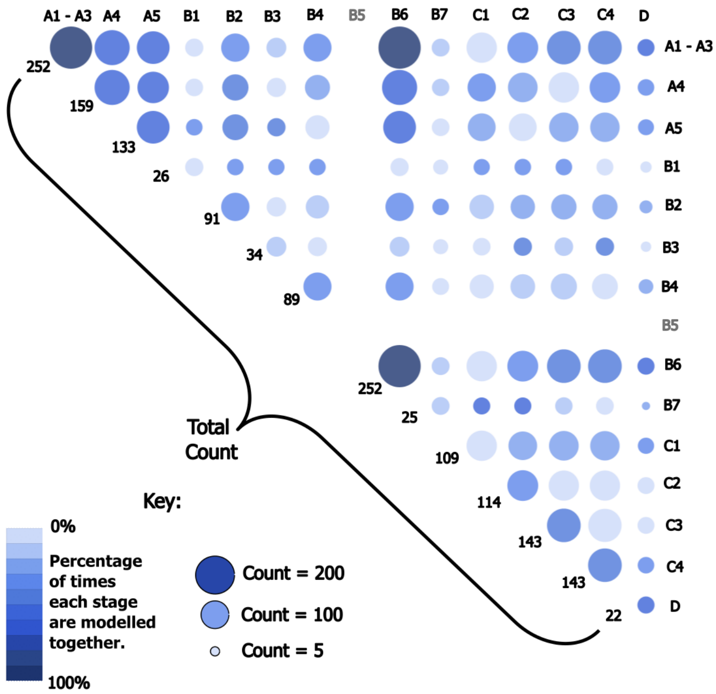


Figure 2.9: System boundary of whole life retrofit case studies with clear system boundaries (252 out of 289). Scope of whole life assessment undertaken by publications (where clearly explained), split by LCA stages as defined by BS EN 15643-4:202129 [2]. Stage B5, titled refurbishment, was not included in the results as each case study has already been found to be a refurbishment case study. Intersection of columns and rows indicate the number of studies having considered both scopes on the intersection row and column, for example, 90 papers consider B2 and B6 together while only 20 consider both B2 and B7.

the future.

As more standardised guidance is developed in industry for completing whole life carbon assessments, such as the RICS whole life carbon guide in the UK [12], a potential solution would be for academia to follow suit in adopting these guidelines. This would mean future case studies would follow the same methodology and be making the same assumptions where data is not available.

Different environmental indicators are shown to impact the results of whole life assessments. For example, applying retrofit of solar photovoltaic (PV) panels to New Zealand's office stock, was found to reduce overall carbon emissions but increase the abiotic depletion of resources [109]. This is especially relevant when thinking at scale, because if a retrofit measure is needed en masse to reach carbon targets, but uses an unsustainable amount of resources, it is not necessarily suitable for application.

In reality, the focus of the current research base is on carbon [$kgCO_2$] or carbon equivalent

[$kgCO_2e$] emissions with 86% of case studies containing assessment of this impact category. Only 30% of studies contained assessment of an environmental indicator other than energy or carbon within their work.

2.2.1.1 Embodied carbon calculations

A Life-Cycle Inventory (LCI) is a key stage of a whole life assessment as it involves data collection for all inputs, such as material and energy consumption, and outputs, such as material wastage and emissions, which occur over the building or product's lifespan [120]. Dixit et al. [121] found that different LCI methods, can lead to varying final results. This is studied in depth by Venkatraj & Dixit [122] who compared the key methods for calculating the LCI in an embodied energy study :

- Process-based - a bottom-up approach, using actual energy-use data or collected and processed data that is found in databases [122, 123].
- Input-Output (I-O) methods - energy tariffs are used to convert the monetary flows between energy sectors and other industry sectors into energy flows [122].
- Hybrid I-O methods - process based data is used for available energy data, before relying on the I-O method to complete the full boundaries of the study [122].

Though there are advantages to using actual collected data due to its relative reliability, data availability issues within a process-based study have been known to cause underestimation of the total embodied impacts [122]. These issues in process-based studies lead to errors caused by the truncation of the product's system boundaries [122, 124]. For example, in a renovation case study scenario, using aggregated and disaggregated I-O hybrid methods, increased embodied energy results by -3 - 79% and 68 - 125% respectively compared to a process-based method depending on which material was modelled [122].

Though the I-O method overcomes the data availability issues it is known to make assumptions which make results less reliable. The I-O method has complete system boundaries, but the assumptions made of proportionality of emissions between different sectors can lead to inaccuracies [124, 125].

Each type of error would be further inflated when whole life impacts are asssessed at a larger scale. For example, where process analysis is used within at scale case studies, as stated by multiple publications [109, 126, 105], the embodied impacts of retrofit measures could be being underestimated considerably. This would lead to an overly favourable assessment of retrofit when considering how easy it will be to meet carbon budgets and targets.

Therefore, a hybridised I-O, process analysis method has been advocated within publications for its increased accuracy [122, 124]. However, at scale publications which use a hybridised has been found to be used in just one at scale publication from the literature search [127].

2.2.1.2 Operational carbon calculations

Understanding whole life carbon emissions requires good knowledge of the operational energy consumption within a building. Commonly used modelling software for understanding energy consumption includes thermal dynamic models such as EnergyPlus [128], TRNSYS [129] and IESve [130]. Though these programs are used due to their proficiency and detail [131], they can be time-consuming [132] and other simplified energy models, such as fast running thermal physics models, have been used in past work when quantifying impacts for large amounts of stock [50, 111]. These simple models typically require the calculation of average monthly heat losses and gains to a space, in comparison to dynamic models where calculations are completed at a much more regular period. For example, EnergyPlus weather files are provided for every hour of a typical year [133].

Other at scale energy modelling techniques include the analysis of existing metered energy consumption data, such as the work of Godoy-Shimizu et al. [134] where metered energy consumption was used to model the operational carbon emissions from English school buildings [134]. This method poses advantages of being from actual in-use data but does pose difficulties when trying to model the impact of retrofit, as the individuality of each school is not taken into account [134].

The level of detail within dynamic models means they have clear advantages compared to fast running thermal physics models [135]. For example, when comparing simple versus dynamic models to assess the energy consumption of a historical building, Adhikari et al. [136] found a difference of 22-38% from metered consumption for the static model compared to 10-24% for the dynamic. However, simplified models have the advantage of a faster computational speed. For example, when considering at scale modelling and early stage decision making, the level of available detail is limited, making simplified models also a good choice [135].

Even dynamic modelling relies on making many assumptions, including the occupancy schedule, equipment use predictions, temperature setpoints and HVAC schedules. Occupant behaviour affects all of these assumptions and is something that is often very difficult to predict by designers [137]. Rodrigues & Freire [138] show the differences in energy use with different occupancy patterns. An office occupancy pattern would require 16-30% lower heating needs and 24-89% higher cooling needs, compared to a typical residential occupancy pattern [138]. Further, Adhikari et al. [136] found the biggest difference in modelling results was not due to the software but the data being inputted. The difference between metered and modelled energy was 52-63% when using standard U-Values compared to using measured U-values, which led to a difference of 22-38% between metered and modelled energy. These findings demonstrate the challenges of energy modelling at scale when available data is limited, and also that occupancy patterns must be ensured to be representative when modelling at scale.

2.2.2 Applications at scale

With over 80% of UK buildings relying on fossil fuel heating systems [43, 44], some form of intervention is required en masse if net zero targets are to be met. Modelling of retrofit at scale aims to understand the whole life impacts of this for many different buildings and/or building typologies. Case studies at scale can use a top-down, bottom-up or hybrid approach. A top-down method disaggregates information from a larger dataset to the required scale. These methods typically utilise aggregated historical databases, such as national energy consumption, which are analysed to understand trends and influences in the behaviour of large quantities of buildings [139]. A bottom-up approach scales up from more granular data, where the analysis of individual buildings is used to create a larger model by understanding the prevalence of those buildings within the geographical boundaries of the study [140]. A hybrid approach adopts both of these methodologies and in theory, the advantages of both approaches can be combined while minimising the impact of the disadvantages [122]. In the context of embodied energy calculations, a hybrid method has been demonstrated to provide more complete results than the most commonly adopted bottom-up approach [122].

One common bottom-up method of extrapolating whole life retrofit assessment to a larger scale is the creation of archetypes. Archetypes are individual building models which are used to represent many buildings, meaning they are multiplied by the total floor area or number of each archetype within a specific area. Within this method there is a perceived increase in complexity in non-residential buildings compared to residential, which is demonstrated through the number of archetypes developed in each publication. For example, at a country level, 6 archetypes were used to represent the UK higher educational stock from a sample of 1951 buildings [141], 17 archetypes were used to represent 5698 office buildings throughout New Zealand [109] and 16 archetypes were used to represent a sample of 13,701 office buildings in Spain [142, 143]. In comparison, 16 archetypes were used to represent 2.2 million Greek single family dwellings [144]. To represent the European Union's housing stock, one publication adopts 24 archetypes [91] and another study uses 24 archetypes analysed over 28 climate conditions [92].

From the archetype approaches adopted in current literature we can conclude either a larger level of individuality for non-residential buildings or an oversimplification within residential building assessments which may lead to misleading results. This could cause difficulties when trying to perform assessments at scale as there will need to be more archetypes to represent these differences between buildings. Each study is highly reliant on data availability and the validity of the chosen archetypes. The impacts of any simplifications will also be magnified once the results are scaled up. As such, an appropriate level of knowledge of the current building stock is required to appropriately assign accurate archetypes.

Another bottom-up method uses spatial mapping. Geographic Information Systems (GIS) [145, 111, 146, 147] and 3D city models [148, 149] have been used to estimate the envelope surface area and key geometric parameters of buildings which in turn influence energy consumption [9] and will therefore have potential benefits from using purely archetypal methods. This could be especially useful when applied to non-residential buildings, which, as demonstrated [142, 143, 141, 109], can have a greater tendency to vary within the same building typology and have also been shown to vary more widely in terms of building geometry compared to residential [150, 151]. Publications have also demonstrated the feasibility of using spatial mapping to identify how carbon emissions and savings change between location [111, 152] and building typology [153]. Mapping can help visualise results, allowing for a clearer demonstration of the differences between different areas and typologies, as well as carbon hotspots within urban areas that could be a focus for urban planners [111].

In some studies a hybrid approach was adopted, which involves both bottom-up and top down methods [91, 154]. Allacker et al. [91] used a hybrid approach to quantify operational impacts from European residential retrofit while Seo, Foliente and Ren [154] adopted a bottom-up approach to quantify operational savings, but a top-down method for embodied impacts using Input-Output analysis (I-O).

The vast majority of papers focused on European geographical boundaries, with all papers at the continental level being based in Europe [91, 92]. Both the creation of archetypes and analysis of emissions requires data to provide a sufficient understanding of the system boundaries being assessed. From a European perspective, databases such as TABULA are commonly used [146, 92, 91, 153, 155] for residential building assessments and provide a comprehensive assessment of European residential building stock divided into size and age classes [156]. This is key data that informs energy consumption (See Chapter 3) and the appropriate retrofit measures (See Chapter 4). Whether this type of data is available for other parts of the world may be a key barrier to understanding global building stocks, and may make it challenging to apply existing, commonly adopted methods to other parts of the world. One publication which has taken a global approach is Nematchoua, Sadeghi and Reiter [72] who apply neighbourhood level carbon assessments but from a global perspective. It is shown that data availability provided challenges for this modelling as not all countries provide updated data on their respective energy-mixes, construction standards, and also the urban morphology of every country was not assessed [72]. This highlights challenges if data was wished to be extrapolated to higher scales for specific countries with no available data.

2.2.3 Economic assessments and optimisation

Financial constraints are a huge barrier toward retrofit uptake at scale. For example, the retrofit school buildings in the UK is shown to be directly driven by Local Authorities [64], of which currently face a major funding gap [157]. Publications also demonstrate a further barrier, which is the conflicting results between the cost of retrofit and the environmental impacts. For example, when comparing between different residential archetypes in Melbourne, the economic payback time of retrofit is found to be considerably longer than environmental payback time [154]. The same pattern was found when comparing Spanish office archetypes, where 88% of retrofit measures applied would reduce life-cycle carbon emissions, but only 28% of the measures would reduce life cycle cost [143]. For the Spanish city of Barcelona the retrofit scenario with the best impact on life cycle carbon and energy had the highest upfront economic cost and longest economic payback period [158] . These examples demonstrate the key cost barrier industry faces when trying to implement retrofit at scale. Despite this, Monzón-Chavarrías et al. [158] found that if the entirety of Barcelona's stock was retrofitted to the most financially costly level, nearly €60 billion of cost savings would be achieved over the stock's extended lifespan. The benefits from economies of scale have also been demonstrated as Abokersh et al. [159] found a minimum community size needed for solar district heating to become financially beneficial. These financial studies highlight the importance of government incentives and policy rather than relying solely on individual actors who may not be able to afford upfront costs.

Another solution to the high economic cost of retrofit could be multi-objective optimisation. Where single objective optimization was undertaken on retrofit, the optimal solutions for cost and greenhouse gas emissions were in conflict with each other, again highlighting this barrier for retrofit [160]. Multi-objective retrofit optimization, which has been demonstrated at scale [160], allows for both economic and environmental impacts to be optimised simultaneously. For residential archetypes in Switzerland, Wu et al. [160] found a multi-objective optimal solution with a 76% reduction in life-cycle emissions and a 3% increase in overall Life-Cycle Cost (LCC). By optimising both economic and environmental impacts simultaneously a trade-off between the two could be achieved. An assessment of the cost and carbon impacts of Canadian residential archetype retrofit showed that all solutions that led to an overall cost saving, also led to an overall reduction in life-cycle emissions compared to the base case [115].

The optimal retrofit solution for carbon and economic savings has been found to vary between different archetypes [115, 160], showing the benefits of an 'at scale' approach, as findings from a single building type cannot be easily translated to an area's entire stock. Petkov et al. [161] show that when planning refurbishment strategies, adopting a fleet-level approach, where the strategy aims to meet policies for the entire portfolio rather than on an individual building basis, leads to an overall 8% cost reduction with similar total carbon emission reductions. Though mass retrofit will come at a cost, optimisation could be used to minimise this cost. Optimising multiple constraints alongside whole life carbon and financial cost, such as circularity and ease of installation could help find the best retrofit interventions that are practical for application at scale and where these should be installed to be most effective. Another solution is the development of materials and retrofit measures that can be produced at a lower cost and installed quicker with minimal complexity to reduce the cost of labour.

Many optimisation tools use complex dynamic models for energy consumption calculations, which are computationally costly and require a large set of inputs not suitable for understanding buildings at scale. Sharif and Hammad [132] also created a methodology for the optimization of many different retrofit measures, using multi-objective optimization to find the best outcome in terms of three parameters - total energy use, LCC and LCA. Each optimization took on average 170 hours which is a lengthy period considering that only one floor of one building was assessed [132]. Reducing computational time and being able to understand optimal solutions for a large range of building forms, construction typologies and ages would be highly useful. This may require moving away from the use of dynamic simulations and instead developing more simple energy models.

2.3 Implications of whole life retrofit studies

2.3.1 Operational and embodied emissions

When assessing the whole life impacts of retrofit, a number of papers have found carbon payback periods for different retrofit interventions which are well below the typical building lifespan, of 50 years [112, 113, 114, 117, 162, 155, 163, 164, 165, 92, 127, 166]. Gustafsson et al. [167] found that the refurbishment scenario with the highest embodied impacts, in terms of material fabrication and replacement, had the lowest overall environmental impact. This is agreed upon by Hu [126] who found that deep retrofit on a U.S. campus led to the largest decrease in life-cycle emissions compared to moderate or basic retrofit scenarios. Siérra-Perez et al. [168] conducted an LCA on both a conventional, retrofit to minimum EU standards, and Enerphit retrofit of a school in Spain. Enerphit is the term used to describe buildings which have been retrofitted to a Passivhaus level, which would mean the building is able to achieve extremely low energy use. The Enerphit model, with cork insulation, released over double the embodied emissions in terms of Global Warming Potential (GWP [$kgCO_2e$]), but performed 30% better than the conventional model over 50 years [168].

Therein lies an argument, that due to the haste operational energy reductions are required, these should be prioritised and embodied emissions ignored due to their perceived limited impacts.

However, there is evidence that the embodied impacts of retrofit can vary significantly. Ardente et al. [162] assessed 6 retrofit projects on different public buildings around Europe. In all but two of the cases, carbon payback times of each individual measure were found to be low - under 5 years after installation. However, in the case of the 'Provehallen' in Copenhagen the installation of insulation in the building took over 30 years to repay its carbon debt which is a considerable length of time [162]. This is an unusual result as all the other insulation installations had a carbon payback time below 2 years. It is unknown why the carbon payback period is significantly higher for this building, but results show the total embodied carbon of insulation installed per floor area [$kgCO_2e/m^2$] is much larger, and the energy savings from insulation [$GJ/yr.m^2$] much smaller in the case of Provehallen compared to the other five case studies [162]. It is perhaps the case that a more carbon intensive insulation material is installed in the case of Provehallen or that the MEP strategy is less sensitive to the impact of insulation. The difference in carbon payback period between each case study shows potential for the effects of retrofit implementation to vary widely for different building types which impacts the significance of embodied carbon.

Large variations in results were also found when Pomponi et al. [52] investigated the impacts of various types of double skin facade (DSF) when retrofitting a typical UK office building. 128 combinations were assessed where the orientation and width of the cavity were altered in turn. Carbon payback times varied widely from as low as 6.4 years to over 50 years for certain building orientations. The orientation of a building, alongside other factors such as building form are characteristics which cannot readily be altered in an existing building and therefore shows the potential for different retrofit measures to be preferable for different buildings.

Further variations in embodied emissions are demonstrated for renewable energy systems. Multiple studies show that solar PV has a positive impact of whole life carbon emissions within retrofit case studies [109, 95, 169, 113]. When Ghose et al. [109] assess the impacts of 17 office archetypes it was found that though there were overall carbon savings from the stock. However, when looking at each case study individually, solar PV did not reduce whole life carbon emissions where the roof area was less than 50% of the total gross floor area (GFA) or where there was considerable overshadowing from surrounding buildings. This again highlights the wide range of carbon payback times found in different case studies. In this case it seems clear that average results cannot be assumed for every office building, and that the individualities of different case studies would potentially cause requirements for very different retrofit measures. While Ibn-Mohammed et al. [170] found that solar thermal would have an overall negative impact on whole life carbon emissions, Opher et al. [95] found a very low carbon payback time for these panels within their case study. Each building will have potentially different climate, roof area, orientation, and shading which would impact the efficacy of solar panels within the project. It poses a potential problem for designing retrofit at scale from a bottom-up approach ie. using archetypes.

As we assess retrofit at scale the impacts of using different materials become even more important.

Li et al. [50] compared different retrofit scenarios to assess whether retrofit measures would allow England's housing stock to fall within its carbon budget. Carbon budgets have been developed to set restrictions and goals on carbon emissions within different sectors and countries. It was found that the two retrofit scenarios that fall below England's most stringent carbon budget would only achieve this with a selection of low embodied carbon insulation materials showing that the importance of embodied carbon assessments and material choice are emphasised when retrofit is considered at scale [50].

This importance of insulation choice is also shown by Gulotta et al. [92] who quantify the environmental impact of different insulation types at a European scale. It is shown that the carbon payback time is 4.74 years for wood wool board compared to 0.56 years for stone wool on a stock-wide EU level [92], due to a worse thermal performance for wood wool requiring thicker insulation [92]. Though both these are well below the typical lifespan of a building, the current predictions estimate a 7% deficit in the EU meeting its current carbon targets [171], showing why it is important to assist with overall carbon reduction through ensuring the use of sustainable materials.

From a purely embodied carbon perspective, Pittau et al. [172] calculate the potential carbon storage impact of different insulation materials for retrofit of the EU housing stock. It was found that straw, if applied to European stock, has the potential to temporarily remove up to 3% of carbon emissions from all EU emitting sectors in comparison to non-biogenic materials like the current most commonly adopted insulation type of EPS [172]. The importance of aggregating impacts at scale is demonstrated by the fact that at building level the impact of carbon storage would be minimal. It should be noted that straw has a susceptibility to moisture and humidity which increases the risk of mould growth and degradation potentially causing practical difficulties if implementing at scale [173]. Further, care must be taken when using insulation as a carbon sink as another biogenic material, timber insulation systems [172] has been demonstrated to have an overall net positive global warming impact by 2050 when applied at scale. This is due to the longer growth period of timber compared to straw which reduces its short term impacts as a carbon sink [172].

Work on material choice often focuses on insulation (See Figure 2.6) but there are various options for different materials in other aspect in other retrofit measures such as mechanical systems and glazing materials. Various commonly used refrigerants in heating and cooling systems have extremely different GWP [174] and if refrigerant leakage occurs, as is shown to be common [175], cause significant emissions. This is particularly pertinent given that mass intervention of heat pumps is a key strategy for decarbonisation within a number of countries [98, 96]. For example, Europe plan to phase out all fossil fuel heating systems by 2040 [98] and Canada requires 10% of homes to be heated by heat pumps by 2030 to meet climate targets [96]. Further research in the field of material choice, accounting for a wider range of retrofit measures, may help highlight the large variation in whole life carbon emissions from different carbon mitigation pathways.

2.3.2 Demolition versus refurbishment

When considering the world's existing building stock, another possible solution to high operational emissions would be to demolish and replace a building with a more energy efficient one. The embodied impact of this at scale would undoubtedly be significant.

This embodied impact is explored by Marique and Rossi [176] who performed an LCA for two different scenarios for a public office building in Belgium. A deep retrofit scenario was designed by architects, including the extension of available floor area, new ventilation system and added insulation to the existing envelope. The rebuild scenario had the same operational performance as the retrofit case study. The refurbishment scenario was found to emit 56.6% of the total carbon emitted during the new build project. This is agreed upon by both Pittau et al. [177] and Hasik et al. [178] who also completed a comparison between new build and retrofit, but for industrial buildings in Italy and the USA respectively. Building refurbishment was found to always be the most sustainable scenario, even with the inclusion of material recovery and re-use within the demolition and reconstruction scenario.

However, there is a problem in the assumption that a refurbished building can necessarily achieve the same operational performance as a new construction. Therein lies a question as to whether, over time, a more operationally efficient new construction could outweigh the higher upfront embodied emissions compared to retrofit. There are several factors that cannot be altered within retrofit projects which will have an impact on energy use, such as building form, orientation, and thermal mass of a building's structure. Pomponi et al. [52] have demonstrated that different building orientations can have a big impact on the effectiveness of a retrofit measure, which can cause carbon payback times above the lifespan of the measure.

Building geometry, e.g. form, is another factor not readily changeable within an existing building. Building form defines the relationship between exposed surface area and the internal volume of a building. Therefore, form provides a proxy for the relative importance of the heat losses through walls, floor and roof and the heat loss through the infiltration of cold outdoor air due to ventilation losses. In fact, form is shown to impact the energy efficiency of a building [179, 180, 181, 182] as well as the embodied carbon of new constructions [181]. Gauch et al., [181] provide a comprehensive sensitivity study into a typical multi-storey building design. Within this, it is shown that increased building compactness ($\frac{Floor Area}{Surface Area}$), has considerable influence on both the embodied and operational efficiency of the construction. In fact, building shape and size, alongside frame type and layout, were the most significant variables influencing embodied carbon, construction cost and heating and cooling loads [181].

From a retrofit perspective, the required insulation levels to achieve a similar energy efficiency level are higher for buildings with a larger volume to floor area ratio [53]. Therefore, understanding the impacts of form has applications for whole life carbon assessments of retrofit as it impacts both operational and embodied carbon of a building. An inefficient building form may limit the achievable energy savings, altering conclusions for demolition versus refurbishment comparisons compared to a building of a more compact geometry.

To compare demolition and new construction to retrofit, a non-residential building case study assessment has been undertaken in the early stages of this PhD project for a retail and office building [63]. In this scenario the new construction is modelled as significantly more operationally efficient than the refurbishment scenario. Over a 50 year lifespan, refurbishment of the building led to the lowest whole life carbon emissions, even if 2030 embodied carbon standards

($300kgCO_2e/m^2$) of new construction were achieved, which is considerably improved from current standard practice [63]. This finding relied on refurbishment of not only the building fabric but replacement of existing gas boilers with an air source heat pump. The refurbishment model which retained gas heating systems had the highest emissions over the 50 year period, despite thermal improvements [63]. The results modelled here included significant decarbonisation of the UK's electricity supply which is another cause of uncertainty when appraising the significance of increased embodied carbon against the potential operational carbon savings from new construction. Further assessment including comprehensive sensitivity analysis of building lifespan and electricity emissions would be useful.

When further new construction versus retrofit case studies have been conducted at both the individual building and larger scale, conflicting results have been found, with multiple publications showing retrofit has lower environmental impacts [116, 148, 183, 184, 185, 186, 127, 187, 188, 189, 190, 191] and others demonstrating scenarios where new construction is preferable [108, 141, 192, 193, 194, 195, 196]. The complexities of this comparison are clear, with the chosen building's lifespan shown to impact what conclusion is made [108]. This conflicting conclusion demonstrates the difficulties in comparing and drawing wider conclusions from building level case studies. As building characteristics, e.g. fabric efficiency and geometry, are likely to change between individual case studies, it thus remains difficult to draw generalized trends from current individual demolition versus refurbishment case studies.

At the country-scale, Pauliuk, Sjostrand and Muller [197] model 26 different scenarios for the reduction of carbon emissions in the Norwegian residential sector. This included scenarios with complete demolition and reconstruction of buildings compared to scenarios with complete retention and renovation. Those scenarios in which renovated buildings were prioritised were found to have lower cumulative carbon emissions. By comparison, carbon savings within reconstruction scenarios were significantly offset due to upfront embodied carbon emissions [197]. There were similar findings at the neighbourhood level, where refurbishment of existing buildings is compared to a passive house new construction over a 50 year period. The refurbishment model was found to have lower carbon emissions despite having significantly higher yearly operational energy consumption, $50kWh/m^2$ in comparison to $15kWh/m^2$ for the new construction [127]. Further, analysis of a residential Australian suburb found that demolition and reconstruction led to an overall increase in life-cycle energy consumption over the 20 year study period, despite operational savings [186]. These studies demonstrate that the embodied impacts of new construction are significant and it cannot be assumed that operational savings would lead to lower whole life carbon emissions. The integration of whole life impact assessments before any demolition is important. This would have to be considered alongside other factors such as the service lifespan of each building, meaning it may be incorrect to assume that a refurbished building can last the same period of time as a new construction. Depending on the environmental payback time of refurbishment measures, if a building is nearing the end of its structural service life, delaying demolition for a short period may not be appropriate.

It has been found that non-residential buildings have higher replacement rates than residential [198, 199], attributed to the higher rates of occupancy and ownership change [198]. Alongside those higher rates, Figures 2.3 - 2.5 show that research into non-residential buildings is less common than residential, especially when applying retrofit modelling at larger scales such as the national and continental level. For these reasons there is a need to explore topics such as new construction versus refurbishment at scale for a wider range of typologies. We have demonstrated that from an archetype perspective there is evidence that non-residential buildings also have a higher level of individuality compared to residential stock. Alongside this, building size [150] and depth [151], are also shown to vary more widely in non-residential compared to residential stock which may impact which scenario leads to a lower environmental impact. In fact, Hawkins and Mumovic [141, 192] found that a new build scenario led to an overall reduction in carbon emissions in comparison to retrofit options for archetype higher educational buildings. However, there was no retrofit scenario where both the fabric and the mechanical systems were updated simultaneously and it is not stated whether the demolition of the original building is accounted for within new build scenarios, calling into question whether it can be claimed that a new higher educational building would be lower carbon. Further analysis in this topic could help us understand which non-residential building and construction typologies may require demolition.

There are other arguments both for and against the demolition of existing building stock. For example, the preservation of historical buildings is important in older cities to retain cultural heritage. However it is shown that, though refurbishment was the most environmentally beneficial option for a historical Portuguese building, the savings were not as high as expected due to the need for structural strengthening [200]. The rebuild option was also more economically beneficial compared to the retrofit [200]. Alongside this, improving these factors can be technically challenging in existing buildings as they can have hidden or difficult areas to access or be expensive to improve [201]. There is clearly a balance to be struck between resource and carbon consumption and providing safe and comfortable spaces for occupants to live and work. If a building is nearing the end of its practical or liveable lifespan and will need to be demolished in the near future, then it could be preferable to demolish the building sooner rather than use significant amounts of materials during retrofit which will likely end up in landfill.

2.3.3 Meeting government targets and carbon budgets

When retrofit assessments are scaled up beyond the building level, these models can be used to assess the scale and urgency with which retrofit is required when trying to meet government carbon budgets or targets. Li and Densley Tingley [155] assessed the impacts of different retrofit rates for solid wall insulation for pre-1919 housing stock in England. By adopting the Committee on Climate Change's predicted insulation rate rather than current UK practise, a saving of approximately $80MtCO_2e$ would be achieved by 2050. This is 4-5% of England's carbon budget [50]. Li et al. [50] calculated whole life impacts of different retrofit scenarios and assumed that England's entire housing stock was immediately retrofitted. Despite this mass implementation, only whole house retrofit would fall within the most stringent carbon budget [50], highlighting the urgency with which retrofit needs to be implemented. In fact, multiple studies have also shown that renovation rates need to increase considerably to meet these targets - in the US by 1.5 times compared to historical levels [202], in Luxembourg from 0.5% - 3% of homes per year [111], in Portugal from 0.4 - 3.3% [145] and in Ireland a total of 34% of homes retrofit by 2030 in comparison to current national plans where 23% would be improved upon [89].

Studies have highlighted that fabric efficiency improvements alone are insufficient to meet government targets for Germany [149] and Sweden [153, 203] and the carbon budget in England [50]. This is an argument for whole house retrofit, and in fact, Li et al. [50] have highlighted the need for mass heat pump deployment within England's housing stock.

Whilst new mechanical systems, e.g. heating systems, are shown to be essential to meet government targets, they have a considerable embodied impact which needs to be understood [204, 94]. A key limitation of Li et al. [50] is that the LCA was only cradle-to-gate, excluding maintenance, replacement and disposal, but mechanical systems will likely require replacements and maintenance over a 30 year period [205]. Whether carbon budgets are still met once replacement is accounted for is an important question for future research. Material decarbonisation in the future could reduce the embodied impact of these replacement cycles, but the success of this is shown to be reliant on many different factors, such a grid decarbonisation and demand for new stock, that are not controlled by industry [206]. The development of systems with reduced replacement rates or increased end-of-life re manufacturing and re-use is another method to reduce this carbon impact.

Targeting of specific retrofit measures [207] and buildings [89] has also been shown as beneficial to reducing whole life impacts. Saner et al. [207] optimised greenhouse gas emissions for a municipality in Switzerland. An average renovation rate of 67% of all residential roofs and windows in the region was found to be optimal from a whole life perspective, with only 5% of floors being optimal to retrofit. Hegarty and Kinnane [89] show that operational carbon reduction in line with Irish residential carbon targets can only occur with strategic prioritisation of retrofit for the worst performing homes. Again, by understanding results at scale we know when and how best to target buildings in order to meet climate targets.

2.3.4 The importance of electricity decarbonisation

Though there are clearly demonstrated benefits from mass retrofit, Ostenbring et al. [147] show that carbon targets set by the City of Gothenburg will not be met through the installation of retrofit measures alone and therefore relies on decarbonisation in other sectors to meet this target. Other publications [202, 89, 109, 153, 145] have also demonstrated the benefits and necessity of decarbonisation of electricity supply when coupled with mass retrofit. Göswein et al. [145] found that a Portuguese neighbourhood would only meet the Paris 2°C carbon budget if retrofit rates were increased from the current annual rate of 0.4% to 3.3% and the electric grid underwent a fast and immediate transition to net zero by 2050. Ghose, McLaren and Dowdell [109] also show that increasing the electric grid's share of renewable sources will significantly increase the reduction in emissions in New Zealand, especially when no on-site renewables are installed.

These collective findings show how urgent action in other sectors such as electricity production will positively benefit the built environment. Electricity decarbonisation becomes even harder as mass implementation of low carbon strategies such as electric heat pumps and electric cars is completed and increases total electricity consumption [48]. This decarbonisation also comes with significant embodied carbon costs. For example, when modelling future stock scenarios in Sweden to meet governmental targets, the cumulative embodied greenhouse gas emissions from new renewable power plants outweighed that of the renovation and new construction of offices and dwellings combined [105]. Not only does this further show the need for material decarbonisation but also highlights the importance of retrofit itself. By using energy efficiency measures such as insulation we can minimise energy demand and reduce pressure on electricity supplies.

2.3.5 Entire building stock assessments

Looking at the building stock as a whole helps demonstrate how retrofit fits within the wider context of decarbonisation of the built environment. With predicted global population growth of 1.7 billion by 2050 [208], the requirement for new quality housing is clear. Hegarty and Kinnane [89] model different decarbonisation strategies within the Irish residential sector, aiming to meet national targets for a 51% reduction in operational emissions from this stock while meeting housing needs with 400,000 new homes. This is modelled through retrofit of 34% of total existing stock and focus on reducing emissions from worst performing stock first. However, the increased embodied carbon emissions from both retrofit and new construction largely negate the operational carbon improvements and reduce the 51% reduction to just 5%. In fact, targets are only achieved from a whole life perspective, with complete decarbonisation of electricity, a 62% decarbonisation of future construction materials and a reduction in the size of future homes [89].

These results are agreed upon from a US context where Berill et al. [202] show what is required to meet 1.5 degree warming targets from new and existing buildings. This is only met with complete decarbonisation of electricity supply by 2035, increased renovation rates which includes all fossil fuel heating systems replaced by 2025 and reduced floor area of new constructions with a focus on increased multi-family building stock [202].

The material cost of new construction clearly impacts our ability to meet sectoral climate targets. Helping provide this new floor area through retrofit in our existing stock is a potential growing area of research. For example, in the UK the argument has been posed for re-conversion of larger houses by splitting them into multifamily dwellings, as increasing density also holds benefits for the sustainable provision of services [209]. Understanding the balance of whole life impacts at scale between this kind of adaptive retrofit and new construction could be highly useful for future urban planning and regulation. However, increasing urban density has been shown to be a potentially unattractive prospect for residents [210].

As time passes our needs as a society also change and in 2021, 1 in 7 units within UK shopping centres were empty [211]. The UK Government [1] also predicts that retail buildings will further reduce in number by 2050. However, as the population continues to increase so does the need for more housing and the UK Government aims to construct 300,000 houses per year [62]. There is a need to adapt buildings while also reducing their energy consumption. Studying this from a life-cycle perspective would be highly useful to understand the effects of adaptation, as Rodrigues & Friere [138] show that the optimal thickness of wall insulation changes depending on whether the space is retained as a residential building or converted to an office.

2.4 Research gaps and conclusions

Figure 2.1 demonstrates that the field of whole life retrofit assessments has grown rapidly within recent years. The importance of assessing emissions over the entirety of building's lifespan is apparent, as material payback periods of different retrofit measures vary within and between studies [112, 113, 114, 117, 162, 155, 163, 164, 165, 92, 127, 166, 104]. Further, not only does material choice have the potential to store significant emissions from the atmosphere [172], but it has also been shown to impact whether a country can meet its carbon budget [89, 50].

Though there are large numbers of existing case studies, disparities in system boundaries makes it difficult to draw out comparisons between them. This point is emphasised by the number of case studies, 12, which found refurbishment to be preferable when compared to new construction [116, 148, 183, 184, 185, 186, 127, 187, 188, 189, 190, 191], and the number, 7, which found the opposite [108, 141, 192, 193, 194, 195, 196]. Demolition is already occurring at scale in the UK, with 50,000 buildings demolished per year [59], showing there is a need to develop methods which can demonstrate the key influencing factors for when demolition is preferable for a stock type as a whole.

Studies which assess impacts at scale, for a large number of different buildings and typologies, provide benefits as the impacts of retrofit can be understood for many buildings using the same system boundaries. Assessments at scale also allow for direct comparisons to existing government targets and carbon budgets. Key findings from these studies include the need for electricity [202, 89, 109, 153, 145, 147] and material decarbonisation [89] alongside retrofit, the benefits of retrofitting the worst performing buildings first [89, 161], and the importance of material choice when insulating large amounts of stock [92, 50].

Currently, at scale case studies are skewed towards assessments of residential buildings in Europe. When it comes to non-residential studies, the most commonly assessed system boundary is University buildings, at the relatively small scale of campus level (see Figure 2.5). Therefore, there remains a gap in our understanding of the key drivers that influence different whole life decisions for non-residential stock. Considering that non-residential buildings have higher replacement rates than residential [198, 199], it is also especially important to comprehensively understand the whole life carbon comparison between retrofit and demolition and new construction for non-residential stock.

This chapter has demonstrated that compared to higher educational buildings, schools are less frequently studied. School stock, such as primary, secondary schools and colleges, provide a great potential starting point for understanding the whole life impacts of non-residential retrofit at scale. This is because the retrofit of schools in the UK is directly driven by local governments as they own and manage a large proportion of the stock [64] who should have explicit social goals [212]. For example within the residential sector, social housing has been cited the natural place to begin to scale up retrofit in the UK [212]. Therefore, it is logical to conclude that retrofit of public sector buildings is also likely be a good starting point to scale up non-residential retrofit.

Modelling school stock could not only further our understanding of the whole life implications of non-residential retrofit, but also provide explicit insights into the required pathways for governments to meet key targets in this sector. Due to the high reliance of non-residential buildings on fossil-fuel heating systems within the UK [44] this thesis will also focus on thermal energy retrofit, as the built environment cannot be decarbonised without replacement of these systems.

To contribute to knowledge within this field the overarching aim of this thesis is to **develop**

an understanding, at scale, of the implications of accounting for whole life carbon within different future retrofit decisions and interventions.

In the process of achieving this outcome, Chapters 3 - 5 aim to answer the following key research question as discussed below:

1. ***What influence does building form have on the lowest whole life carbon intervention for existing buildings?***

   Non-residential buildings, which are less widely studied at scale, have been shown to vary more widely in terms of building shape and size than residential [150, 151]. This variation, known as building form, has been shown to influence both energy consumption and the upfront embodied carbon cost of construction [53, 9, 179, 180, 181]. With opposing views on the carbon benefits of demolition demonstrated in this chapter and as new construction is not constrained by the existing form of the building, understanding the connection between form and whole life carbon could be highly useful to provide a comprehensive and fair comparison of different potential interventions.

   Further, past results have shown that prioritising least efficient buildings can be beneficial to meeting carbon reduction targets [89, 161]. However, the influence of building form within this discussion has not been expressly explored.

2. ***What intervention is required to the existing building stock when considering a stock's carbon budget?***

   Existing work modelling how retrofit can help meet England's carbon budget has focused on residential buildings [50] and only from an upfront embodied carbon and operational perspective.

   Though the importance of material choice has been demonstrated for insulation systems at scale [50, 92], when one considers impacts over a building's entire life it becomes clear this is not the only important comparison. For example, different refrigerants used in heat pumps have a wide range of values for total global warming potential [213], which impact a buildings' whole life carbon due to refrigerant leakage. It is important to understand the impact of different whole life decisions including replacement rates as well as the pathways by which government decarbonisation targets can be met. This includes the potential for certain building forms and types to benefit from demolition and replacement when assessing whole life carbon emissions.

To answer these research questions, two different methodological approaches are developed. The first, aims to calculate a building's energy consumption and whole life carbon emissions for a large amount of stock in a time effective manner. This approach is validated against existing building case studies where metered energy consumption is available.

Secondly, the analytical connection between energy consumption and whole life carbon to building form will be demonstrated, which will be validated against an existing established energy model [135].

Application of both these methods aims to provide key insights into the whole life carbon impact of retrofit, at scale, to understand how key building characteristics influence future retrofit decisions, as well as the requirements and barriers to meeting government carbon targets and reducing overall emissions of the English school stock.

Chapter 3

Assessing building energy consumption at scale

3.1 Introduction

To understand whole life carbon impact of retrofit, one of the crucial elements is a quantification of the energy consumption. Operational energy currently accounts for the majority of built environment emissions, showing why an appropriate assessment of current and future energy consumption is highly important. Therefore, this chapter introduces a method which can be used to quantify the energy consumption of English school buildings at scale.

The developed method is then verified using metered energy consumption data for 234 school case studies around the UK.

Chapter 2 demonstrates a large variation in different methods for modelling energy consumption of retrofit, ranging from fast running thermal physics models with quick application [135] to more detailed dynamic energy models [128, 129, 130].

In this piece of work, the geometry of each archetype will be modelled in a one-by-one approach as non-residential buildings have been shown to vary more widely in size and shape compared to residential [150, 151]. A one-by-one approach is defined as modelling each building individually, allowing for a more precise understanding of the influence of each building's unique geometry. This stands in contrast to methods where a uniform energy consumption intensity [89] or retrofit energy improvement factors [134] are applied to every building of a similar age or construction. By undertaking a one-by-one approach, this study aims to understand the influence of this increased complexity, including the key characteristics which influence the discussion of demolition versus refurbishment - see Chapter 4 for further exploration of this.

Therefore, fast running thermal physics models will be adopted, as dynamic models have been shown to be considerably time-consuming when quantifying energy consumption for many different scenarios [132]. Due to various simplifications, simple energy models are seen as having limited accuracy in comparison to more detailed dynamic thermal simulation [136]. Though past research has demonstrated that simple thermal physics models can be used [50, 111], it is important to understand whether these models will accurately predict energy consumption of a building. Therefore, verification against metered energy consumption case studies is undertaken in this chapter.

This chapter adapts the degree-days model, an established simplified energy model for heating energy consumption that accounts for the key influencing factors on total heating energy consumption such as building geometry, fabric efficiency and typical average monthly weather patterns. It's speed of implementation also makes it a good choice for early design decisions where large amounts of detail and inputs, such as exact occupant behaviour, are not likely to be collected [135].

Data collection is another key stage of energy modelling at scale. It is important to understand what are appropriate inputs for energy modelling such as the geometry of a building, the thermal efficiency of the fabric and ventilation systems as well as occupancy patterns which can represent each typology at scale. Verisk UK Buildings is used because it is a widely available data-set, through OS Digimaps, which provides a comprehensive set of information useful for energy modelling. This not only includes key building geometry, but also building typology and building age which is shown to inform the fabric efficiency of a building [46, 214, 215]. Past studies which aim to model the energy consumption of schools in the UK, use datasets which are not freely available to researchers and reduce the likelihood of repeating existing methods [216].

The following section outlines the methodology for energy modelling of school buildings at scale, followed by details of the 234 metered energy consumption case studies which will be used. Further, results will be provided comparing heating, thermal and electrical energy modelling to metered energy consumption results. This will be proceeded by conclusions and a discussion of the limitations of the developed method.

3.2 Methodology

This methodology will show the simple yearly total energy model that is developed for this piece of work and how it will be applied to the metered energy consumption case studies.

There are three key steps to this method, the first combines existing simplified energy consumption methods to create non-computationally time consuming model for estimating energy consumption of school buildings. The second involves data collection of all inputs into the energy model including geometry, age, typology and weather. The third section explains how this model has been applied to a set of school building case studies to understand how well the model can be applied at scale using the existing available inputs.

3.2.1 Energy consumption

Total energy consumption [kWh] can be described by splitting it into its component parts:

$$F_{total} = F_{heating} + F_{DHW} + F_{kitchen} + F_{electricity} \tag{3.1}$$

where $F_{heating}$ is the total energy consumption from heating the space, F_{DHW} accounts for total hot water usage by occupants, $F_{kitchen}$ refers to any fossil fuel usage due to cooking and $F_{electricity}$ is the total electricity consumption from occupant behaviour such as equipment and lighting as well as any electrically run mechanical systems such as ventilation and cooling systems.

This work focuses on reducing carbon emissions from existing buildings in a UK context. This is a cool-temperate climate, as defined by Passivhaus climate categories [217], and therefore will create a model for buildings that are naturally ventilated and without any mechanical cooling. This is shown to be an extremely commonly adopted strategy for schools within the UK, with over 85% of schools within the available combined school database found to be naturally ventilated [218]. Further, natural ventilation is commonplace in other countries for different building types including residential [219, 220] and non-residential [46], especially for older buildings [221] which require the most retrofit and were built before cooling and mechanical ventilation were typically installed.

Total thermal energy of these existing buildings can be defined as:

$$F_{thermal} = F_{heating} + F_{DHW} + F_{kitchen} \tag{3.2}$$

and total electricity consumption, $F_{electricity}$, can be used to describe only occupant related impacts such as lighting and equipment usage.

3.2.1.1 Heating energy consumption

To estimate total heating energy consumption for each school the degree-days model will be used.

The model relies on the calculation of a base temperature [$°C$], θ_b, which is defined as the external temperature where no active heating is required due to the balance between heat being lost through fabric and ventilation and gained through internal and solar gains. Subtracting the average outdoor temperature from this value therefore allows for the total temperature difference that mechanical systems are required to heat to provide a comfortable space. From θ_b, the total fuel consumption to be estimated as:

$$F_{heating} = \sum_{m}^{12} \frac{24 n_{(h,m)} U'}{\eta_{heating}} \frac{(\theta_b - \theta_{o,m})}{1 - e^{\frac{2.5}{\sigma_\theta}(\theta_b - \theta_{o,m})}} \tag{3.3}$$

where $n_{(h,m)}$ is the number of days in each month of the heating season, η is the efficiency of the heating system, $\theta_{o,m}$ is the monthly average outdoor temperature. This method accounts for temperature fluctuations on a monthly basis [135] which has its advantages over extremely simplified methods. The denominator, $1 - e^{\frac{2.5}{\sigma_\theta}(\theta_b - \theta_{o,m})}$, is a correction factor proposed by Hitchin [135] to estimate the impact of varying temperatures throughout the month. $\frac{2.5}{\sigma_\theta}$ is a location specific constant to account for the standard deviation in temperature throughout the month [135].

The total heat loss coefficient [kW/K], U′, can be defined as:

$$U' = \frac{\sum_n A_n U_n + \frac{1}{3} N V}{1000} \tag{3.4}$$

where A and V are the area [m^2] and internal volume [m^3] respectively. U is the U-value

$[W/m^2K]$ of each element, n, and therefore used to describe heat lost through the building fabric and N is the total ventilation and infiltration losses $[hr^{-1}]$ so used to describe the exchange of internal with external air.

To understand the base temperature, the methodology outlined in CIBSE Guide TM41:2006 [135] is used, assuming the building is intermittently occupied.

3.2.1.2 Hot water

Hot water (DHW) usage $[kWh]$, F_{DHW} is estimated through adaptation of the method outlined [222, 223]:

$$F_{DHW} = \sum_{m=1}^{12} \frac{4.18}{3600\eta_{DHW}} \Delta\theta_m * n_{(o,m)} * l * A_{floor} \tag{3.5}$$

Where η_{DHW} is the total efficiency of the hot water system, including distribution and system losses and boiler efficiency. $\Delta\theta_m$ $[K]$, is the temperature difference between incoming cold and outgoing hot water. It has been shown that the incoming cold water temperature varies depending on the time of year and therefore, an average monthly value has been found [223]. l $[L/m^2]$ is an area weighted average of total typical hot water production for all different types of zone within the space. $n_{(o,m)}$, is the total occupied days per month $[days]$. The kitchen energy benchmark outlined below includes hot water consumption for kitchen related activities and, therefore, this zone is not accounted for in F_{DHW} calculations.

3.2.1.3 Kitchen

Kitchen gas energy consumption $[kWh]$, $F_{kitchen}$, includes all the processes required for cooking - such as gas stove usage and hot water consumption. This is calculated using typical benchmarks provided by CIBSE TM50:2021 [224], κ, $[kWh/meal]$:

$$F_{kitchen} = n_{meals}\kappa \tag{3.6}$$

The number of meals, n_{meals}, is calculated as:

$$n_{meals} = \sum_{m=1}^{12} A_{floor} * o_d * n_{(o,m)} * \mu \tag{3.7}$$

where $n_{(o,m)}$, is the total occupied days per month $[days]$, o_d the occupancy density $[people/m^2]$ and μ which is the proportion of people within the building that want a meal [225].

3.2.1.4 Electrical energy consumption

This thesis focuses on thermal energy retrofit and therefore electricity consumption, $F_{electricity}$, does not need to be split out between lighting and equipment usage. $F_{electricity}$ needs to be in the correct magnitude to assess whole life carbon emissions fairly.

CIBSE TM46 [88] provides benchmark data for electricity consumption of $40kWh/m^2$ for schools and seasonal public buildings [88]. However, these benchmarks were first published in 2008, so an assessment was undertaken to see if it is still applicable today.

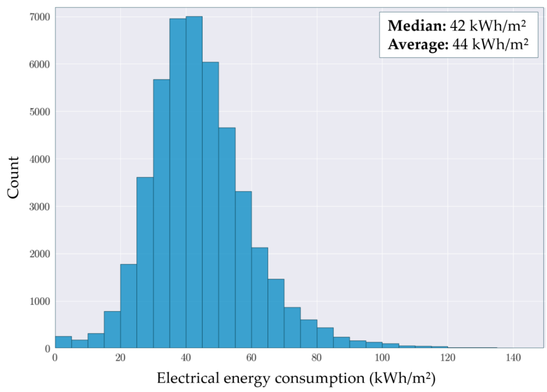


Figure 3.1: Histogram to show the distribution of energy consumption, within the naturally ventilated schools and seasonal public buildings in the DECs database.

Display Energy Certificates (DECs) provide metered energy consumption for all public building's above $1000m^2$ which is also split up based on the CIBSE TM46 typologies. The entirety of England and Wales 'schools and seasonal public buildings' within the DECs database is downloaded. Repeated DECs were removed using the postcode, with the most recent DEC for each postcode retained. Further, only 'heated and naturally ventilated buildings' whose heating did not run off electricity were isolated so that only small power, lighting and unregulated consumption are included in the electricity data. This left 48,272 data points for schools and seasonal public buildings.

The median, $42kWh/m^2$, and average, $44kWh/m^2$, values shows that schools have a typical electricity usage very similar electricity consumption to that of the CIBSE TM46:2008 benchmarks, $\epsilon = 40kWh/m^2$, which allows for electricity consumption to be estimated:

$$F_{electricity} = \epsilon A_{floor} \tag{3.8}$$

Further investigations of this value and comparison to the modelled occupancy internal gains is provided in Appendix B.1.2.1.

3.2.2 Data collection

This section provides the key model inputs, with explanation of how they are collected and defined for each building. The main source of data is Verisk's UK Buildings, accessible through OS Digimaps [3]. This service provides a polygon, downloadable as a geopackage, for each building, containing several key attributes such as building typology, height, area and age.

3.2.2.1 Geometry data

Geometry data from Verisk is processed for each building separately using Python and manipulation of geopackage data for each school to find:

- Exposed perimeter - P_f $[m]$
- Plan area - A_{plan} $[m^2]$
- Building height - H $[m]$

A_{plan} can be used to define the roof area [m^2] and ground floor area [m^2].

There is a lack of clarity within Verisk manuals on how height data, H, is collected [3]. Specifically, it is unclear whether the data collected is the highest, lowest or an average point on the roof. This is especially a problem for pitched roofs where these values can differ widely.

Given this uncertainty, a method has been developed to estimate the number of floors, x, using an archetype value for floor-to-floor heights, H_{f_f}:

$$x = \begin{cases} \lfloor (H)/H_{f_f} \rfloor, & \text{if } H >= H_{f_f} \\ 1, & \text{if H} < H_{f_f} \end{cases} \tag{3.9}$$

The results are always rounded down when dividing height by H_{f_f} as shown in equation 3.9.

Therefore, as long as the height of any pitched roof is not higher than H_{f_f}, this method should provide an accurate number of floors. Within the UK it is shown that typically the height of a pitched roof would not exceed H_{f_f} as defined in Table 3.1 [226].

Assuming a single zone space, where the internal volume is not disaggregated into separate rooms, the building geometry data can then be estimated as:

$$H_{f_c} = \begin{cases} H_{f_c}, & \text{if } H >= H_{f_f} \\ H - (d_f), & \text{if } H < H_{f_f} \end{cases} \tag{3.10}$$

$$H_{wall} = (x * H_{f_f}) + d_f \tag{3.11}$$

$$A_{wall} = P_f * H * (1 - g) \tag{3.12}$$

$$A_{window} = P_f * H * g \tag{3.13}$$

$$A_{floor} = x * A_{plan} * \zeta \tag{3.14}$$

$$V_{internal} = x * H_{f_c} * A_{plan} * \zeta \tag{3.15}$$

where H_{f_c} is the floor to ceiling height $[m]$, d_f is a typical ground floor thickness $[m]$ and g is the glazing ratio of the building. The floor area and internal volume of the space are also multiplied by a gross internal ratio, ζ, which is used to account for external walls which would take up the plan area [227]. Further, any building's perceived to be unheated spaces, e.g. sheds, have been remove. The classification for these buildings is where $A_{plan} < 50m^2$ (see Appendix B.1.5).

3.2.2.2 Building age archetypes

The age category has been used to define key building performance parameters such as U-value $[W/m^2K]$ and infiltration rate $[hr^{-1}]$. All the inputs which change depending on building age are shown in Table 3.1. This has been found through building regulations [46, 228], typical standards for pre-regulation construction [25, 229] and existing literature [131].

Age has been chosen to define these key inputs due to the development of and changes to building regulations within the last 60 years with vast improvements to these initial regulations as demonstrated in Table 3.1. Infiltration rates are split up as pre and post 2002 as this was when airtightness regulations were introduced [46].

The fuel type for all heating systems is assumed to be gas or biomass independent of age with an average efficiency of 0.8 [230, 46]. The glazing ratio and solar gain factor for every building is assumed to be 26% [231] and 62% respectively [46].

The typical lifespan of a flat roof and a window is 30 years [232, 233]; therefore, typical U-values for roof and window are no older than these values. It is assumed within pre regulation pitched roofs that a small amount of loft insulation has been installed as this is one of the most commonly installed retrofit measures in the UK with 66% of homes with lofts have at least 125mm of loft insulation [234].

Table 3.1: Inputs for different age categorisations within the model, that define building performance.

		U-Value $[W/m^2K]$					
Verisk Age	Age Category	Wall	Window	Floor	Roof - P/F**	H_{f_c} $[m]$	Infiltration Rate $[hr^{-1}]$ ***No. floors:***
Historic	Pre 1919	1.7	2.2	1	**1.1**/1.4	4.5	***1***: 0.675 **2**: 0.50 >=**3**: 0.45
Interwar	1919-1945	1.5	2.2	1	**1.1**/1.4	3.5	
Post war*	1945-1976	1.7	2.2	1	1.1/**1.4**	3	
	1976-1985†	1	2.2	0.94	0.55/**0.55**		
	1985-1990	0.6	2.2	0.6	**0.35**/0.35		
	1990-2002	0.45	2.2	0.45	**0.25**/0.25		
Modern*	2002-2010	0.4	2.2	0.25	0.2/**0.25**	3	***1*** : 0.35 >=**2**: 0.25
	2010-2021†	0.35	2.2	0.25	0.2/**0.25**		
	2021-2023	0.26	1.6	0.18	0.16/**0.18**		
References: [46, 131, 25, 228, 229, 3]							
*Due to a lack of definition of Verisk age values, this table is the authors own interpretation. **Pitched/Flat roof - **Bold text = archetype roof type** † values are used to represent the Verisk age classification.							

Table 3.1 shows that Verisk age categorisations span several improvements to U-values within building regulations. For example, there is no further specification in terms of age bands, provided for either post war or modern buildings. Therefore, it is assumed that the post war category spans from 1945 - 2002, and within this period there are several improvements to building regulations. This demonstrates a key issue when using Verisk age data, as the building performance of post war and modern buildings could fall within several U-Value categories. An assumption of the median U-value within each category will be used to model post war and Modern age categories. Any buildings unclassified by age are assumed to be post war as this

is the median value.

3.2.2.3 Building typology archetypes

Typology inputs are split between primary, secondary schools and colleges. The occupancy patterns for each typology are defined using CIBSE Guide A [131] and typical area guidelines for each typology [17]. The difference between each typology is minimal, as shown in Table 3.2, with the key difference being hot water usage. Primary schools are not required to provide changing facilities, i.e. hot showers, but higher educational buildings are.

Further details on how these are calculated is provided in Appendix B.

Table 3.2: Inputs for different building typologies within the model.

Input	Primary school	Secondary school	College
Set point temperature [$^{\circ}C$]	19.0	19.0	19.0
Occupancy density* [$person/m^2$]	0.38	0.37	0.36
Occupied hours [hrs/day]	10.0	10.0	10.0
Occupancy gains* [W/m^2]	30.7	29.8	29.3
Lighting gains* [W/m^2]	11.8	11.8	11.8
Equipment gains* [W/m^2]	0.38	0.37	0.36
Hot water use* [L/m^2]	0.7	1.9	1.9
Ventilation rate [$L/s.person$]	8.0	8.0	8.0
Kitchen gas usage [$kWh/meal$]	0.41	0.41	0.41
Total occupied days [$days$]	195.0	195.0	195.0
Meal ratio	0.65	0.65	0.65
References: [235, 236, 131, 224, 225, 237]			
*All values are averaged over 24 hours, a methodology for this is given in Section B.1.2 of Appendix B.			

3.2.2.4 Weather inputs

Weather data has been categorised through the met office regions [19], which provides outdoor monthly average temperatures, as shown in Appendix B.1.3, Table B.5. Solar gains are required to be inputted into the degree-days equation, averaged over 24 hours across a month [W/m^2]. Solar heat gains [$kWh/m^2/day$] for a North, South, East and West facing wall were found for each month of the year [20]. An average of each wall direction was then found. The assumption that there is an equal window surface on every direction of each building has been made. Appendix B.1.3, Table B.6, provides solar gain values - an average of data for North, East, South and West facing walls [20].

3.3 Validation against case studies

To validate the developed methodology, this chapter will compare modelled to metered energy consumption for 234 school case studies.

3.3.1 Case study characteristics

Two different samples of case study data were used to assess the strengths and limitations of the model:

- A sample of data from the Energy Sparks open source website [238]. This allowed us to compare both heating and DHW and kitchen energy use separately. All schools within the sample that had yearly heating, hot water, kitchen and electricity consumption available were included. A total of 164 primary schools were retrieved.
- A sample of all secondary schools and colleges within the South Yorkshire Mayoral Combined Authority (SYMCA) [239]. A total of 71 schools were found which had metered energy consumption available through the DECs database [10]. Those with none or limited data, such as where $F_{thermal} = 0$, were removed.

All schools within the sample were heated using fossil-fuel heating systems.

When comparing metered versus modelled results, the line of best fit, coefficient of determination, R^2, and average percentage error are calculated. The line of best fit would be $y = x$ if modelled data were to match metered energy consumption perfectly. Therefore, the variation from $y = x$ can be assessed to understand how well modelled results reflect metered data. The coefficient of determination, R^2, aims to understand how well a model fits a dataset. Values vary between zero and one, with a high value implying limited variation between the line of best fit and the data points. A percentage error very close to zero implies that when aggregated, the total metered and modelled energy consumption are very similar.

The most recent yearly consumption data, 2023 for all but 5% of case studies where only 2020 - 2022 data was available, is used within the study, with the exception of nine schools whose recent data is found to be likely unrealistic. This reasons for this is outlined in Appendix B.1.4 and for these schools, 2020 data was adopted.

3.3.2 Understanding annual variation in energy consumption

Despite the most recent energy consumption data being used in this analysis, the fact that energy consumption is stochastic in nature and will change yearly is also accounted for. For example, UK domestic thermal energy consumption is shown on average to increase by 6.9% from 2020 to 2021, which can be partially explained by an average temperature decrease of 0.5°C [240].

Therefore, **a minimum error** value has been designed to account for anomalous metered energy results and the yearly changes to energy consumption. This is defined as the minimum possible error between metered and modelled consumption when considering all recent metered consumption values.

DECs data for all schools from 2019-2023 has been collected and minimum error can be defined as:

$$Error_{min} = \begin{cases} 0, & \text{if: } F_{DEC_{min}} <= F_{thermal} <= F_{DEC_{max}} \\ \dfrac{100(F_{thermal} - F_{DEC_{min}})}{F_{DEC_{min}}}, & \text{if: } F_{DEC_{min}} > F_{thermal} \\ \dfrac{100(F_{thermal} - F_{DEC_{max}})}{F_{DEC_{max}}}, & \text{if: } F_{DEC_{max}} < F_{thermal} \end{cases} \tag{3.16}$$

which shows that if the modelled results fall between the highest and lowest DECs data then the minimum error is classed as zero. Only data from the last 5 years has been collected to reduce the likelihood of old or out of date information being used. Further, if there was a large change to floor area ($> 10\%$) then this data was excluded.

3.3.3 Data quality issues and sensitivity study

Exploring the 234 case studies further evidenced several issues with Verisk data quality. It is claimed that where no LiDAR data is available an average height for that typology is used [241]. By analysis of 234 case studies we can see this value in Veirsk is 17.8m as Figure 3.2 shows. In fact, 24% of the sample have 17.8m as the recorded height despite being only 1 storey tall.

Limited age data is also shown in Figure 3.2 as over 54% of school properties within the sample contain at least one unclassified polygon.

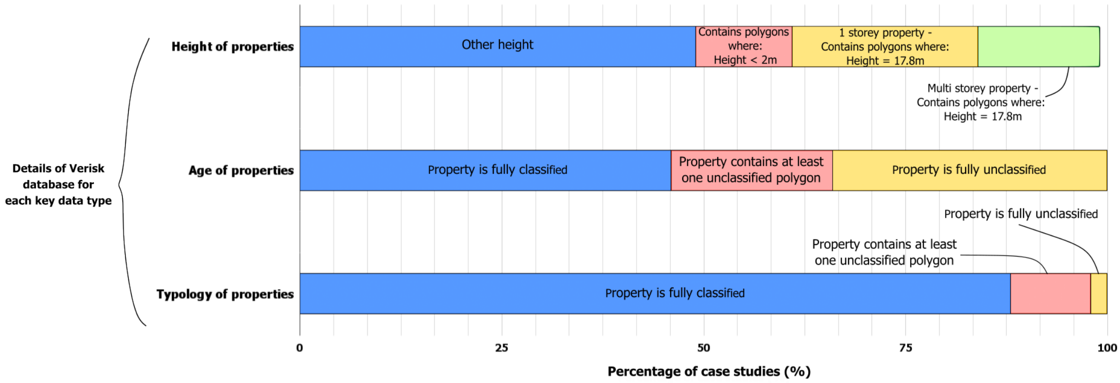


Figure 3.2: Bar Chart to show potential issues with Verisk data availability [3].

Investigations have also revealed that some polygons are not split by building height accurately. An example of this is shown in Figure 3.3, where a single polygon of a constant height within Verisk can actually be split into multiple building storeys.

Figure 3.3: Example and evidence of poor segmentation of Verisk polygons. The left hand figure demonstrates Verisk polygon segmentation [3]. The right hand figure shows a manual disaggregation of total number of storeys. This was undertaken using Google aerial 3D view [4].

Due to the highlighted data quality issues with Verisk, three different methods of data collection have been undertaken which are outlined in Table 3.3.

Quantifying energy consumption using all three methods allows for a sensitivity study of the impact from using different data-points within the Verisk dataset compared to manually collected data e.g. actual satellite, aerial view and historic maps data. Therefore, the use of fast running thermal energy models can be appraised on its own merits rather than due to potential issues with Verisk data.

Table 3.3: Different methods of data collection that are modelled in this thesis. Abbreviations (Abbr.) are used to describe each method where **V** = Verisk data, **M** = manual data collection and **O** = only one type of data collection is used. **L** and **N** mean the largest and newest area respectively are adopted within age classification.

Data collection method			**Geometry data**	**Age data**
Method and summary		**Abbr.**		
Verisk only - Uses only Verisk data to define geometry and age of building.		**VO**	• Data retrieved from Verisk. [3]. • Geometry defined as in Section 3.2.2.	• Verisk age categorisation using Table 3.1.
Verisk and manual data - Uses both Verisk and manual data collection.	**Largest area age**	**VML**	• P_f and A_{plan} are taken from Verisk [3]. • The number of floors, x, is collected manually using Google Street and aerial 3D View [4]. • If x varies within a single Verisk polygon, the value of x which takes up the largest proportion of A_{plan} is adopted. • The typology of each polygon is also manually assessed.	• Utilises historic OS digimaps [242] and Google Earth's historical satellite imagery [243]. • Provides an actual date range for building construction. • Uses the most recent date, assuming some intervention has occurred since construction. • Where building age varies within a single polygon, **the age covering the largest area is adopted**.
	Newest area age	**VMN**		• Where age varies within a single polygon, **the most recent age is adopted.**
Manual only - Manual data collection was undertaken to define geometry and age data.		**MO**	• Manual measurement of geometry data in Verisk [3]. • If x varies within the same polygon (e.g. Figure 3.3) this is accounted for. • OS Digimaps replaces Verisk data where polygons are inaccurate.	• Utilises OS historic digimaps [242] and Google Earths historic satellite imagery [243]. • Provides an actual date range for building construction. • Uses the most recent date with age range.

3.4 Results

3.4.1 Heating energy consumption

Modelling results for heating energy consumption is compared to metered data for the 164 primary schools where heating energy is disaggregated from total thermal consumption. This is shown in Figures 3.4a - 3.4h alongside the respective percentage error.

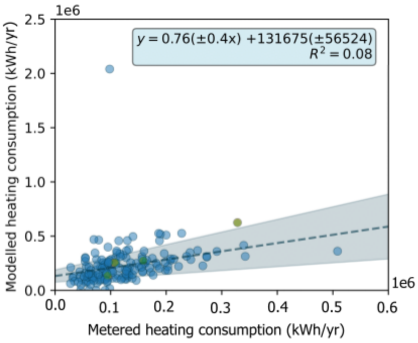
Linear regression results vary widely depending on which data collection method is adopted. The coefficient of determination, R^2, for the VO method is 0.08, which is extremely weak. R^2 aims to understand how well a model fits a dataset. Therefore, a very small value implies high variation between the predicted linear regression and the results.

The high variation is clear within Figure 3.4a, especially one data point where metered energy consumption is overestimated nearly 2000%. This data point was explored and shown to be caused by a now demolished building, still present as a Verisk polygon but not present within DECs metered consumption data. Figure 3.4b shows a large skew to overestimating heating energy results when using the VO method, with an average error of 110%. The cause of such a large error will be explored further in Section 3.4.2.1.

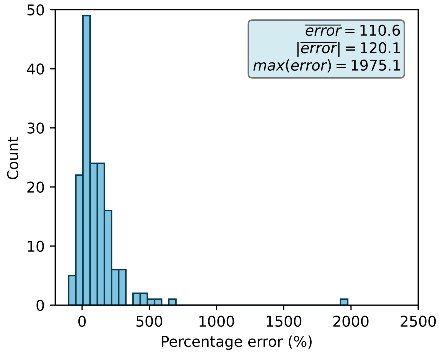
Hybridised data collection methods show more promising results with VMN, VML and MO having a much lower average percentage error of 7.2%, 17.1% and 14.4% respectively. The R^2 of approximately 0.5 for each method still implies high variation within the results.

There is evidence that the metered energy data has not been accurately dissagregated between heating and hot water and kitchen consumption. For example, CIBSE Guide B.1 states in benchmark guidance that DHW consumption typically takes up 9% of total energy [24]. Within the metered energy consumption data there are 3 properties where DHW and kitchen consumption takes up over 60% of total energy and 2 properties where this takes up less than 4% of total consumption. This could be the cause of such a high spread in results and a safer form of comparison would likely be total thermal energy consumption.

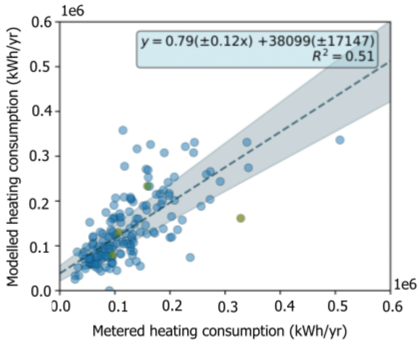
Heating only results show that on average, with more detailed data the model does not significantly under or overestimate the metered consumption, which allows us to continue with expectations that assumptions such as occupancy patterns are on average correct and future retrofit modelling should result in a fair reduction in heating energy consumption.



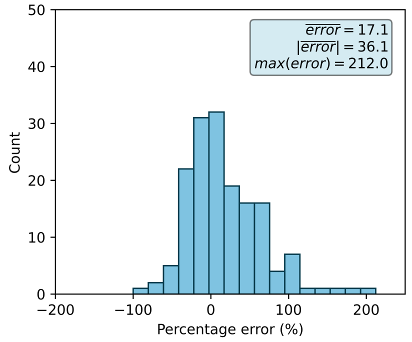
(a) **VO** scatter plot.



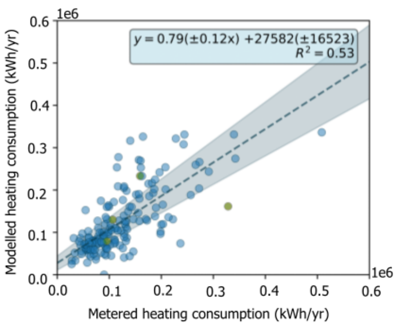
(b) **VO** histogram of percentage error.



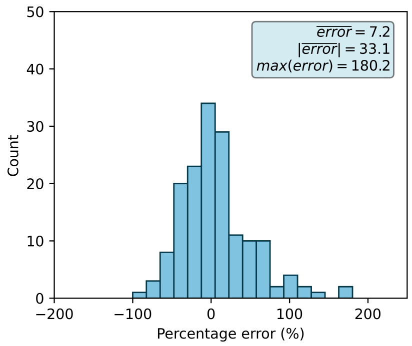
(c) **VML** scatter plot.



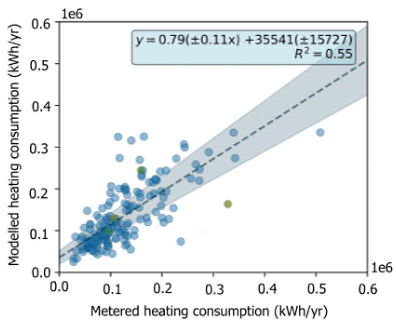
(d) **VML** histogram of percentage error.



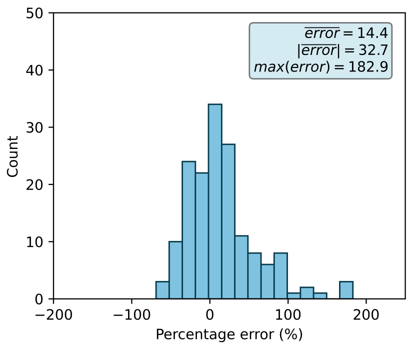
(e) **VMN** scatter plot.



(f) **VMN** histogram of percentage error.



(g) **MO** scatter plot.



(h) **MO** histogram of percentage error.

Figure 3.4: Scatter plots to show metered versus modelled data for **heating yearly energy** for different data collection methods (See Table 3.3). The plots in green show those properties with swimming pools, which have been removed from the calculations of fit. Histograms show the percentage error: $\frac{100(F_{modelled} - F_{metered})}{F_{metered}}$. VO plot has a different y-axis due to large differences between modelled and metered results.

3.4.2 Thermal energy consumption

Total thermal energy is assessed, also allowing for the 71 secondary schools within the sample to be included and consideration of a total of 234 case studies shown in Figures 3.5a - 3.5i.

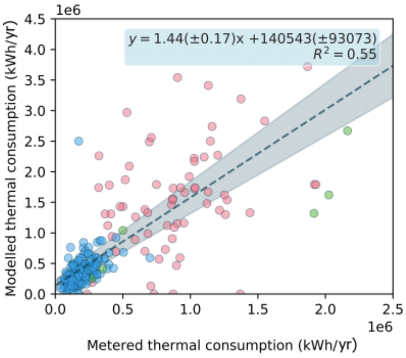
Thermal energy consumption provides a reduction in average percentage error and a considerable increase in R^2, compared to heating only. This further implies that the breakdown of total thermal energy was inaccurate for some properties. An R^2 value of approximately 0.8 is calculated for VMN, VML and MO methods which implies that the line of best fit accounts for the majority of variance between modelled and metered data.

There is an increase in maximum error, when going from heating to thermal energy, from 182-260% for even the MO method, which is extremely high. This is due to a secondary school where the main school building was demolished and replaced in the last 3 years, with Verisk and digimap polygons not yet updated to reflect this. With such a large change in floor area from 20,383m^2 to 9788m^2 according to DECs it is understandable why error is so high. This highlights a limitation with Verisk data as it could be out of date or incorrect, something which is explored further in Section 3.4.2.2.

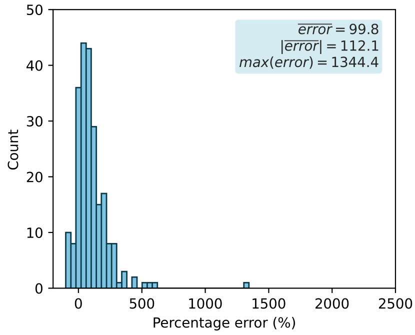
Another example of incorrect input data is shown in Figure 3.5a where a collection of properties have an estimated thermal consumption of zero for VO data collection. This was found to be due to inaccurate typology categorisation, where properties were assigned to be something other than educational (e.g. Office only) and has been manually fixed for VMN, VML and MO methods.

Comparing VM with MO methods shows relatively little improvements to accuracy due to manual measurements. Average absolute percentage error is reduced by 2-3% through adopting the MO data collection. Considering that this method relies of the manual measurement of each polygon, a small reduction comes at the cost of a large increase to data collection time.

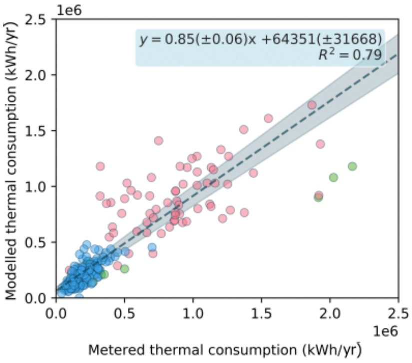
The lines of best fit in Figure 3.5 have been calculated excluding properties with swimming pools. This is because pool consumption is outside the remit of this thesis as the focus is on reducing space heating emissions through retrofit. In fact, Figure 3.5 gives a visual representation of the impact of properties with swimming pools which when modelled are consistently underestimated by the model.



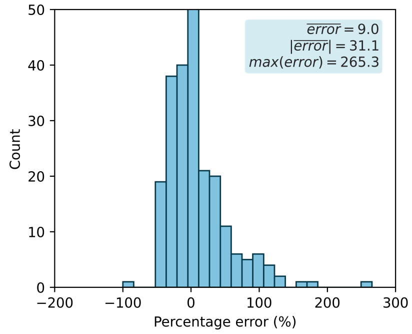
(a) **VO** scatter plot.



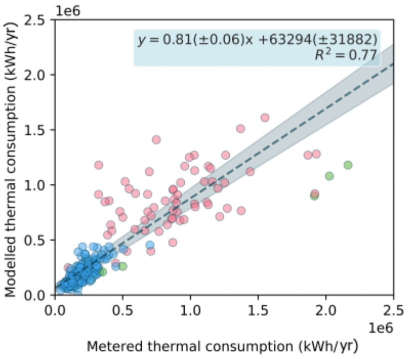
(b) **VO** histogram of percentage error.



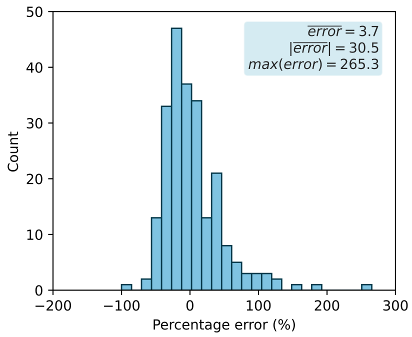
(c) **VML** scatter plot.



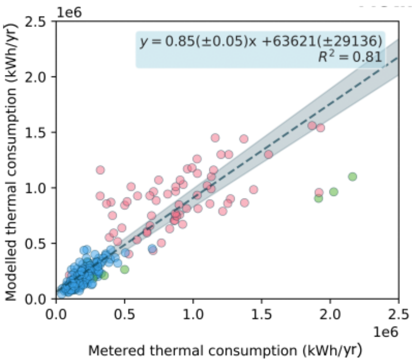
(d) **VML** histogram of percentage error.



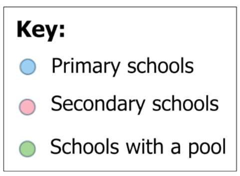
(e) **VMN** scatter plot.

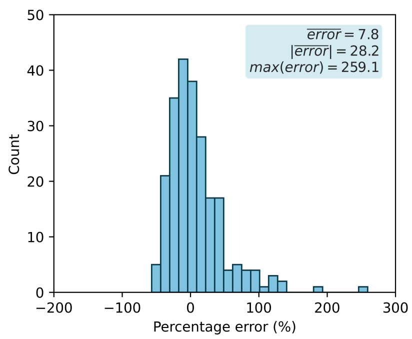


(f) **VMN** histogram of percentage error.



(g) **MO** scatter plot.



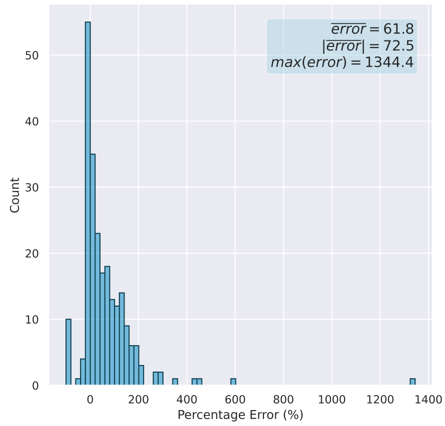


(i) **MO** histogram of percentage error.

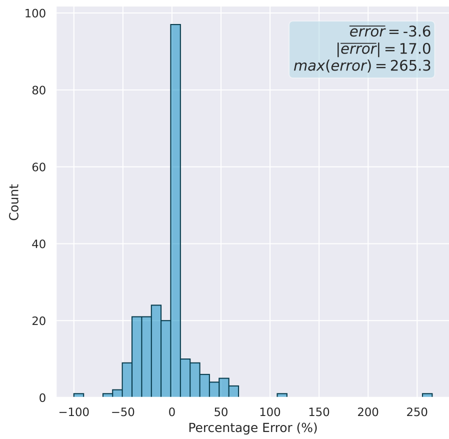
Figure 3.5: Scatter plots to show metered versus modelled data for **thermal yearly energy** for different data collection methods (See Table 3.3). Within the scatter plot blue highlights primary schools, red secondary and green those properties with swimming pools. Histograms show the percentage error: $\frac{100(F_{modelled} - F_{metered})}{F_{metered}}$. VO plot has a different y-axis due to large differences between modelled and metered results.

Removing properties with pools improves the line of best fit towards $y = x$, with MO gradient moving from 0.75 to 0.85. However, for the VO method removing these properties from the data set draws the gradient of graph further from $y = x$, from 1.30 to 1.44 This shows a consistent overestimation of energy consumption in this method, for both typologies of schools.

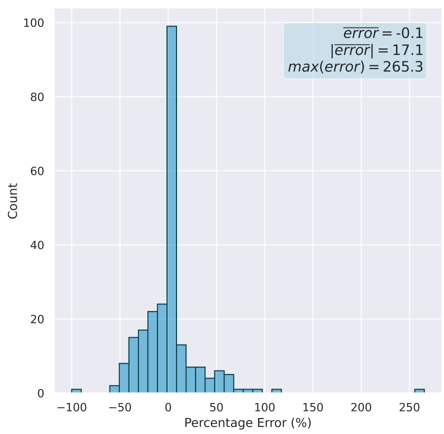
Section 3.2 outlines the methodology for the calculation of a **minimum error**, as energy use is prone to fluctuations each year. The **minimum error** is shown in Figure 3.6, showing that 18 - 36% of data points are now classed as having zero error, depending on the data collection method. For the MO method 46% of properties now have an error below 5%.



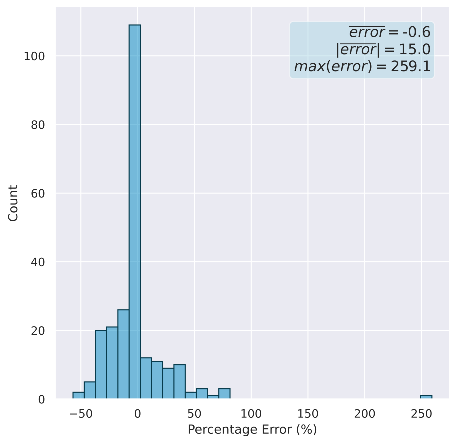
(a) **VO** histogram of percentage error.



(b) **VMN** histogram of percentage error.



(c) **VML** histogram of percentage error.



(d) **MO** histogram of percentage error.

Figure 3.6: Histograms show the minimum percentage error for yearly thermal energy consumption - calculated as in Section 3.3.2. See Table 3.3 for definitions of each data collection method. VO plot has a different y-axis due to large differences between modelled and metered results.

Results show that high error is still found for even the most detailed data collection methods, MO, with an average absolute percentage error of 15%. The full impact and acceptability of this error will be explored in Chapter 4 in terms of retrofit decisions and the error will be investigated further now to understand potential causes. However, the aggregated average error is now 0.1 - 3.6% for the VMN, VML and MO methods. This result shows that at an aggregated or stock level, the total error for thermal energy consumption is very low, which allows for thermal energy modelling at scale.

3.4.2.1 Verisk error exploration

It is shown in Figures 3.5a - 3.6d that the VO method, using only Verisk data, has considerably higher error than where manually collected data is used.

Therefore, three different scenarios have been tested to understand why the VO method has provided inferior results to more manual methods:

- **Modern** - Where unclassified age data is found, modern building standards will be used instead of post war.
- **Polygons** - Polygons are downloaded and manually sorted. Non-existing polygons are deleted, and any polygons of the wrong typology label which are part of the property are retained.
- **Age** - After polygon sorting the historic digimaps age data is used in lieu of Verisk age data.
- **Height** - After polygon sorting the actual number of storeys is used in lieu of height data.

The total error and minimum error between the modelled scenarios outlined above and metered consumption were then calculated.

Results in Figure 3.7 show that inaccurate height data makes the largest difference to percentage error. One issue being that 37% of schools contain the archetype height of 17.8m which would predict a 4 storey building. This is especially unlikely for primary schools which are typically one storey tall [244]. In fact, even if 17.8m data points are removed the average building height of the primary school polygons using Verisk is 7.9m. This is taller than a typical two storey residential house [245], despite only 13% of primary school polygons being more than 1 storey tall. The impact of inaccurate height data is therefore a key limitation to this dataset.

Figure 3.7 shows that replacing age data provides a reduction of 5% on average absolute mini-

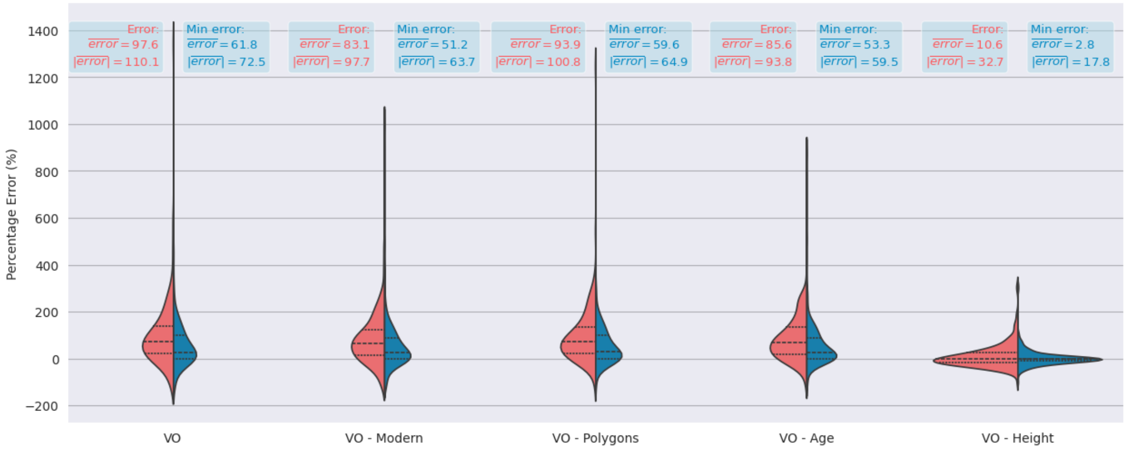


Figure 3.7: Violin plots to show the differences in percetange error due to different data collection methods. Red values represents the percentage error and blue the calculated minimum percentage error.

mum percentage error compared to the VO - Polygons method. A larger improvement is made to average percentage error by adopting modern standards for any unclassified data instead of post war. One likely contributor to this reduction in average error is the significant reduction in maximum error. The high maximum percentage error in the VO method is caused by a property with a large overestimation in predicted floor area. Therefore, by modelling this school as modern, which is more thermally efficient, one reduces the impact of floor area overestimation.

Another possible contributor to the reduction in error is that post war performance data is not representative of the unclassified schools within the sample. Future work which uses Verisk age data needs to ensure that the distribution of ages applied to any unclassified data is representative of the entire sample. See Appendix D.1 for how gaps in data are filled when modelling the entire English school stock.

3.4.2.2 High error exploration

Even when modelling is undertaken using the most accurate available data, there are results with a very high percentage error between metered and modelled energy consumption. Therefore, those with a high error despite using the MO data collection method are explored further in this section.

Figure 3.8 shows the breakdown of those results which have a minimum percentage error above 20%. This value has been chosen because it allows us to explore highly anomalous results, those average absolute percentage error (15 - 17% for VM and MO methods).

Figure 3.8 shows 36% of polygons have a known potential explanation for high minimum percentage error. 4% of properties having swimming pools, 6% have evidence of major refurbishment, found through research into news articles [5, 6, 7, 8], something which is not accounted for in our data collection method, and the remaining have known issues with data quality such as significant floor area inaccuracy and limited age data that spans over many U-value categories.

The remaining high error data, a total of 47 schools, has been plotted by age and split into overestimation (UO) and underestimation (UU) categories. 67% of the underestimated data is post 2002 which is significantly larger as a proportion of the total dataset where 36% of all properties are post 2002. This is interesting because we should know the most about post 2002

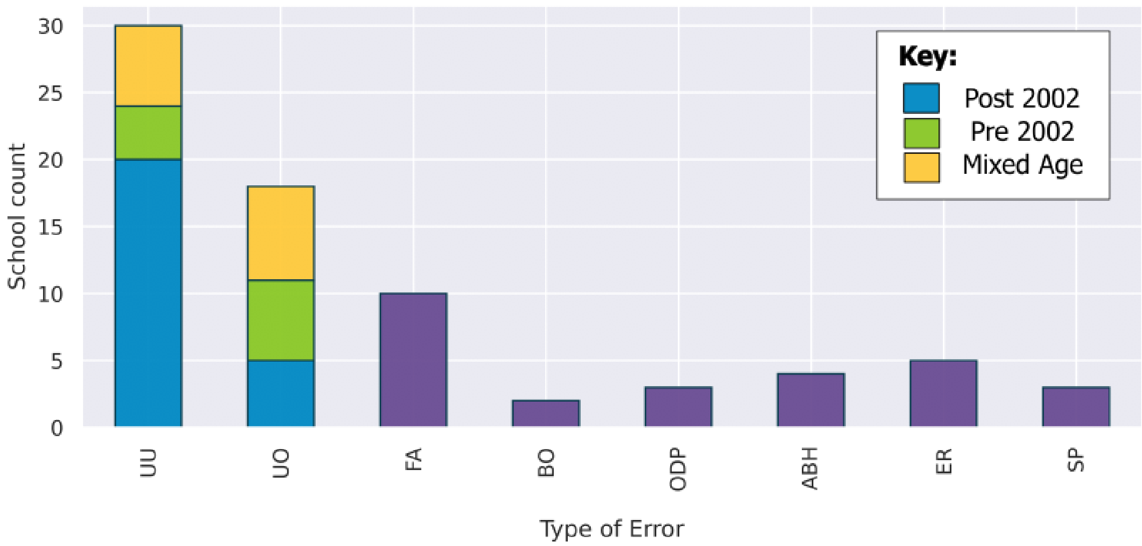


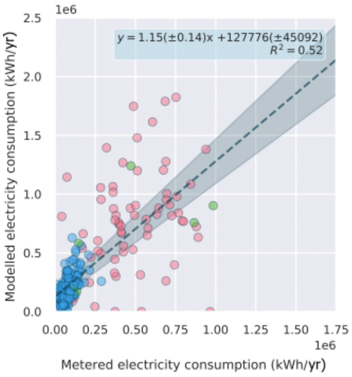
Figure 3.8: Bar plot to show the different types of error for properties that have a percentage error above 20%. UU = Unclear - underestimated, UO - Unclear - overestimated, FA = Significant floor area inaccuracy, BO = Lack of clarity on building ownership, ODP = Out of date Verisk and Digimap polygon, ABH = Limited age data, ER = Evidence of major refurbishment [5, 6, 7, 8], SP = Swimming pool.

data due to the implementation of building regulations for both U-values and air tightness. It could imply larger variation in usage, such as set point temperature, within these buildings. It could also imply that these properties are not constructed to the standard they are designed to. This is referred to within industry as the performance gap [246].

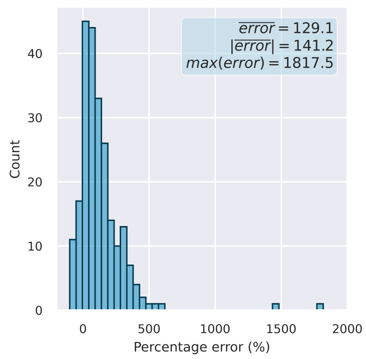
These results demonstrate the importance of sensitivity analysis on thermal performance standards and occupant behaviour when modelling at scale due to the impact this will have on total energy consumption. This in turn impacts the proportional savings from retrofit measures as well as the total carbon emissions and therefore ability to meet carbon budgets.

3.4.3 Electrical energy consumption

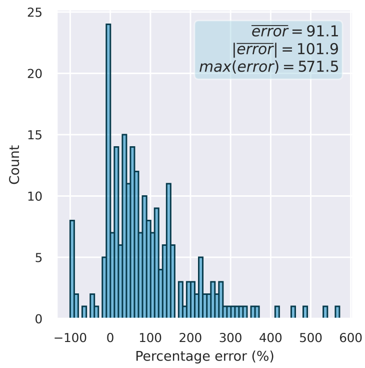
Figure 3.9 shows the correlation between modelled and metered electricity consumption, using each different method of data collection.



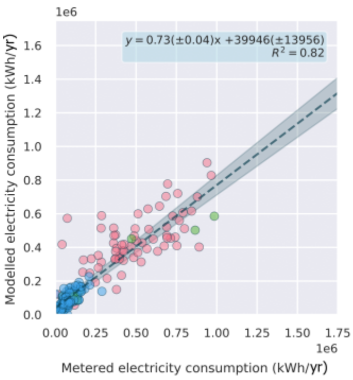
(a) **VO** scatter plot.



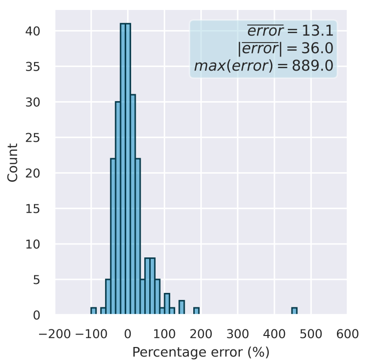
(b) **VO** histogram of percentage error.



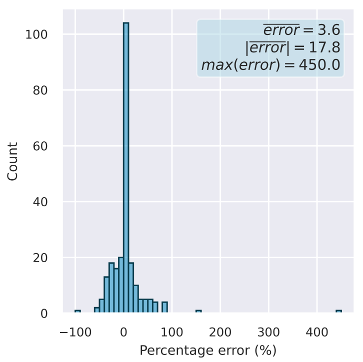
(c) **VO** histogram of minimum percentage error.



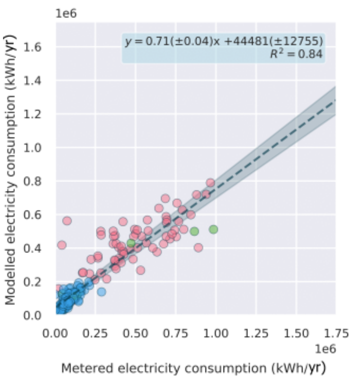
(d) **VM** scatter plot.



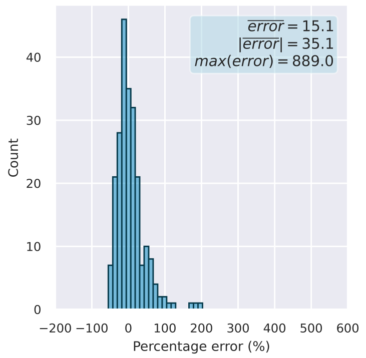
(e) **VM** histogram of percentage error.



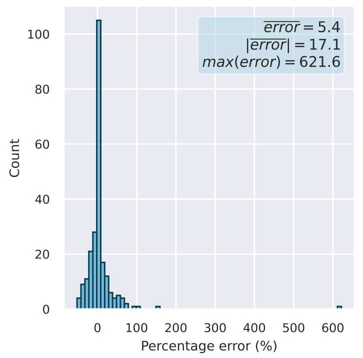
(f) **VM** histogram of minimum percentage error.



(g) **MO** scatter plot.



(h) **MO** histogram of percentage error.



(i) **MO** histogram of minimum percentage error.

Figure 3.9: Scatter plots to show metered vs modelled data for **electricity yearly energy** for different data collection methods (See Table 3.3). Histograms show the percentage error and minimum percentage error. VO plot has a different y-axis due to large differences between modelled and metered results.

As electricity consumption was predicted by multiplying $\epsilon = 40kWh/m^2$ by the predicted floor area results show that electricity consumption is strongly correlated to the floor area, as the average aggregated error is reasonably low using the VM and MO methods of data collection. This also explains why the VO method has such a high percentage error due to inaccuracies in height resulting in the consistent overestimation of total building floor area.

There are still outlier schools with very high minimum percentage error, the highest being 450-621%. This case was explored further and it was found that this property has extremely low metered electricity consumption of 4-8kWh/m^2 which is unlikely to actually be the case, considering the typical benchmark is 40 kWh/m^2. This draws the attention the uncertainty of every comparison made as there is evidence that the metered consumption itself may also contain error.

In this section we have only accounted for non HVAC related electricity consumption which may explain why some values are underestimated in certain properties. In fact, DECs shows that 43% of the studied secondary schools and 5% of the primary schools have some form of mechanical ventilation strategy in place. The focus of this work is on naturally ventilated schools, as at scale the vast majority of school buildings are naturally ventilated [218]. However, Chapter 4 will explore both the thermal and electrical impact of ventilation retrofit strategies.

3.5 Conclusions and limitations of energy modelling at scale

Results show that with the most detailed available data, the developed model provides baseline energy consumption with an average error close to zero, especially if the variation in yearly metered energy consumption is accounted for. However, even with this level of detail, there are still models on an individual school level with very high error compared to metered energy consumption. This may be due to occupancy behaviour, which will vary between individual schools, so by aiming to use typical occupancy patterns we can gain an understanding of the total impact of energy consumption at scale, but predictions for individual buildings will vary.

These results highlight a limitation to the developed method, which is that while results are acceptable at the aggregated stock level, they would not necessarily be informative at the individual building level. This is explored further in Appendix D.1 where these methods are further interrogated to apply retrofit modelling to the case study of the entire English school stock. This chapter has shown that not only are there large gaps in data availability, but also issues with data accuracy even where data is available. This is found to be especially true for building height. In Appendix D.1 these issues have been overcome by applying a distribution of archetype data to missing and inaccurate data. From this, we can conclude that currently available building data does not allow for accurate modelling of each school in the country. This is a finding not just applicable to existing energy models, but many fields of research where this data is used to model at scale, one example being the calculation of the vertical extension potential of existing buildings [247].

With this in mind, it may be assumed that the best way to model energy consumption would be instead to undertake a top-down statistical analysis of available metered energy consumption for schools (DECs), which would provide metered consumption data for a minimum of all school buildings with a floor area $> 1000m^2$. Indeed, this method was adopted when quantifying the impact of retrofit on the UK school stock in past research [134]. In this case any missing data was assigned a random energy use intensity $[kWh/m^2]$ with an aim of also reaching an average error close to zero compared to actual consumption. Therefore, the final value for energy consumption can be reached to the same extent as using energy modelling, but using actual metered consumption data which may be considered more accurate.

However within this publication, for retrofit modelling, a very simplified approach was undertaken. Efficiency reduction factors were applied to all the stock to simulate the impacts of retrofit, based on work which created archetypes from a defined geometry [230]. This chapter has demonstrated the large influence that geometry data can have on total energy consumption. The relationship between building geometry and both energy consumption and whole life carbon will be further explored in Chapter 4.

A key focus of this thesis is to understand the influence of specific building characteristics on early stage decision making, such as what level of retrofit is necessary, and when demolition may be beneficial. To assess this, a whole life carbon assessment of individual buildings will be undertaken in conjunction with modelling energy consumption [134], as both embodied carbon and energy consumption are shown to be influenced by building form [181, 53]. Therefore, the following chapters will continue the use of thermal physics models, as this allows for a more comprehensive understanding than top-down modelling of how different buildings will be impacted by different retrofit measures. Even if individual building performance cannot be explored in detail, by using thermal models we can still understand the aggregated influence at stock level of differing key characteristics of individual buildings.

It is important to note that using Verisk height data would not lead to an average error close to zero and in fact results in this chapter imply that height data is consistently overestimated within the dataset. Therefore, future energy modelling must take care when using existing datasets, especially as any errors are further magnified once applied to a larger scale.

3.5.1 Limitations

This piece of work focuses on naturally ventilated buildings with no cooling systems in place, as is typical of school stock in England [218]. Future work, which adapts this model to include mechanical ventilation and cooling within the baseline energy calculations would be highly useful to allow for application to many different typologies and countries.

When exploring case studies with a high level of error, there was a skew towards underestimating the energy consumption of newer buildings, post 2002, compared to metered data. This is an unexpected result as these are the schools with the most specified building regulation performance standards. There are several potential reasons for this pattern, such as differences in occupancy behaviour or poorer construction standards than expected from building regulations. Any future modelling at scale needs to take this into account, especially post retrofit. For example, in more thermally efficient buildings, occupants may be able to afford an increase in internal temperatures due to lower heat losses. Therefore, post retrofit occupancy could change dramatically and must be accounted for. This is something that has been demonstrated to occur in residential buildings and is known as the rebound effect [248].

Chapter 4

The parametric contribution of building form to retrofit decision making

4.1 Introduction

Past work has shown the importance of considering building geometry, shape and size within building design. For example, Zerefos et al. [180] demonstrated a modelled reduction in energy consumption of 8% by adopting a prismatic shape in lieu of orthogonal for a warm climate. Fleur et al. [53], calculated the life-cycle economic cost and energy saving from refurbishment of four typical Swedish apartment blocks. Those with a larger shape factor, internal volume to floor area ratio, required more ambitious intervention measures to achieve similar energy intensity [kWh/m^2]. Within Chapter 3, we have also demonstrated that uncertainty in building height has a large influence on the comparison between metered and modelled energy consumption results. These results show the potential for retrofit decision making, from a whole life carbon perspective, to change between buildings due to their key size and shape qualities.

These geometric characteristics are known as building form, which defines the relationship between exposed surface area and the internal volume of a building, allowing for understanding of the relative importance of the heat losses through walls, floor, roof and ventilation losses [9]. Therefore, understanding how building form influences whole life carbon of existing buildings could be highly useful when making comparisons of demolition versus refurbishment as a new building is not constrained by the current form of the building.

This chapter aims to take a key step in understanding the building geometry drivers which influence whole life carbon decision making by answering the following research question:

- ***What influence does building form have on the lowest whole life carbon intervention for existing buildings?***

By answering this question, we can understand the importance of building form when making future decisions to limit carbon emissions. This chapter aims to answer the research question by developing an analytical expression which allows for key rules of thumb to be developed for early stage decision making. This allows for a theoretical understanding of the parametric contribution of form to total energy consumption and whole life carbon as well as a practical assessment of how this impacts future intervention decisions from a whole life perspective.

When discussing energy efficiency, building form can be measured in many ways with one commonly used metric being surface area to volume ratio ($\frac{S}{V}$) which calculates the ratio of external surface area to internal volume. Indeed, buildings with smaller $\frac{S}{V}$ are shown to have lower energy consumption [182, 179]. However, this value is not dimensionless and is influenced by building size leading to two buildings of the same exact shape, but different sizes, having different values [9].

A measure of compactness, γ, has been defined which is the ratio of building surface area (S) to minimum surface area required to enclose the same volume (S_{min}). By creating a scale-independent measure of form this value is not influenced by building size unlike $\frac{S}{V}$ [9].

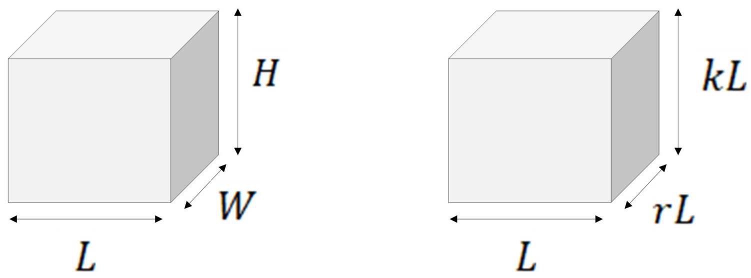
$$\gamma = \frac{1}{3\sqrt[3]{4}} \frac{2rk + r + 2k}{\sqrt[3]{r^2k^2}} \tag{4.1}$$

This measure requires the calculation of slenderness (k) and aspect ratio (r) as:

$$k = H/L \tag{4.2}$$

$$r = W/L \tag{4.3}$$

Visualisation of these two parameters is provided in Figure 4.1. In regards to aspect ratio (r), in multi-storey building design, a small aspect ratio, combined with a larger floor area per storey reduces not only heating and cooling energy consumption but the upfront embodied carbon emissions [181].



$$k = \frac{H}{L} \qquad r = \frac{W}{L}$$

Figure 4.1: Sketch to show how slenderness, k, and aspect ratio, r are defined for rectangular forms. It is shown that values of Height, H, and Width, W, can now be described in terms of only k, r and Length, L. These definitions are used in past work [9] to define a term of compactness, γ (See Equation 4.1).

By defining form as a single parameter such as γ, $\frac{S}{V}$ or solely r, one cannot distinguish between the potential differences in the thermal performance of different building surfaces. Where this difference is high, which commonly occurs due to the relative poor performance of glazing compared to other elements, these shape factors do not account for worse performance of certain building forms.

In this chapter r and k are kept separate in the form of an analytical expression rather than a single value. By doing this we can account for the difference in performance of different fabric elements and quantify the connection between building form and whole life carbon decision making as well as energy consumption.

Firstly, the following section aims to ensure that the values of r and k are appropriate to be used for actual building forms [9]. Secondly a methodology is outlined, developing an analytical expression which can express both energy consumption and whole life carbon emissions of retrofit in terms of building form. The analytical expression will be then validated against the degree-days model. Results will then be quantified for both energy consumption and a parametric comparison of different intervention decisions including three typical retrofits scenarios and new construction. Metered energy data from Chapter 3 is also used to understand whether inaccuracies in metered versus modelled data impacts retrofit decisions from a whole life carbon perspective. These results will be followed by concluding remarks.

4.2 Impact of rectangular form assumptions

Both r and k rely on the assumption of rectangular form. D'Amico and Pomponi [9] acknowledge this but claim that this form is prevalent within building stock, and therefore is an acceptable assumption. This section aims to understand whether assuming rectangular form is acceptable for a large number of actual buildings, and therefore whether these factors should be used in future work. The results provide an appraisal of the assumption of rectangular form used in this chapter as well as the past work of D'Amico and Pomponi [9], helping to also understand whether the value of γ developed in past work is an appropriate measure.

A sample comprised of the entirety of UK educational building polygons is taken from Verisk. The data is collected and cleaned through removal of any repeated polygons, as the data is downloaded in overlapping sections. Each polygon attached to another is merged to create a single building form and buildings smaller than $50m^2$ are excluded (See Appendix B.1.5). As discussed in Section 3.3.3 Chapter 3, the Verisk database uses an archetype constant height where data is not available. Therefore any polygons with this height value are removed to increase the chance of having only actual building heights within the sample. This leaves a total of 76,398 polygons for further investigation.

We can then define key geometry for each polygon as:

- **Surface area** $[m^2]$:

$$A_{Surface} = (P_f H) + A_{plan} \tag{4.4}$$

  where A_{plan} is plan area $[m^2]$, H is height $[m]$ and the external perimeter $[m]$, P_f, is calculated by measuring the external length of every polygon. Floor area is not included , which is in line with the work of D'amico and Pomponi [9]. Floor area is only excluded within this direct comparison to $\gamma(k, r)$. Indeed, heat losses from the floor are accounted for within the rest of the modelling undertaken in this body of work.

- **Volume** $[m^3]$:

$$V = A_{plan} H \tag{4.5}$$

- **Length** $[m]$ must be estimated for each building, assuming that it is of rectangular form. This is calculated by finding the minimum rotated rectangle, which is the rectangular shape of the minimum area which completely bounds the polygon and is shown in Figure 4.2. The Length is then estimated as the maximum value out of the four sided shape.

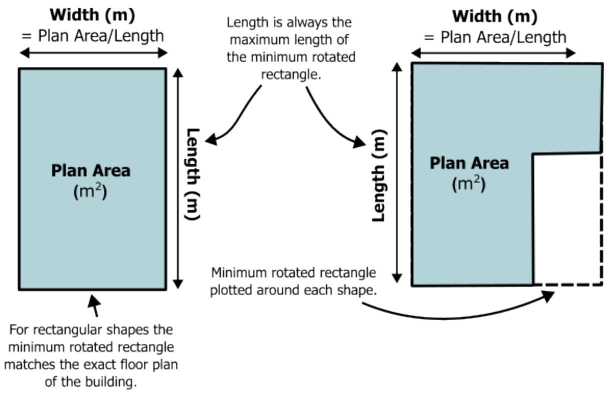


Figure 4.2: A sketch to explain how Length, L, and Width, W, were calculated for all shapes.

- **Width** $[m]$ can now be estimated by dividing the plan area by the length. This ensures that building floor area is still accurate (See Figure 4.2).

$$W = A_{plan}/L \tag{4.6}$$

- **Surface area to volume ratio** $[m^{-1}]$:

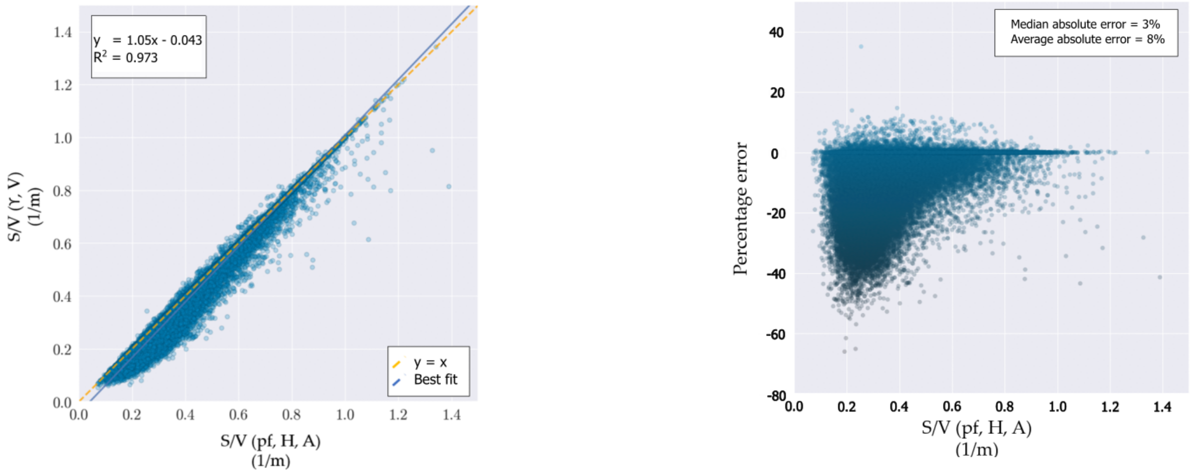
$$\frac{S}{V}(P_f, H, A_{plan}) \quad (m^{-1}) = \frac{A_{Surface}}{V} \tag{4.7}$$

This allows for an estimation of Surface area to volume ratio in two different ways as this value can also be defined in terms of building compactness [9]:

$$\frac{S}{V}(\gamma, V) \quad (m^{-1}) = 3\sqrt[3]{\frac{4}{V}}\gamma(k, r) \tag{4.8}$$

Figure 4.3a shows a plot of both S/V values and Figure 4.3b shows the percentage error between the two values.

Figure 4.3a shows a line of best fit very close to $y = x$ with a high R^2 value implying highly clustered data around this line. Also, a very low median and average percentage error of 3% and 8% respectively, implies that aspect ratio and slenderness values are appropriate for defining a buildings geometry.



(a) A plot of $\frac{S}{V}(P_f, H, A_{plan})$ against $\frac{S}{V}(\gamma, V)$ (m^{-1})

(b) A plot of percentage error $\frac{\frac{S}{V}(\gamma,V)-\frac{S}{V}(P_f,H,A)}{\frac{S}{V}(P_f,H,A)}$.

Figure 4.3: Scatter graphs to show to relationship between two different methods of calculating surface area to volume ratio for the entire Verisk UKbuildings educational stock.

However, there are some polygons with very high error. The top 3 residuals are shown in Figure 4.4 and shows that highly irregular forms are present within the stock. These complex cases have multiple courtyards which vastly increase the exposed perimeter and would lead to inaccurate results.

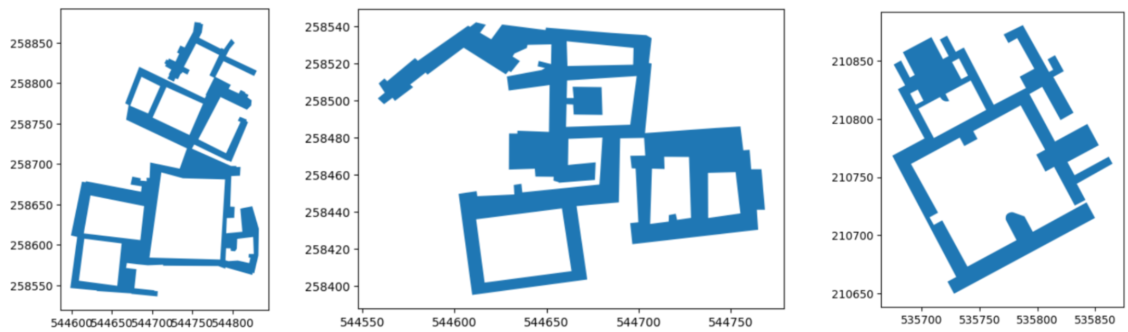


Figure 4.4: The top three highest residuals for assumptions of rectangular form within the UK educational building database.

Appendix C.1 also provides examples where inaccurate polygon identification within Verisk leads to unrealistic building forms. Figure C.1 provides examples where Verisk has incorrectly identified walkways and walls as part of the building floor plan which emphasises that for the vast majority of actual forms this rectangular form assumptions are appropriate.

To conclude, this investigation shows that for the vast majority of forms, rectangular form can be assumed. However, there is a limited number of highly complex shapes for which rectangular form cannot be used to describe the building geometry.

4.3 Drivers of building form in schools

The previous section has highlighted a range in key building form factors within the UK educational stock. Past work has assumed the same building form for all school buildings within a defined construction era when conducting indoor environmental quality modelling [249]. Indeed, there have been several eras of school construction each with distinct design principles that have influenced building form.

Within the UK, compulsory education was first introduced in the 1800s, and school sizes therefore increased dramatically [250]. Within this period the individual classroom became commonplace, often clustered around a central hall [250]. High floor-to-ceiling heights were used to encourage natural daylighting and ventilation and buildings were often multiple storeys tall to accommodate many children on limited urban sites [251].

Beginning in the early 20th century, ventilation for hygiene reasons became a key driving force behind school designs [250]. As cities spread, larger sites were made available for new school constructions allowing for single storey and ‘open’ schools to be designed [250]. Classrooms were often designed as detached from the central hall or open-air courtyards were used to ensure ventilation to all rooms [250]. Therefore, this ‘open’ design implies a large external surface area to provide space for glazing.

Within the immediate post-war period, the country faced several key constraints which directly influenced school construction. The country faced economic struggles and material shortages [252]. Further, one in five schools were damaged during the war, a problem exacerbated by rising school-age population [229]. Therefore more compact forms were designed, being less costly to build and heat - floor to ceiling heights were reduced alongside total circulation area [229]. As natural lighting was still seen as important, complicated outlines and asymmetrical plans were used in designs to allow for wall openings and natural light to enter rooms [229].

Compact forms became even more widespread as a balance between natural and artificial light was encouraged within the mid to late 20th century. Relying more heavily on artificial light allowed for deeper plans and more economic constructions [253]. This principle is encouraged in modern day, with design guidance stating that primary schools should be planned as compactly and economically as possible [244].

It is shown that the key drivers on older school building forms have been ventilation followed by economic cost savings. It is therefore possible that early 20th century schools varied more widely in form efficiency due to the trend for open rather than compact schools. However, with the increased usage of private sector architects throughout the 20th century, diversity in school design and form remains [253].

A focused attention on energy efficiency started during the oil crisis in the 1970s [253] and energy efficiency standards for non-residential buildings were also introduced within this period [46]. These energy efficiency standards became considerably stricter within the 21st century [46], and our understanding of the influence of form on energy efficiency has also increased (as shown in Section 2.3.2 of Chapter 2). Therefore, available design guidance for schools, e.g. *Better spaces for learning* [254], now specifically encourage consideration of passive design principles including designing building form to improve energy efficiency of a space [254].

A whole life carbon case study comparison of a modern and historic school is provided in Section 4.5.3. This comparison therefore also provides further examples on building forms of two different construction eras.

4.4 Methodology

The Methodology outlines an analytical expression to understand and connect building form to the total energy consumption and whole life carbon of a building. The first section focuses on thermal and specifically heating energy consumption as this has the most complex relationship to form and is followed by whole life carbon calculations for retrofit.

In Chapter 3 we have shown that at scale, simple energy models can be used to estimate the aggregated energy consumption of existing school buildings. Therefore, this section uses the degree-days model as a starting point as well as a reference for comparison. Throughout this section, the developed analytical expression is compared to the degree-days model to understand its potential limitations.

4.4.1 Thermal energy consumption

To quantify the whole life carbon impact of retrofit measures in terms of building form, the energy consumption of a building must first be understood. As demonstrated in Equation 3.2 of Chapter 3, we can split thermal energy consumption in heating, $F_{heating}$, hot water usage F_{DHW} and kitchen gas usage $F_{kitchen}$.

The assumption that F_{DHW} and $F_{kitchen}$ are independent from building shape and form has been made for the following reasons:

- Hot water usage has been shown to be dependant on the number of occupants [255].
- Kitchen gas usage is shown to be dependant on the number of meals prepared [224].

These values are dependant on occupancy density, o_d, $[people/m^2]$ which is independent of form as it is normalised by floor area.

Heating energy consumption, $F_{heating}$, is the most challenging factor to parametrize because the degree-days model is reliant on defining the heat loss through building fabric and ventilation which have a complex relation to building form. Heating energy consumption is considered as a balance between heat lost through a building's fabric and ventilation and heat gained due to internal occupant behaviour and solar gains. Additional heat provided by heating systems can then be used to ensure a comfortable space.

The rate of heat lost through a building element is dependant on the thermal performance of that element. This can be described using the total fabric conductance $[W/K]$ calculated as:

$$U'_{fabric} = 2L^2(kr + k)(wU_{wall} + gU_{window}) + L^2r(U_{roof} + U_{floor}) \tag{4.9}$$

where the area of each element has been defined using the length of the building, L, and building form factors slenderness, k, and aspect ratio, r, as shown in Figure 4.1. For example, $A_{floor} = L^2r$. The glazing ratio is g and $w \equiv (1 - g)$.

The heat lost through ventilation is dependant on the amount of cold air being exchanged with indoor air. The total ventilation and infiltration conductance $[W/K]$ is dependant on the total volume flow rate of this air and its respective thermal properties. As these thermal properties do not change much between different typical air temperatures a constant value of $\frac{1}{3}$ can be assumed [131]:

$$U'_{ventilation} \approx \frac{NV}{3} @\theta_{typical} \tag{4.10}$$

We define the ventilation rate, N, as the total number of complete exchanges of outdoor air within the building per hour, [hr^{-1}]. N is calculated using a constant background infiltration to account for leakage and additional ventilation from opening windows during the occupancy, averaged over 24 hours. This allows for the volumetric flow rate of air to be expressed as:

$$U'_{ventilation} = \frac{NL^2 xrH_{fc}}{3} \tag{4.11}$$

where x is the number of floors in the building and H_{fc} is the internal floor to ceiling height [m], which is assumed to be a constant typical value across floors.

The sum of U'_{fabric} and $U'_{ventilation}$ provides the total building heat loss coefficient [kW/K]:

$$U' = L^2 \frac{2(kr + k)(wU_{wall} + gU_{window}) + rU_{roof} + rU_{floor} + \frac{NxrH_{fc}}{3}}{1000} \tag{4.12}$$

where the values have been divided by 1000 to convert from Watts to kiloWatts as typically heating energy consumption is given in kWh/m^2.

These values can then be used to determine the rate of heat lost or gained [kW] at any given internal required, θ_{sp}, and external temperature, θ_o, [°C]:

$$Q_{loss} = U'(\theta_{sp} - \theta_o). \tag{4.13}$$

Occupants, electronic equipment and lighting as well as solar energy through glazing all produce heat within a space. These internal gains allow for heating energy consumption to be lower than the total heat lost through a building's fabric and ventilation.

Occupancy related internal gains [kW/m^2], q_o, are calculated by averaging typical occupant, q_{oc}, equipment, q_e, and lighting, q_l, gains over a 24 hour period.

An area weighted average of a typical space breakdown for a school [17] and using typical occupancy schedules , χ_{oc}, χ_e and χ_l, allows for the internal gains to be estimated:

$$q_o = \frac{1}{24} \sum_{hrs}^{24} (q_e \chi_e + q_l \chi_l + q_{oc} \chi_{oc}). \tag{4.14}$$

Internal gains values [kW/m^2] are estimated from CIBSE Guide A [131]. Appendix B.1.2 provides internal gains values for each space alongside typical space breakdowns and occupancy schedules for each school typology.

Final solar gains through glazing, q_s, must also be calculated and averaged over the 24 hour period. Given the focus here on the relationship between building form and this impact on energy consumption, an average solar gain value, q_{sol}, [kW/m^2] has been adopted, calculated as the wall area weighted solar gain for a square-plan, south facing building. As the glazing ratio is assumed to be constant for each wall, this scenario assumes that an equal amount of solar gains are entering from South, North, West and East facing walls. Therefore, q_s can be approximated as:

$$q_s = q_{sol} s_g \alpha \tag{4.15}$$

where s_g is the solar gain factor which dictates how much heat is transferred through the glazing and α is the typical frame factor of a window.

The adoption of a gains utilisation factor, η', is outlined in BS EN ISO 3479 and is used to help account for the temperature variations during the day within the building and materials. This is calculated using the method outlined in CIBSE Guide TM41:2006 [135] and is dependant on the total internal gains to the space as well as the heat loss coefficient.

Therefore the total corrected internal gains, Q_g, is:

$$Q_g = [2L^2 q_s g(k + kr) + L^2 xrq_o]\eta'. \tag{4.16}$$

This can be used to correct our internal temperature, through calculating a internal base temperature, θ_b:

$$\theta_b = \theta_{sp} - \frac{q_g}{Z} \tag{4.17}$$

where $Z = \frac{U'}{L^2}$ and $q_g = \frac{Q_g}{L^2}$ and shows that L^2 is cancelled out of this equation.

By substituting θ_b into equation 4.13 the heat lost from the building can be estimated at any given time of the year. Taking the sum over the entire heating season when the building is occupied and heated and dividing by the floor area, $A = L^2 xr$, allows for the total energy consumption intensity over the year [kWh/m^2] to be calculated as:

$$f_{heating} = \sum_m \frac{24n_{(h,m)}Z}{xr\eta_{heating}}(\theta_b - \theta_{o,m}) \tag{4.18}$$

where $f_{heating}$ is the fuel consumption normalised by floor area [kWh/m^2], $n_{h,m}$ is the total heated days in the month, $\eta_{heating}$ is the overall efficiency of the heating system and $\theta_{o,m}$ is the average monthly outdoor temperature [$°C$].

As with the degree-days methodology discussed in Chapter 3, a constant $\theta_{o,m}$ is used, and a correction factor is required to estimate the impact of varying temperatures throughout the month:

$$f_{heating} = \sum_m \frac{24n_{(h,m)}Z}{xr\eta_{heating}} \frac{(\theta_b - \theta_{o,m})}{1 - e^{\frac{2.5}{\sigma_\theta}(\theta_b - \theta_{o,m})}} \tag{4.19}$$

Equation 4.17 does not account for the impact of occupied and unoccupied hours throughout a 24 hour period. Building heating systems are typically, however, switched off for a period when the building is not occupied. A building will store some heat for a period after the heating system is switched off and typically building heating systems will need to be switched on before occupancy to allow for preheat of the space. This means that the average internal temperature varies over 24 hours from either θ_{sp}, or θ_o [$°C$].

To account for this and adjust θ_{sp} accordingly, the thermal properties of the building are accounted for to understand how much heat could be stored within the fabric. The thermal time constant, τ, [hr] is used to understand the response time of the building to temperature changes, where different thermal mass and thermal performance will impact this:

$$\tau = \frac{2(kr + k)(wc_{wall} + gc_{window}) + xrc_{ceiling} + xrc_{floor}}{3600Z}. \tag{4.20}$$

The total thermal capacitance, c, [$kJ/K.m^2$] of each exposed building element, is defined as density multiplied by specific heat capacity multiplied by the exposed thickness of the material, which is then multiplied by the exposed area of the element.

The estimated size of the plant within the building is also required as this can be used to understand the preheat time before occupancy begins. This thesis simplifies plant size calculations, by not accounting for the impact of different types of operation, as the degree-days model is shown to be relatively insensitive to plant size [135]. Therefore, we can define plant size [kW],

Q_p, as a function of the heat lost in the space during the coldest period of the year:

$$Q_p = \frac{\beta(\theta_{sp} - \theta_{winter})}{\delta} L^2 Z \tag{4.21}$$

where δ accounts for heat losses due to distribution, 0.85 [256], within the space and β is a multiplier to oversize the building plant, 1.6 [24], as is commonly undertaken in practice [46]. θ_{winter} is the minimum design temperature for a cold temperate climate [$°C$].

The preheat period, Ψ, [hr] and the switch off period, Ω, [hr] are calculated by inputting the equations 4.12, 4.20 and 4.21 into the methodology outlined in Degree-days TM41:2006 [135] and rearranging to cancel out all geometric parameters expect for τ:

$$\Psi = -\tau ln[\frac{Y^2 - 2Y\Delta\theta + \Delta\theta^2}{Y^2 - Y\Delta\theta} + (\frac{\Delta\theta Y - \Delta\theta^2}{Y^2 - Y\Delta\theta})e^{\frac{-t_u}{\tau}}] \tag{4.22}$$

$$\Omega = t_u + \tau ln[\frac{Y^2 - 2Y\Delta\theta + \Delta\theta^2}{Y^2 - Y\Delta\theta} + (\frac{\Delta\theta Y - \Delta\theta^2}{Y^2 - Y\Delta\theta})e^{\frac{-t_u}{\tau}}] \tag{4.23}$$

where $\Delta\theta = \theta_{sp} - \theta_o$, $Y = \frac{Q_p}{ZL^2}$ and t_u is unoccupied hours in the space. These values allow us to adjust our indoor temperature, to account for differences over the 24 hour period [135]:

$$\overline{\theta_i} = \frac{\theta_o t_u}{24} + \frac{\tau(\theta_{sp} - \theta_o)}{24}[e^{\frac{\Psi}{\tau}} - e^{-\frac{\Omega}{\tau}}] + \frac{\tau Y}{24}[1 + \frac{\Psi}{\tau} - e^{\frac{\Psi}{\tau}}] + \frac{\theta_{sp} t_o}{24} \tag{4.24}$$

where t_o is the occupied hours [hr]. This value shows that L^2 is completely cancelled out and leaves the only geometric parameters of k, r, and number of floors, x. This can be inputted into Equation 4.19 to provide an estimate of heating energy consumption for a building of rectangular form.

4.4.1.1 Exploring complex parameters

To simplify this analytical expressions further, the complex parameters within the equation which are still influenced by building form are explored in further detail. This aims to understand exactly how they change depending on different values of slenderness and aspect ratio. These are the denominator ($D = 1 - e^{\frac{2.5}{\sigma_\theta}(\theta_b - \theta_{o,m})}$), η', Ψ and Ω.

Each of these parameters for every polygon within the UK educational stock, as in Section 4.2, is calculated to understand their relationship with k, r and x. Not only does building form change energy consumption but fabric and ventilation efficiency will impact the amount of heat lost from the space. Each polygon is therefore modelled for three different building performance levels of Historic, Part L2B and Enerphit and the extremes of outdoor conditions within the heating season - October and January. A Part L2B modelling scenario is the performance level stipulated by UK building regulations for existing non-residential buildings. This scenario includes insulation of the floor, roof and walls alongside replacement of the existing glazing and heating systems.

An Enerphit model is the retrofit equivalent to Passivhaus with extremely high fabric and ventilation efficiencies required. Alongside these improvements, mechanical ventilation with heat recovery (MVHR) will be modelled. Enerphit stipulates extremely airtight building meaning MVHR is advised due to the need for reliable ventilation [16]. The key data for this modelling is provided in Table 4.1 with further detail in Appendix C.4.

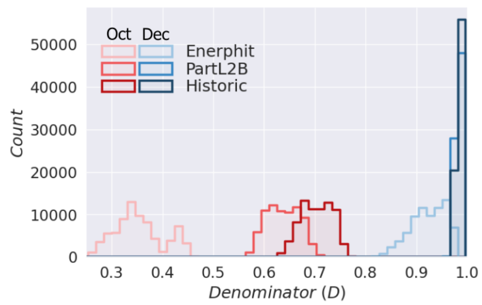
Table 4.1: Key building performance metrics for each modelling scenario. U-value for Enerphit wall assumes internal insulation as the chosen refurbishment method which has a limited U-Value [16]. Historic buildings glazing is assumed too be single glazed with timber frame. Further details are provided in Appendix C.4

Input	Historic	Part L2B	Enerphit	References
Wall U-value $[W/m^2K]$	1.7	0.35	0.35	[25, 228, 16]
Glazing U-value $[W/m^2K]$	4.8	1.6	0.6	[131, 228, 257, 258]
Roof U-value $[W/m^2K]$	2.3	0.16	0.15	[131, 228, 16]
Floor U-value $[W/m^2K]$	1.0	0.25	0.15	[131, 228, 16]
Infiltration rate $[hr^-1]$	0.675	0.3	0.05	[131, 259]
Heat recovery efficiency	-	-	0.9	[21]

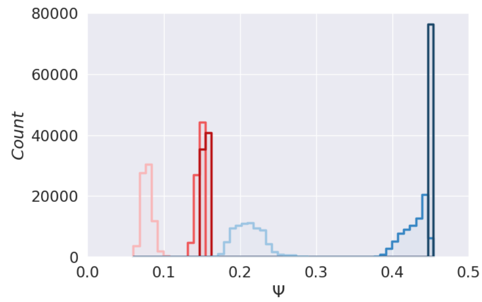
Figure 4.5 shows the distribution of values of D, Ψ, Ω and η' for the entire UK educational stock. It is shown that for each parameter, the majority influence is from the building performance or the outdoor conditions rather than the geometry of the building. There is relatively little spread for any factor between different values of slenderness, aspect ratio and number of floors.

Increase in spread for better performing buildings is demonstrated and especially apparent in

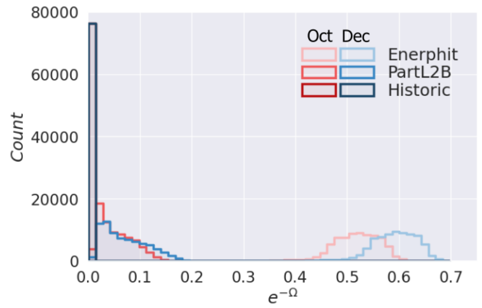
Figure 4.5c. Though we will assume this to be a constant value, the impact of doing so will be explored in Section 4.4.2.1.



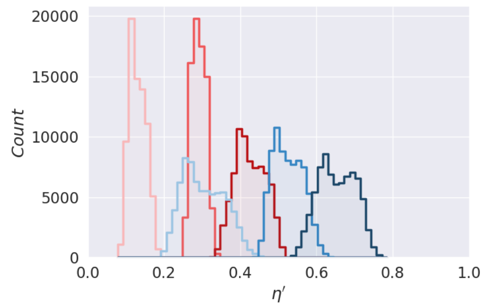
(a) Distribution of Denominator values



(b) Distribution of Ψ values



(c) Distribution of Ω values



(d) Distribution of η' values

Figure 4.5: Values of components within the degree-days model for 3 building types. The worst performing being Historic, then Part L2B which assumes a building refurbished to current UK building regulations and Enerphit which is a refurbishment standard equivalent to Passivhaus standards. The coldest and the warmest month in the heating season are shown.

The variation in each parameter is limited, and therefore constant values for D, Ψ, Ω and η' are estimated which are applicable to a wide range of building forms. These values are estimated depending on the building performance and typology but use typical geometry to create a constant. This typical geometry is based on the typology of the building, using the average floor area of that typology and assuming a simple square-plan building. As the building energy efficiency improves, which includes improvements to the U-value of each element and infiltration rate of the fabric, the impacts of solar and internal gains as well as internal mass become more important which means assuming constant values is more likely to impact model accuracy. In fact, in Section 4.4.2.3, the model performance of Historic and Enerphit efficiency levels are compared.

The Denominator strongly tends towards 1 in cold weather. Warmer temperatures have a larger spread in values but as these months have lower total energy consumption the impact of this spread is reduced. This body of work has focused on reducing heating consumption, which makes the impact of colder months the focus of this work. Therefore denominator is assumed to be $D \approx 1$.

Warmer periods within the heating season have lower energy consumption and it is likely that there will be a slight underestimation of the total annual energy consumption.

Ψ and Ω require the calculation of τ. Therefore, τ will be calculated for a typical geometry dependant on the typology of the building. Typical values for a primary school with the average size being $1000m^2$ (square plan) [260, 261] and one storey tall [244] is assumed as the 'typical building' with the following qualities:

- Surface area to volume ratio (S_c) = 0.9
- Wall to total surface area ratio (W_c) = 0.22
- Roof to total surface area ratio (R_c) = 0.39
- Floor to ceiling height [46] = $3.5m$

This allows for an area weighted average of the U-value, U_{av} and the thermal capacitance, c_{av} to be estimated and a constant τ to be calculated:

$$\tau_c = \frac{2c_{av}}{3.6[2U_{av} + \frac{2N}{3S_c}]} \tag{4.25}$$

which allows for internal volume to be expressed as a function of the surface area and cancels out any geometric parameters from the equation.

Equations 4.26 - 4.28 demonstrate how a constant value for η' is also estimated, using a roof to surface area ratio, R_c, and wall to surface area ratio, W_c of a typical building, again assuming a single zone space ($x = 1$):

$$\gamma_c = \frac{2q_o R_c + 2q_s g W_c}{\frac{\Delta\theta_c}{1000}[2U_{av} + \frac{2N}{3S_c}]} \tag{4.26}$$

where q_o is the total internal gains [kW/m^2] from equipment, lighting and occupants, q_s the total solar gains [kW/m^2].

Another simplified assumption for $\Delta\theta_c$ must also be made by replacing τ,Ψ, and Ω with constant values:

$$\Delta\theta_c = \theta_o - \frac{1}{24}[\theta_o t_u + \tau_c(e^{\Psi_c} - e^{-\Omega_c}) + \tau_c Y(1 + \Psi_c - e^{\Psi_c}) + \theta_{sp} t_o]. \tag{4.27}$$

Inputting $\Delta\theta_c$ into the methodology outlined in BS EN ISO 3479 the gains utilisation factor is calculated for the reference typical building:

$$\eta_c' = \frac{1-\gamma_c^{0.8+\frac{\tau_c}{70}}}{1-\gamma_c^{1.8+\frac{\tau_c}{70}}}. \tag{4.28}$$

4.4.2 Analytical expression

Having taken D, η', Ψ and Ω as constants, the only remaining variables in equation 4.19 and 4.24 that are influenced by building form are the values of Z and τ, where $Z = \frac{U'}{L^2}$ and τ is the thermal time constant.

When writing out the entire equation for heating energy consumption we can separate values into three respective parts. The first being all the heat losses, thermal mass and heat gains which are influenced by the form of the building walls and glazing ($\frac{k}{x} + \frac{k}{rx}$):

$$\begin{aligned} C_1 \equiv \frac{n_{(h,m)}}{\eta D}[(\theta_o t_u + \theta_{sp} t_o - 24\theta_o)(\frac{2wU_{wall} + 2gU_{window}}{1000})] - \frac{48gn_{(h,m)}q_s\eta'}{\eta D} + \\ [\frac{n_{(h,m)}\Delta\theta}{3600\eta D}(e^{\Psi} - e^{-\Omega}) + \frac{n_{(h,m)}Y}{3600\eta D}(1+\Psi-e^{\Psi})](2wc_{wall} + 2gc_{window})). \end{aligned} \tag{4.29}$$

The second, aggregates the influence of the heat losses through the roof and ground floor ($\frac{1}{x}$):

$$C_2 \equiv \frac{n_{(h,m)}}{\eta D}[(\theta_o t_u + \theta_{sp} t_o - 24\theta_o)(\frac{U_{roof} + U_{floor}}{1000})]. \tag{4.30}$$

Finally, the third provides an indication of the effects of internal gains and thermal mass of the ceiling and floors which are dependant on floor are and not influenced by building form so are therefore constant:

$$\begin{aligned} C_{3_{heat}} \equiv \frac{n_{(h,m)}}{\eta D}[(\theta_o t_u + \theta_{sp} t_o - 24\theta_o)(\frac{NH_{fc}}{3000})] - \frac{24n_{(h,m)}\eta' q_o}{\eta D} + \\ [\frac{n_{(h,m)}\Delta\theta}{3600\eta D}(e^{\Psi} - e^{-\Omega}) + \frac{n_{(h,m)}Y}{3600\eta D}(1+\Psi-e^{\Psi})](c_{ceiling} + c_{floor}). \end{aligned} \tag{4.31}$$

Together, these allow us to express heating energy consumption as $[kWh/m^2]$:

$$f_{heating} = C_1\frac{k}{x} + C_1\frac{k}{xr} + \frac{C_2}{x} + C_{3_{heat}}. \tag{4.32}$$

As previously stated, we can also bundle the total hot water usage and kitchen gas usage as a function of the occupancy density [$people/m^2$], o_d. These are by definition independent of form when energy consumption is normalised per floor area. This allows us to express the values of f_{DHW} and $f_{kitchen}$ as a constant [kWh/m^2]:

$$C_3 \equiv C_{3_{heat}} + \sum_{m}^{12}[\mu * o_d * \kappa * n_{(o,m)} + \frac{4.18 * n_{(o,m)} * \Delta\theta_m * l}{3600\eta}] \tag{4.33}$$

where $n_{(o,m)}$ is the number of occupied days, μ is a total meals per occupant ratio, κ is typical Kitchen gas usage [$kWh/meal$]. l is typical hot water usage [L/m^2] and $\Delta\theta_m$ is the monthly typical temperature difference of incoming cold water and the hot water system [255].

This allows us to express total building thermal as an analytical expression for energy usage as:

$$f_{total} = \underbrace{C_1\frac{k}{x} + C_1\frac{k}{xr} + \frac{C_2}{x} + C_3}_{\text{thermal consumption}} + \underbrace{C_4}_{electricity} . \tag{4.34}$$

where $C_4 = \epsilon = 40kWh/m^2$.

4.4.2.1 Direct analytical expression estimation

This section now investigates the appropriateness of the analytical expression in the form of $f = C_1\frac{k}{r} + C_1\frac{k}{xr} + \frac{C_2}{x} + C_3$, to further understand the impact of any assumptions made within the model.

First, using the degree-days methodology (y), we modelled the sample of UK educational polygons to find thermal energy consumption assuming historic, Part L2B, and Enerphit standards of building performance.

Second, non-linear least squares is used to finds values for the constants (C_1, C_2, C_3) based on the analytical expression which best fits the degree-days model results (using the Python function - *scipy.optimize.curve_fit* [262]).

We use this data, shown in Table 4.2, to re-calculate the energy consumption (y_0).

Table 4.2: Results from estimating the constants for C_1, C_2 and C_3.

Input	Analytical expression
Historic	$119\frac{k}{x} + 118\frac{k}{xr} + 80\frac{1}{x} + 64$
Part L2B	$5.9\frac{k}{x} + 5.9\frac{k}{xr} + 1.7\frac{1}{x} + 29$
Enerphit	$3.1\frac{k}{x} + 3.1\frac{k}{xr} + 1.1\frac{1}{x} +$

Therefore we now have two values of energy consumption, y which is calculated from the degree-days model and y_0 which has been fit to this data using the shape of the analytical expression. Figures 4.6a-4.6f shows an extremely close correlation between the two results, with maximum residual $(\frac{y-y_0}{y})$ never being above 0.05 for any building performance level. This shows that the analytical expression works well for a variety of building forms as well as fabric and ventilation performance levels as there is no reduction in accuracy for more or less efficient building types.

Therefore, the form of the analytical expression remains in line with the full implementation of the CIBSE degree-days model and shows that this surface form can be used to calculate results to the same extent as existing simple energy models.

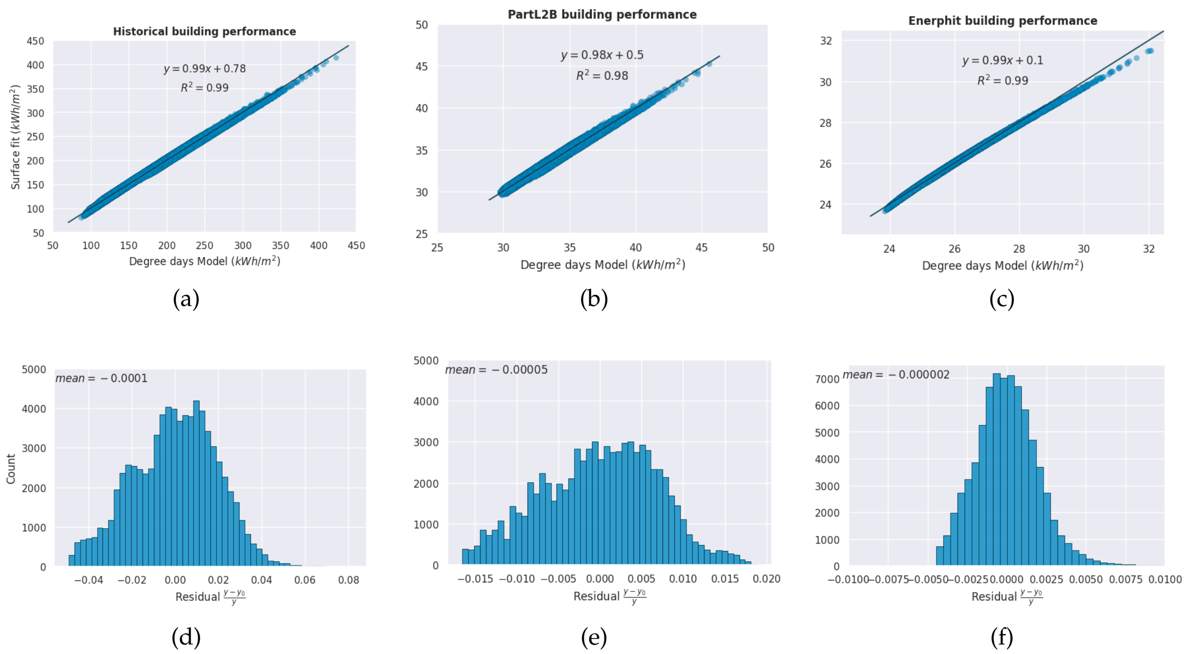


Figure 4.6: Scatter graph to show the correlation and histograms show the distribution of residuals $(\frac{y-y_0}{y})$ between the degree-days model (y) and the best-fit analytical expression (y_0) thermal energy results for Historic, Part L2B and Enerphit buildings.

Despite varying values of floor to ceiling heights within the dataset, the connection between the degree-days model and the analytical expression is still very strong. This shows that for typical combinations of U-value and ventilation losses, a constant floor to ceiling height, H_{f_c}, can be assumed. This assumption only becomes problematic if we combine very low U-values with very high ventilation losses as the volume of the building is therefore now the major contributor to total losses, which is reliant on the floor to ceiling height. In these cases an additional variable of floor to ceiling height may need to be assigned. This scenario is not something that would likely occur as fabric retrofit measures also influence the ventilation losses in a building. Further, in Chapter 3 it is shown that when modelling at scale, it is more accurate to assume a constant floor to ceiling height due to issues with currently available height data.

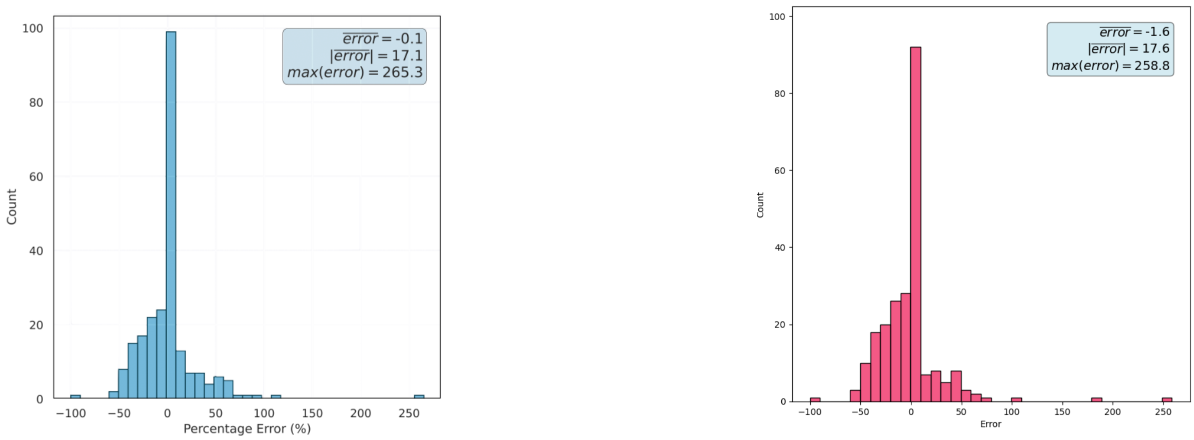
Another key assumption made is that the glazing ratio and solar gain through the glazing is equal for each face of the building. In Appendix C.2, sensitivity analysis shows that the assumptions of an average solar gain value only a changes results by on average 0.25% and a maximum of 2%.

4.4.2.2 Comparisons against case study data

To further understand the capabilities of the analytical expression and the assumptions of rectangular form, the energy consumption was calculated using the analytical expression for every case study school and compared with the degree-days model used in Chapter 3. The minimum error was calculated, see Section 3.3.2, where metered energy data is collected over 5 years, to understand it's variation. If the model's results fall between the minimum and maximum metered energy values this is classed as zero error.

These results, as shown in Figure 4.7, demonstrate a slight increase in average absolute error compared to Chapter 3 results from 0.16 to 0.17. Alongside this there is a small decrease in the number of buildings with zero error reduces from 89 to 80 schools. When comparing the gradient of the graph, metered versus modelled, this reduces from 0.77 to 0.75 if we adopt the analytical expression.

Potential reasons for the difference not only includes the assumption of rectangular form, but also other simplifications made when using the analytical expression. For example, rather than splitting the building by building height or age, we merged each into a single building to calculate slenderness and aspect ratio. Therefore, if there were differences in age or number of floors between properties this is not accounted for.



(a) **VML** histogram of minimum percentage error.

(b) **Analytical expression** histogram of minimum percentage error.

Figure 4.7: Histograms to show the minimum percentage error of baseline energy consumption for 235 school case studies. The pink histogram uses the analytical expression and rectangular form assumption. The blue histogram uses the degree-days model and exposed perimeter.

As the average error still lies around near zero and the error distribution remains the same, this implies that the analytical expression still holds despite simplifications.

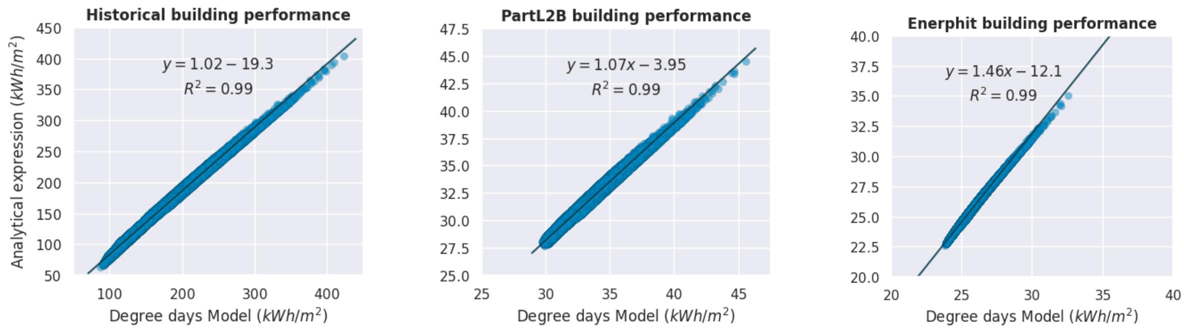
4.4.2.3 Limitations for extremely efficient retrofit scenarios

Though it is shown in Section 4.4.2.1 that the expression in the form of Equation 4.34 does remain in line with the full implementation of the CIBSE degree-days model, there are limitations to our assumptions when expressing D, η', Ψ and Ω as constants.

By comparing the analytical expression to using full degree-days energy model these limitations can be understood. In Figure 4.8 both degree-days modelling and the analytical expression have been run for the entire sample of polygons using Historic, Part L2B and Enerphit performance.

As previously mentioned, the analytical expression has a tendency to underestimate energy consumption due to the assumption that $D \approx 1$. As the building performance improves this tendency reduces but the gradient of the graph worsens. As a building's performance improves, the relative impacts of η', and thermal time constant, which inform Ψ and Ω, should increase, while being kept as constants here.

This is especially the case for η' as the internal gains at higher efficiency now take up a much larger proportion of the total results. As energy consumption increases so does the internal gains factor compared to the constant value which has been calculated. As total gains are subtracted, this helps explain why lower efficiency buildings tend to be overestimated at higher energy consumption levels.



(a) (b) (c)

Figure 4.8: Scatter graph to show the correlation between the degree-days model and the analytical expression thermal energy results for Historic, Part L2B and Enerphit buildings.

For the real set of UK school buildings, this overall error is low with an average percentage error between the analytical expression and the degree-days being ±10%, ±5% and ±2% for Historic, Part L2B and Enerphit buildings respectively.

This shows that our methods of calculating a constant τ, η', D, Ψ and Ω pose an additional simplification in comparison to the degree-days model. It must therefore be assessed what impact this additional simplification will have on overall retrofit decisions. This is explored further in Section 4.5.2 where a transition period is calculated which shows where this inaccuracy impact results.

4.4.3 Retrofit decisions

We can now use the parametrized thermal energy consumption and combine this with predicted embodied emissions from different potential intervention measures to understand the influence of building form on retrofit decision making alongside total whole life carbon.

Two possible interventions are refurbishment of the existing building to a higher standard or demolition and replacement with a more efficient construction. These can both reduce energy consumption to various degrees but also both have very different embodied impacts which need to be accounted for.

Accounting for whole life carbon emissions requires quantification of the parametric connection between operational carbon, embodied carbon and building form which can then be used to compare different intervention strategies.

Equation 4.34 demonstrates the relationship between thermal energy consumption and slenderness, aspect ratio and number of storeys. This form can also describe total whole life carbon emissions because both the operational emissions [$kgCO_2e/m^2$], e_o, and the embodied carbon [$kgCO_2e/m^2$], e_e, are dependant on the form of the building.

We estimate yearly operational carbon [$kgCO_2e/m^2$], e_o, as the yearly energy consumption multiplied by the respective operational carbon factor [$kgCO_2e/kWh$], σ, of the fuel used:

$$\begin{aligned} e_o &= \sigma_{fuel} f_{thermal} + \sigma_{elec} f_{electricity} && (4.35) \\ &= (C_{oc1}\frac{k}{x} + C_{oc1}\frac{k}{xr} + \frac{C_{oc2}}{x} + C_{oc3}) + C_{oc4} && (4.36) \end{aligned}$$

where $C_{oc} = \sigma_{fuel} C$.

For any retrofit scenarios where a ventilation system is installed additional electricity consumption, C_{vent}, will be estimated using a typical Specific Fan Power [$kW/m^3/s$] multiplied by the estimated total hours of usage and typical air flow per floor area [m^3/sm^2] each year [263]. The total operational electricity carbon for systems with a ventilation system is therefore $e_{elec} = C_{oc4} + \sigma_{elec} C_{vent}$.

Total e_o is then calculated by summing over the appropriate lifespan of the building. The factors, σ_{fuel}, may change year on year due to the decarbonisation of electricity supply.

The embodied carbon of each retrofit scenario is now calculated by collecting appropriate data using Environmental Product Declarations (EPDs), manufacturers data and scientific journal papers. For each element this was estimated from an A1 - C4 boundary as defined by BS EN 15643:2021 standards [2]. The lifespan of each building element, see Table C.2 - C.3 Appendix C, was used to estimate the number of replacements which occur over the lifespan or study period (B4).

Embodied carbon data used is provided in Appendix C.4.2. Glass wool has been chosen as the main insulation material due to its relatively low embodied carbon and low combustibility [264, 265], making it appropriate to be applied at scale. The ASHP model uses R513A refrigerant which is typically used, but provides lower embodied carbon than some other options [213].

For insulation installations, each element's thermal resistance $[m^2K/W]$ is provided in Appendix C.4.2 which allows for the estimated thickness of insulation to be calculated:

$$d_{ins} = \lambda R_{ins} \tag{4.37}$$

where λ is the thermal conductivity $[W/m.K]$ of the insulation product and R is the required thermal resistance $[m^2K/W]$ of the insulation to achieve the correct U-Value.

The embodied carbon data for MEP, such as heating systems are collected using the functional unit of $kgCO_2e/kW$. Therefore, they were calculated by estimating the total plant size for each system as in Equation 4.21 [131]. Ventilation system data is provided in $kgCO_2e/Ls^{-1}$. Therefore, a predicted maximum size for the system $[Ls^{-1}/m^2]$ was calculated using Equation 4.38.

$$Q_{vent} = o_d v \tag{4.38}$$

where o_d is the maximum occupancy density of the space $[people/m^2]$ and v the typical air provision per person $[L/s.person]$. The total area of heating distribution pipework and ventilation ductwork was calculated using typical estimates provided by RICS whole life carbon guidance [12].

The carbon emissions of the demolition of the building at the end of its lifespan will be taken as a typical benchmark value of $35kgCO_2e/m^2$ [12].

Those measures which impact wall and glazing area include the addition of wall insulation and glazing replacement as well as the replacement of existing boilers because the size of this is estimated as a function of the plant size which is dependant on the building form (Equation 4.21 [131]). Total embodied carbon of these elements can be expressed as:

$$C_{ec1} = (2\xi_{wall}w) + (2\xi_{window}g) + \frac{(2\xi_{boiler}Y)(wU_{wall} + gU_{window})}{1000} \tag{4.39}$$

where ξ_{wall} $[kgCO_2e/m^2]$ is the embodied carbon of wall insulation, ξ_{window} the embodied carbon of replacing existing windows $[kgCO_2e/m^2]$ and ξ_{boiler} the embodied carbon of replacing the heating system $[kgCO_2e/kW]$.

Insulation of the floor and roof can quantified alongside the influence of heat losses through the roof and floor on total replacement boiler size:

$$C_{ec2} = (\xi_{floor}) + (\xi_{roof}) + \frac{(\xi_{boiler}Y)(U_{floor} + U_{roof})}{1000} \tag{4.40}$$

where ξ_{floor} and ξ_{roof} are the embodied carbon $[kgCO_2e/m^2]$ of insulation measures for each element.

Embodied carbon values which are independent of building form, such as hot water boiler installation and mechanical ventilation with heat recovery (MVHR), and the influence of ventilation losses on the replacement boiler size can be shown as:

$$C_{ec3} = \frac{(\xi_{boiler}YNH_{fc})}{3000} + (\xi_{boiler}Q_{DHW}) + (\xi_{mvhr}Q_{vent}) \tag{4.41}$$

where ξ_{mvhr} $[kgCO_2e/L.s^{-1}]$ is the embodied carbon of MVHR systems. The size of the DHW system, Q_{DHW}, is estimated by calculating the size required to provide sufficient hot water to the occupant based on occupancy patterns [24, 131].

Summing up the respective operational carbon and embodied carbon for each element of building form allows the expression of total whole life carbon $[kgCO_2e/m^2]$ as:

$$\begin{aligned} e_{WLC} = (C_{oc1} + C_{ec1})\frac{k}{x} &+ (C_{oc1} + C_{ec1})\frac{k}{xr} \\ &+ \frac{(C_{oc2} + C_{ec2})}{x} \\ &+ (C_{oc3} + C_{ec3} + C_{oc4}). \end{aligned} \tag{4.42}$$

The whole life carbon emissions of different carbon mitigation scenarios can then be superimposed on top of each other to create a heat map where the lowest carbon option is given for different values of slenderness and aspect ratio. This provides an early stage decision making for the demolition versus retrofit of existing buildings, as shown in the sketch within Figure 4.9.

Those scenarios with more efficient building fabric and systems often require larger input of materials to achieve this. Therefore, though operational carbon, C_{oc}, may be decreasing, embodied carbon would be increasing, C_{ec}. Alongside this, current benchmarks for new construction have a higher embodied carbon cost [51] but may be able to achieve better yearly operational carbon emissions due to the lack of a pre-described building form and more easily achievable fabric and ventilation improvements [52, 53, 54]. Therefore the point at which these operational savings outweigh the increased embodied costs can be modelled in terms of building form. A labelled sketch of how this modelling will work is demonstrated in Figure 4.9.

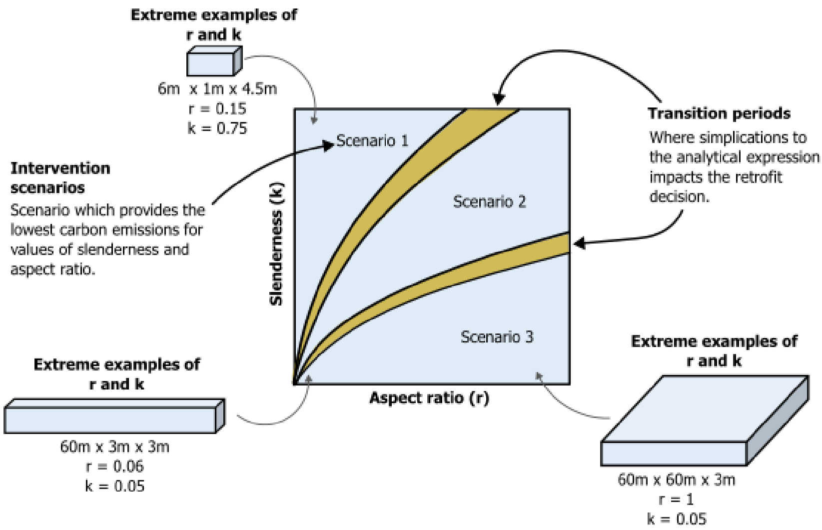


Figure 4.9: Sketch of how intervention decisions are superimposed on the same heat map. These are plotted against slenderness and aspect ratio. Alongside this is a demonstration of what different shapes would look like for extreme combinations of r and k. This shows that practically it is likely that many realistic shapes will fall within certain sectors (This has been explored in more detail in Chapter 5, Section 5.3.8).

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In the previous section we show that at very high fabric and ventilation efficiencies the model begins to overestimate energy consumption for highly inefficient building forms. Therefore, as demonstrated in Figure 4.9 a transition period which accounts for this will be calculated. The methodology to calculate the transition period has been outlined in Appendix C.3 **This transition period is defined as a area where the inaccuracy in the analytical expression would change the lowest carbon intervention decision compared to the degree-days model.**

4.4.4 Modelled scenarios

The focus of this chapter is to understand whether building form impacts intervention decisions for existing buildings, in regards to typical retrofit scenarios and the option of demolition and replacement.

Again, two typical retrofit scenarios will be modelled, both Part L2B and Enerphit as described in Appendix C.4.

Part L2B only requires replacement of MEP to the same standard as before retrofit and Enerphit does not stipulate a specific heating system. Therefore, to allow for fair comparison the same heating systems will be adopted within both scenarios. School retrofit case studies show several MEP strategies are typical, such as biomass boilers [266], high temperature heat pumps [267], low temperature heat pumps [268] combined with underfloor heating [269, 270] or replacement emitters [268] and MVHR [268].

The MEP scenario modelled will be limited, with no assessment of gas or biomass boilers. Due to the relatively long study period of 30 years and modelled electric grid decarbonisation it is unlikely that gas boilers would have the lowest whole life carbon [271, 63]. Heat pumps also have a higher operational efficiency than either gas or biomass boilers [46].

The heating retrofit strategy will replace the heating system with a highly efficient low temperature heat pump and replacing the emitters with new larger surface area radiators. This is seen as the most comprehensive possible scenario, as it involves replacement of all existing heating and hot water systems. Therefore, it will have a higher embodied carbon than other scenarios and provides a likely worst case scenario in comparison to new construction modelling. See Appendix C.4 for embodied carbon data.

4.4.4.1 Studied baseline buildings

Two existing buildings will be modelled, a pre 1919 historic and a post war building both with glazing ratios of 25%, 15% and 45%. Therefore, each will have different retrofit strategies which are appropriate as demonstrated in Table 4.3. These will be modelled as a primary school building typology. For the scenarios modelled throughout Chapter 4, the baseline buildings are assumed to have had no past intervention, with key performance data provided in Table C.1 of Appendix C.4.

Table 4.3: Fabric retrofit scenarios for both modelled existing building scenarios.

	Historic	Post war
Wall insulation	Internal	External
Glazing	Replaced	Replaced
Roof insulation	Loft	Flat roof
Floor insulation	Solid floor	Solid floor

Internal insulation will be limited at 0.35 U-value as stipulated to be sensible by Enerphit [16] to not constrain the internal area.

4.4.4.2 New construction modelling

New construction benchmarks will be used in this section. These benchmarks assume a highly energy efficient new construction where all energy is provided through electricity.

There are different sources of new construction targets, demonstrated in Table 4.4. Comparing these benchmarks show that there is a large spread especially with embodied carbon targets for new constructions. As the RIBA 2030 climate challenge states that buildings should be aspiring to 2030 levels today [11], and this value gives an average between LETI 2020 and 2030 targets, this benchmark is used for the analysis. Further sensitivity analysis for this assumption will be included within Chapter 5.

An additional $35kgCO_2e/m^2$ will be included to account for the demolition of the original building [12]. As the provided benchmarks have a system boundary of A1 - C4 [2], it is assumed that the potential impacts of maintenance, material replacements and any potential material decarbonisation are included within each benchmark.

Table 4.4: Different new construction embodied carbon and operational energy benchmarks from different organisations. Highlighted in yellow are the targets used as a benchmark in this scenario.

Source	Target type	Embodied carbon A1-C4 $kgCO_2e/m^2$	Operational carbon $kwh/m^2.yr$
RIBA 2030 climate challenge [11]	Business as Usual	1000	130
	2020	675	70 (55 for primary)
	2030	540	60 (45 for primary)
LETI carbon targets [272, 21]	Band C - 2020	675	65
	Band A - No target year	400	65
	Band A +	260	65
London WLCA Guidance [273]	Benchmark	1000	N/A
	Aspirational	675	N/A

4.4.4.3 Future modelled scenario

A typical future scenario has been defined with key scenario inputs of:

- **Lifespan** - A 30 year lifespan has been chosen as this is when 2050 net zero targets should be met. Also, 80% of existing buildings are predicted to still be standing by 2050 [56].
- **Electricity decarbonisation** - This scenario models a *Falling short* decarbonisation rate as defined by the national grid [13]. This is due to evidence of decarbonisation in this sector [274] - *See Appendix C, Section C.5 for further details*.
- **Material decarbonisation** - As with electricity, this scenario assumes some material decarbonisation, predicted by existing literature to be a 'business as usual' deployment of decarbonisation strategies - *See Appendix C, Section C.5 for further details*.

Sensitivity analysis of these assumptions is explored in Chapter 5.

4.5 Results and Discussion

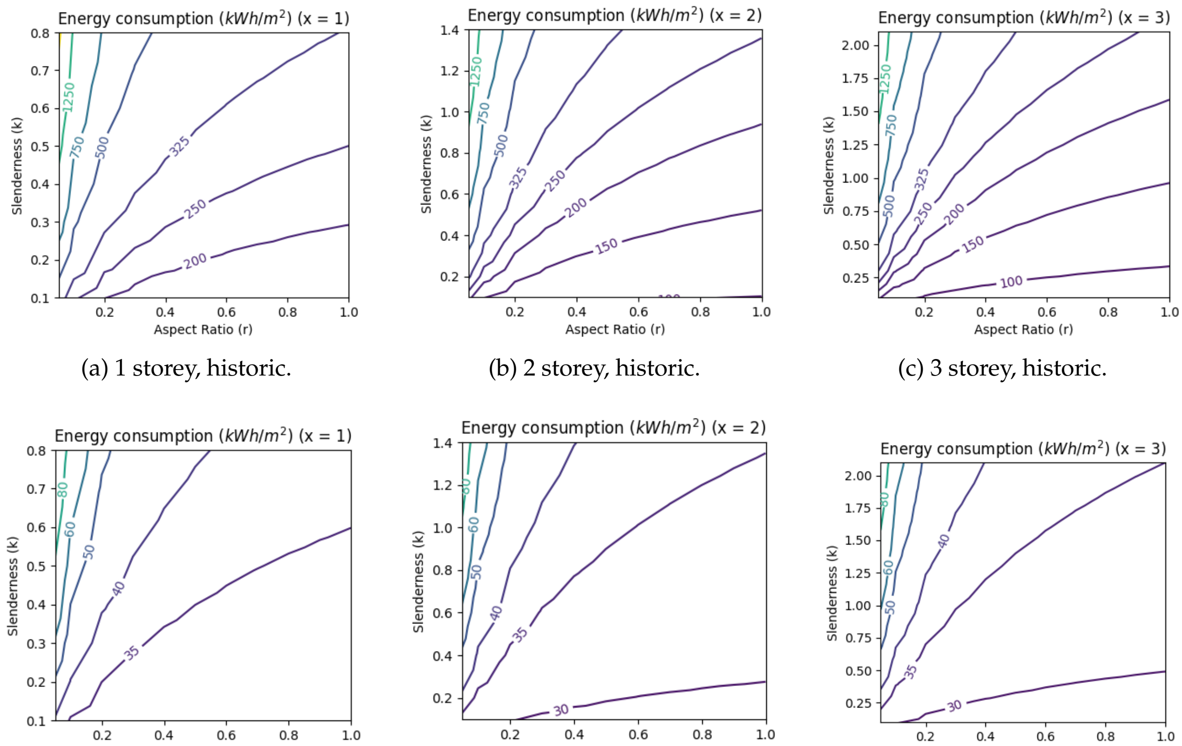
4.5.1 The impact of building form on retrofit potential

Within this section, the results of the analytical expression are explored for only thermal energy consumption, to understand the impact of building form on energy efficiency.

Equation 4.34 demonstrates that energy consumption increases as slenderness increases and aspect ratio decreases. This is logical as those buildings with a larger slenderness will have a larger wall area to heat the same floor area and those with a smaller aspect ratio will have a larger exposed perimeter.

Figure 4.10 shows the analytical expression of thermal energy consumption, plotted as a contour for two extremes of building performance level. Figures 4.10a - 4.10c show the analytical expression for 1, 2, and 3 storey buildings modelled as a typical Pre 1919 (Historical) building. Figures 4.10d - 4.10f model Enerphit performance level for thermal energy consumption. These results demonstrate that energy saving potential changes for different building forms. Enerphit buildings have a smaller range in relative energy consumption compared to Historic. Therefore, the total energy consumption of Enerphit buildings is less influenced by building form. This implies that retrofit of those historic buildings with an inefficient form will provide larger energy savings than those with efficient forms.

These results have implications for targeting retrofit within the non-residential building stock. In fact, review of the literature within Chapter 2 showed that prioritisation of the worst per-



(a) 1 storey, historic. (b) 2 storey, historic. (c) 3 storey, historic.

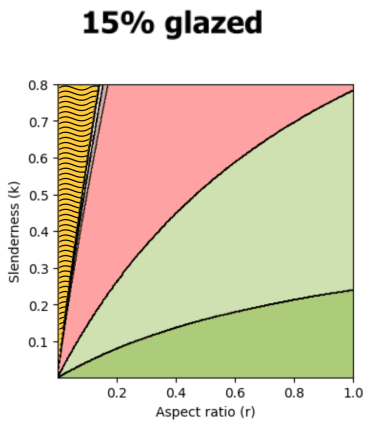
(d) 1 storey, Enerphit. (e) 2 storey, Enerphit. (f) 3 storey, Enerphit.

Figure 4.10: A contour plot to show the distribution of thermal energy consumption [kWh/m^2] in relation to Slenderness and Aspect ratio. Energy performance levels have been modelled as a typical Historic building and at Enerphit levels. **For different number of storeys typical ranges in slenderness are shown as found to be typical for existing buildings.**

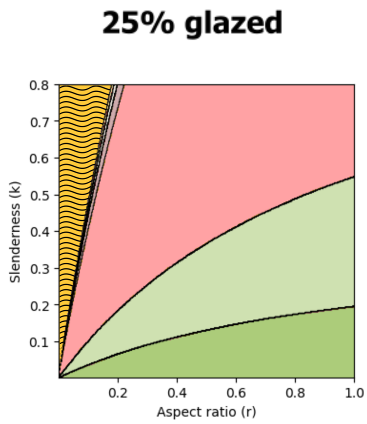
forming residential buildings is important for meeting carbon budgets within Ireland [89]. Alongside this, with the need for immediate carbon emission reductions [40], from an at scale perspective, prioritising retrofitting the most inefficient forms first could be beneficial to meeting carbon targets. Section 4.3 discusses the open design practises common in the early 20th century. This may imply that a reasonable proportion the least efficient building forms were built before energy efficiency regulations and therefore have a high potential for improvements and prioritisation. In Chapter 5, Section 5.3.4 the impact of this prioritisation will be explored.

4.5.2 The impact of building form on intervention decisions

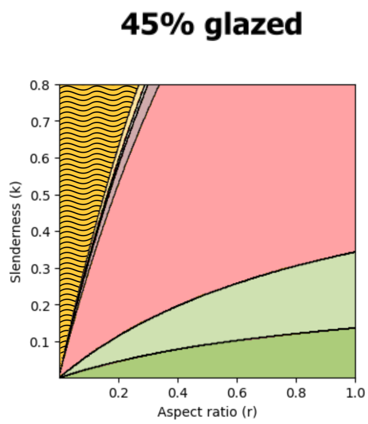
In this section, different typical intervention scenarios for existing buildings are explored from a whole life carbon perspective. The impact of building form on intervention decisions is demonstrated in Figures 4.11d - 4.11e. More efficient forms with a low slenderness and high aspect ratio, require less intervention to achieve low carbon emissions. This is because the



(d) Whole life carbon modelling applied to a one storey (x =1), historic primary school building with a 15% glazing ratio.



(e) Whole life carbon modelling applied to a one storey (x =1), historic primary school building with a 25% glazing ratio.



(f) Whole life carbon modelling applied to a one storey (x =1), historic primary school building with a 45% glazing ratio.

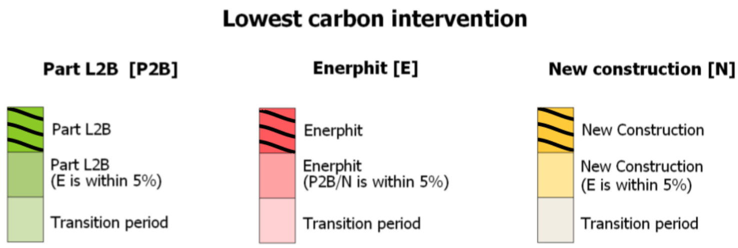


Figure 4.11: Heat maps illustrating the lowest whole-life carbon future scenarios for buildings, for different combinations of slenderness and aspect ratio. Different colours refer to each potential intervention scenarios. The **transition period** shows areas where the results are impacted by simplifications to the analytical expression. In reality, this period also shows areas where the difference in carbon emissions between Enerphit and Part L2B is very small, on average only 2.8 - 5.5 $kgCO_2e/m^2$, similar to the within 5% results. All modelling is undertaken over a 30 year period.

increased efficiency of Enerphit causes less energy savings proportionally in the already efficient forms, and the higher embodied carbon impact due to larger insulation thickness and the requirements for MVHR causes higher overall carbon emissions from this model.

The higher glazing ratio model is shown to have a larger range of building forms where Enerphit is preferable. This is because higher glazing ratios have larger heating energy consumption, due to the less efficient U-values of glass and so the more intrusive intervention scenarios have the lowest carbon emissions.

The importance of embodied carbon modelling is shown as new construction scenario is only preferable in the highly inefficient buildings, despite the modelled new construction being highly operationally efficient.

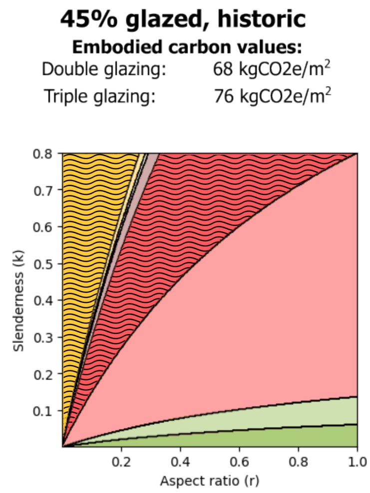
The difference between Enerphit and Part L2B whole life carbon are shown to be within 5% percentage difference of each for the vast majority of different building forms. This is because while the values of C_{oc} are lower for Enerphit, the values of C_{ec} are higher which balances out within the analytical expression.

Figure 4.11 show a large area of building forms within the transition period, particularly between Part L2B and Enerphit. This period defines an area where the inaccuracies in the heating energy model impact retrofit decision. Figure 4.11f where 45% is glazed is shown to have a much smaller transition period which is because the difference between energy consumption for Part L2B and Enerphit is higher at a higher glazing ratio. In fact, within the transition period the difference in whole life carbon between the Part L2B and Enerphit results is on average only 2.8 - 5.5 $kgCO_2e/m^2$ depending on the glazing ratio with a maximum percentage difference of 0.7 - 1.1%. With these results being so similar, it shows why any small changes to the heating energy consumption would impact the overall intervention decision compared to the degree-days model.

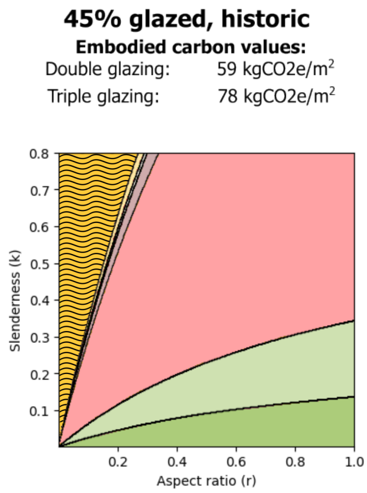
To explore the transition period further, Figures 4.12d - 4.12f show different scenarios designed to show the different extremes of the transition period:

- Figure 4.12d - Historic building, which is 45% glazed, where the embodied carbon factor for glass, ξ_{glass}, has been taken from a different source [275], see Appendix C.4.2. This increases the whole life improvements from undertaking more efficient glazing as the difference between triple and double glazing embodied carbon is smaller.
- Figure4.12e - Historic building, 45% glazed - as in Figure 4.11f.
- Figure 4.12f - Post war building, 45% glazed where external wall insulation is modelled to achieve a U-value of 0.15 for Enerphit and 0.3 for Part L2B. The higher embodied carbon impact of external wall compared to internal wall insulation for a limited operational improvement decreases the whole life improvements within Enerphit modelling.

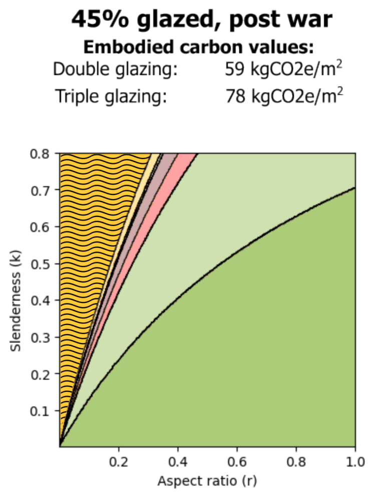
Figure 4.12d shows that where there is a higher contrast in value of C_1, and therefore a larger difference in whole life carbon, the transition period is relatively small. The post war model has a very small difference in C_1 and therefore the transition period is much larger. Results show that increasing the difference in C_1 between scenarios increases the influence of building form. Chapter 3 demonstrates that heating energy changes considerably year on year due to differences in weather and behaviour. Therefore, what we can interpret from the transition period is an area where the differences between the two scenarios is so small that the uncertainty in the heating energy model does not allow for the optimal retrofit decision to be found. Another interpretation could be that the differences are so small, the cheapest retrofit would be the most acceptable scenario within this period.



(d) Whole life carbon modelling applied to a one storey (x = 1), historic primary school building. 45% glazed with glazing data sourced from [275].



(e) Whole life carbon modelling applied to a one storey (x = 1), historic primary school building. 45% glazed with glazing data sourced from [257, 258].



(f) Whole life carbon modelling applied to a one storey (x = 1), post war primary school building. 45% glazed with glazing data sourced from [257, 258].

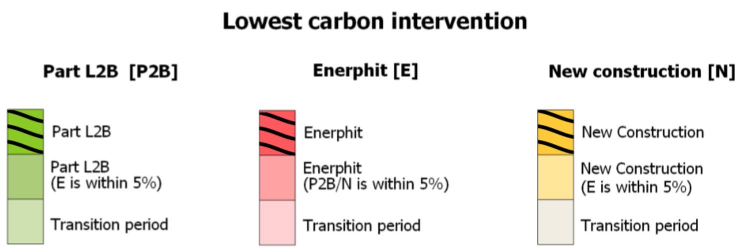


Figure 4.12: Heat maps illustrating the lowest whole-life carbon future scenarios for buildings, for different combinations of slenderness and aspect ratio. Different colours refer to each potential intervention scenarios. All modelling is undertaken over a 30 year period. The transition period shows areas where the results are impacted by simplifications to the analytical expression.

Figure 4.12f shows that the majority of building forms has Part L2B retrofit as the lowest carbon option when modelling a post war building with external insulation. This is likely because the U-value of the Enerphit model is now improved to 0.15W/m^2K compared to 0.3W/m^2K for Part L2B. When differences between the two scenarios are as small as has been demonstrated (within 5% of each other) small changes to the input data can make a large difference to the shape of the heat map. Past research has found optimal U-values, from a whole life carbon perspective, are lower than Enerphit levels, at approximately 0.105 W/m^2K for a similar baseline U-value [276]. However, the value of 0.105 W/m^2K uses glass wool for the insulation material which has considerably lower embodied carbon than the EPS material modelled here, see Appendix D.4. In this thesis, glass wool was not found to be appropriate for external insulation systems and therefore EPS is modelled. This demonstrates the importance of considering material choice when undertaking retrofit comparisons, as this can impact the required thickness of materials.

These results also show that on the whole, the difference between Part L2B and Enerphit results are very small due to the additional embodied carbon cost of installing Enerphit. This further highlights the importance of incorporating embodied carbon within modelling results.

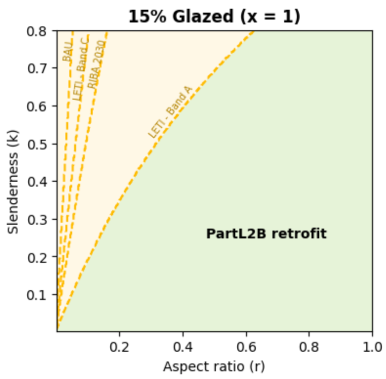
4.5.2.1 Constraints of modelled scenarios

The previous sections have demonstrated that the lowest carbon intervention for typical set of retrofit scenarios is influenced by building form.

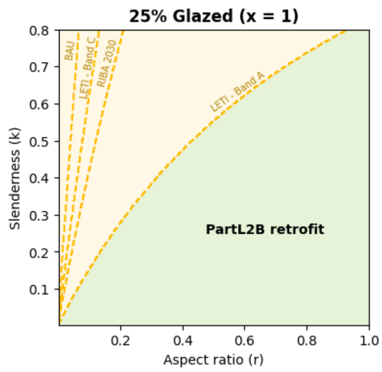
However, the form of Equation 4.42 implies that if we were to find a retrofit scenario that minimises all the constants within the analytical expression (C_1, C_2, and C_3), compared to all other possible scenarios, this would be the optimal intervention independent of building form.

Finding this optimal scenario becomes more complex when one considers the impact of increased quality of glazing replacements and insulation on not only fabric efficiency but infiltration rate. The infiltration rate in turn informs whether mechanical ventilation should or should not be installed to ensure safe levels of fresh air. For example, Passivhaus certified glazing which achieves very low U-values is also shown to achieve higher levels of airtightness than typical glazing [277]. Mechanical ventilation has increased electricity consumption and a high embodied carbon cost which would increase the value of C3. Therefore, finding the optimal intervention scenario requires an understanding of the relationship between airtightness and potential mechanical ventilation requirements which is a highly complex as it requires quantification of each retrofit measure's impact on the total infiltration rate. This is therefore a limitation of this study which would be an interesting area of future work.

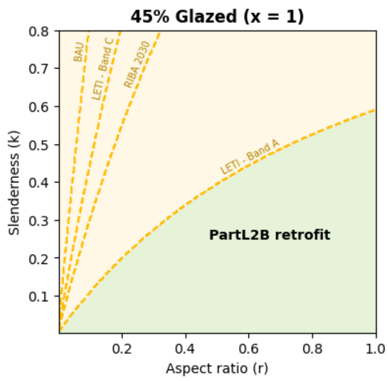
As new construction is not constrained by the form of the existing building, the comparison between demolition and refurbishment will always be influenced by form. Therefore even with the current limitations discussed in this chapter, the developed parametric model provides a highly useful tool for comparison of typical retrofit scenarios against new construction models.



(a) Whole life carbon modelling applied to historic primary school building that is one storey (x = 1) and 15% glazed.



(b) Whole life carbon modelling applied to historic primary school building that is one storey (x = 1) and 25% glazed.



(c) Whole life carbon modelling applied to historic primary school building that is one storey (x = 1) and 45% glazed.

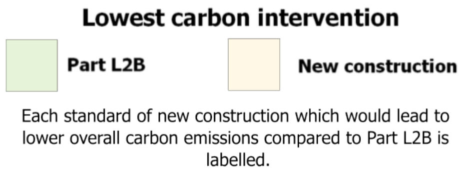


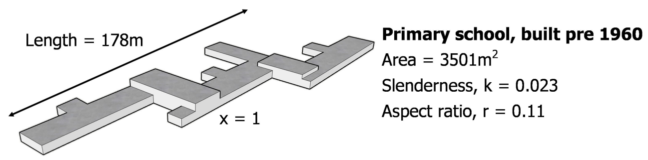
Figure 4.13: Heat maps illustrating the lowest whole-life carbon future scenarios for buildings, for different combinations of slenderness and aspect ratio. Different colours refer to each potential intervention scenarios. The modelled scenarios show comparison of retrofit to Part L2B standard to different new construction benchmarks (See Table 4.4). All modelling is undertaken over a 30 year period.

Figures 4.13a - 4.13c provide a demonstration of the tool where Part L2B retrofit has been compared to different levels of new construction standards to show what would need to be achieved to justify demolition and new construction of different building forms. It should be noted that RIBA 2030, $540kgCO_2e/m^2$, is still an aspirational embodied carbon target within industry [11]. This further highlights the small proportion of building forms within the modelled scenario for which demolition can be justified, despite a very high operational efficiency achieved by all new construction models. LETI Band A embodied carbon standard is currently only a target that is hoped to be achieved in the future [272], and shows that if lower upfront embodied carbon of new construction is achieved building form becomes more pivotal within the decision making process.

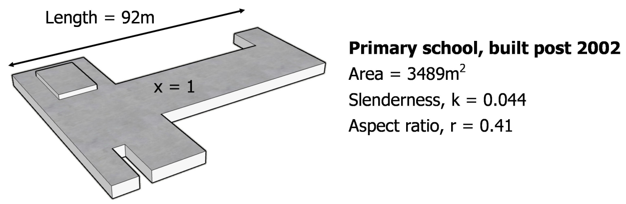
Potential future work could investigate the balance between retrofit and new construction, but using multi-objective optimisation in order to include more factors such as economic cost. For example, highly inefficient forms may also benefit from higher standards of intervention from a cost perspective compared to more efficient forms.

4.5.3 Comparative whole-life carbon analysis of two contrasting school case studies

This section aims to provide whole life carbon comparisons of two contrasting primary school case studies. One construction was built between 1936 and 1955, before thermal efficiency regulations were first put in place. The second was constructed after 2002, when airtightness guidelines had been introduced and the U-value of all elements is limited. Therefore this section aims to demonstrate how energy efficiency and whole life carbon of retrofit varies between different standards of existing construction.



(a) Case study of an uninsulated primary school.



(b) Case study of an insulated primary school.

Figure 4.14: Two example primary school case studies, built in different eras. Both schools are one storey (x = 1) and have a similar plan area according to metered data [10]. Verisk polygons [3] have been used to estimate the length of each building. Key geometry is then calculated using methods shown in Figure 4.2.

Figure 4.14 shows both case study buildings and their respective geometries. The drivers of building form within each construction era is discussed in Section 4.3. Figure 4.14a shows that the older construction has a smaller building depth, likely due to the focus on natural ventilation and lighting within this era. The more modern construction has a more compact form, likely for economic efficiency and the balance between using natural and artificial lighting as discussed in Section 4.3.

Using methods outlined in this Chapter, retrofit modelling is applied to both these buildings. Retrofit is to Part L2B standard of fabric efficiency combined with the replacement of existing gas boilers with air source heat pumps. The whole life carbon breakdown of results, over a 30 year period is shown in Figure 4.15.

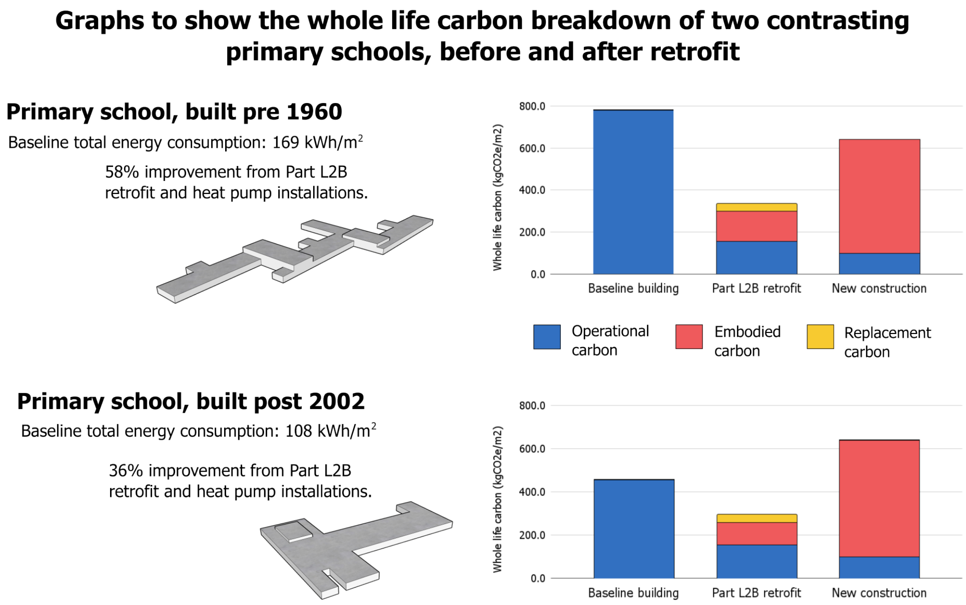


Figure 4.15: Two contrasting whole life carbon school case studies. Modelling has been applied to both schools over a 30 year period. Modelled baseline building emissions are compared to Part L2B retrofit combined with heat pump installation. A further comparison to demolition and new construction, built to RIBA 2030 standards [11], is included. Baseline fabric efficiency data is taken from Table 3.1 which includes the assumption that glazing and roof elements have a maximum lifespan of 30 years. The falling short decarbonisation scenario is modelled (See Appendix C.5).

Figure 4.15 shows that considerable energy efficiency improvements are achieved from retrofit of both the new and old primary school. Even where only minimal improvements have been made to the fabric efficiency, as with the post 2002 construction, heat pumps are able to achieve a higher mechanical efficiency than the modelled gas boiler (where $\eta = 0.8$). Further improvements to operational carbon are achieved compared to energy efficiency which highlights the importance of future electric grid decarbonisation.

A lower embodied carbon input is required to achieve the same Part L2B efficiency within the newer compared to older case study. A large contributor to this, is the fact that the U-value of the floor already achieves Part L2B standards of efficiency. Therefore, there is no need for new insulation and screed within this element.

Making comparisons to demolition and new construction, highlights the importance of considering embodied emissions. Despite lower operational carbon compared to both retrofitted schools, it is not preferable to demolish either. Further, despite a continued reliance on fossil-fuel heating and hot water systems, over a 30 year period, the baseline post 2002 construction still has lower whole life carbon compared to the modelled new construction.

4.5.4 Model validation - whole life carbon decision making

To understand how well we can apply retrofit modelling at scale, retrofit modelling is applied to the case studies defined in Chapter 3. Figure 4.16 shows a comparison of using baseline metered or modelled energy consumption and the impact of this on retrofit decisions. The metered or modelled baseline energy/carbon consumption is compared to the predicted energy/carbon consumption if Part L2B retrofit were to be installed. Figure 4.16 shows where the lowest carbon or energy intervention, for all 234 case studies, would be the same or different if we used modelled or metered baseline energy consumption. A simplified assumption is made at this stage for embodied carbon calculations that the entire existing system would be replaced even if the building already achieves a certain fabric efficiency.

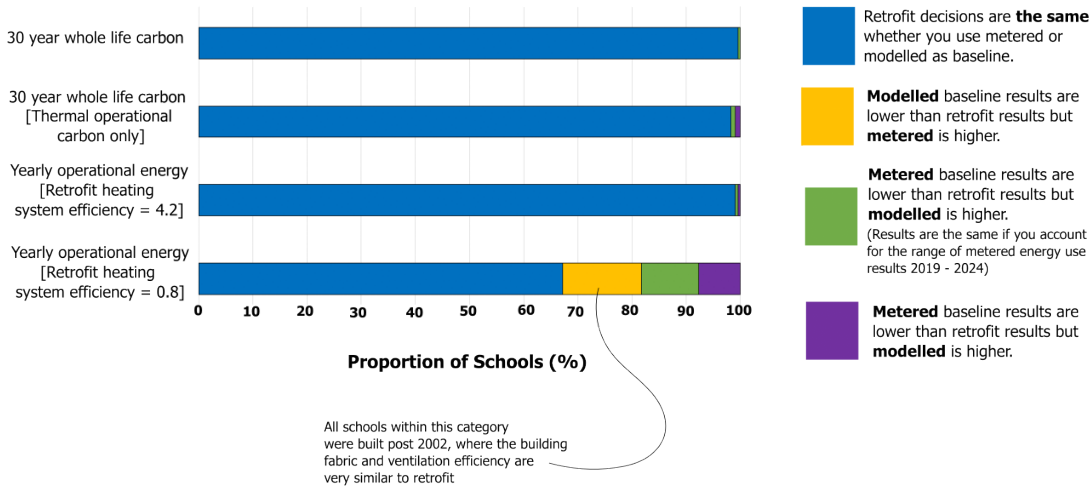


Figure 4.16: A comparison between metered and modelled baseline energy consumption with retrofit decisions. Part L2B retrofit modelling is compared to both baseline metered and modelled results. The lowest carbon/energy decision when comparing baseline and Part L2B results is then noted as the retrofit decision. Blue indicates where the retrofit decision remains the same if baseline modelled instead of metered energy consumption is used. Other colours highlight discrepancies in results.

Comparing baseline to post-retrofit energy consumption shows that 32% of case studies would have a different lowest energy solution when using either metered or modelled baseline energy consumption, if gas boilers are retained.

Figure 4.16 shows that 14% of case studies would have no energy improvement from retrofit in comparison to the modelled baseline data but retrofit does cause an improvement if one uses metered baseline data. These case studies are all built recently, when building regulations are equivalent to Part L2B retrofit standards. We have already explored potential reasons why relatively new buildings could have higher energy consumption than predicted by current regulation, in Chapter 3, Section 3.4.2.1, which may be due to differing usage patterns within the building.

Further, it is shown that 18% of results would have an improvement from retrofit if one used modelled data but no improvements if metered data is used. This value is reduced to 8% if we account for the fact that metered energy use varies annually. Both these points show how when modelling we need sensitivity analysis on different usage patterns, such as set point temperature, as this varies between schools. Not only this, but variation in energy consumption occurs even within the same school, with large changes to metered energy consumption occurring annually. Retrofitting of the school could also change occupant behaviour as those schools may now afford to heat their buildings to higher temperatures or for longer periods.

The disparities in results between metered and modelled data reduces if we account for the use of heat pumps instead of a gas boiler. In this body of work we want to model the move away from fossil fuels by using an air source heat pump. Therefore, the improved efficiency of a heat pump, from 0.8 to 4.25, makes retrofit more consistently appealing even in schools where metered energy consumption is much lower than expected. Despite these efficiency improvements, two school case studies are still modelled as having higher yearly energy consumption post-retrofit compared to the pre-retrofit metered data. This is reduced to just one school if we account for the fact that metered energy consumption varies year by year.

Whole life carbon results, accounting for thermal energy only, show that 2% of schools would have different retrofit recommendations if one used modelled instead of metered baseline thermal energy consumption. This value has increased from comparing just operational carbon which is expected as we have not yet accounted for the fact that higher efficiency buildings would require a lower embodied carbon input during retrofit implying that whole life savings are smaller than is fair.

This is reduced to two schools if we account for variation in energy consumption. As both of these two schools have a limited range in metered energy consumption data, only one value available metered data point, it further highlights why sensitivity analysis on usage is required.

Overall, these results show that for the vast majority of schools, the whole life carbon approach developed here can be used to model retrofit implications. If we assume that post-retrofit modelling is accurate then the lowest carbon solution is correctly identified using the developed energy modelling approach for the majority of schools, especially from a whole life carbon perspective. To undertake this comparison we must assume post occupancy retrofit follows a sensible usage pattern and is installed to the standard it is designed to.

4.6 Conclusions and limitations

This chapter has developed an analytical expression to quantify the parametric contribution of building form to both energy consumption and the whole life carbon of retrofit buildings. By expressing the contribution of form as an analytical expression, rather than a single value, results can account for the differences in performance of each building element - floors, walls, windows and roofs. It is shown that buildings with a high slenderness combined with a low aspect ratio are less efficient in terms of both energy efficiency and the level of intervention required to achieve the lowest carbon emissions. Verification against the degree-days model shows that the analytical expression can be used to express energy consumption to the same extent as thermal physics models.

Returning to the original research question, What influence does building form have on the lowest whole life carbon intervention for existing buildings?, there are two ways in which this can be answered. Firstly, results show a larger variation in energy consumption between building forms when modelling buildings of a lower fabric efficiency compared to those which have been retrofit to a higher standard. This has potential consequences for applications at scale, as prioritisation of less efficient building forms could allow for more immediate reductions in carbon emissions. Currently, the national grid is emitting higher levels of carbon than predicted in the future, decarbonising the least efficient buildings first may allow for easier transition to net zero and assist in meeting carbon budgets. This finding is further explored within Chapter 5 where the pathways required to meet a derived carbon budget for English schools are developed.

Secondly, it is shown that different building forms require different levels of intervention to provide the lowest whole life carbon emissions, with the most extremely inefficient forms benefiting from demolition and new construction. This is also the case when comparing typical retrofit scenarios, as those of inefficient form require a higher standard of retrofit to achieve the lowest whole life carbon emissions over the studied 30 year period.

However, there are similarities in results for the two compared retrofit scenarios, Part L2B and Enerphit, with the majority of forms having a less than 5% difference in whole life carbon between them. This further highlights the need to include embodied carbon within future assessments as the higher embodied impact of the Enerphit model clearly impacts total carbon emissions despite being more efficient operationally. It may be the case that, if an optimal combination of retrofit measures can be found which minimises all constants within the analytical expression, retrofit decisions would be independent of form – an exploration which is constrained to future work.

As new construction is not constrained by the existing form of the building, the differences between whole life carbon of new construction and retrofit are more pronounced making the analytical expression a potentially highly useful tool in future early stage decision making. This tool provides a comprehensive analysis of how the demolition versus refurbishment comparison changes from a whole life perspective for key building characteristics. With such as small range of building forms where current aspirational new construction targets, $540kgCO_2e/m^2$, would achieve lower whole life carbon emissions, demolition of our existing stock cannot be considered trivial within the future decision making process.

Various verifications of the chosen methods have been undertaken in this chapter. It is demonstrated in Section 4.2 that assuming rectangular form is acceptable for large amounts of the building stock. Further, for the 234 assessed case studies, whole life carbon decisions are shown not to change if metered or modelled baseline energy consumption is used. However, if working at the individual building level those forms with large levels of geometric complexity, such as multiple courtyards may not be appropriate which is a limitation to the study.

Another limitation includes the simplifications made when estimating the constants (C_1, C_2 and C_3) within the analytical expression. At very high standards of fabric efficiency, the relative impacts of internal heat gains are increased meaning that assuming a constant internal gains factor is less appropriate. Where the difference between each modelled scenario is small, as is the case for Part L2B and Enerphit comparisons, this can impact the model accuracy for a large proportion of building forms. Future work may benefit from a more precise estimation of these constants. However, it is shown that the average error when applied to the actual UK school stock is small compared to the degree-days model at all standards of fabric efficiency. The impact of these simplifications are also shown to be reduced in scenarios where building form is more influential, such as at higher glazing ratios or when comparing to demolition and new construction.

In conclusion, this chapter has presented a novel quantification of the contribution of building form to both energy consumption and whole life carbon decision making. The results reveal that those buildings of inefficient form benefit from higher levels of intervention to achieve the lowest carbon emissions. Prioritisation of retrofit to buildings with inefficient form could also help reduce carbon emissions of the whole stock more effectively, which will be explored further in the following chapter.

Chapter 5

The impact of retrofit at scale on the English school stock

5.1 Introduction

In Chapter 4 we saw the importance of considering both building form and whole life carbon when making intervention decisions for our existing stock. The impact of considering both of these factors will now be quantified **at scale** to understand what is required to limit the impacts of global warming and meet carbon targets - quantified in the form of a carbon budget. The scope of this case study includes all English primary, secondary schools and colleges.

This chapter therefore aims to answer the following research question:

- ***What intervention is required to the existing building stock when considering a stock's carbon budget?***

The English school stock contains a large area of non-residential stock whose funding is controlled by the government and local authorities [64]. Therefore, as discussed further in Section 2.4, schools are a potentially highly influential starting point for quantifying the whole life carbon implications when retrofitting non-residential stock.

As previously demonstrated in Chapter 3, understanding stock at scale, is a challenge as it requires large amounts of data to quantify key characteristics of each building in sufficient detail. Chapter 2 shows one commonly adopted bottom-up method, which has been applied to

English schools in the past, is the creation of archetypes, which are individual building models that can be used to represent large amounts of stock. For example, the creation of 168 school archetype models were used to represent 9551 primary schools in England, with results found to be in agreement with available metered consumption data [249]. However, Chapter 4 has demonstrated the importance of building form within future decision making, something which cannot be considered fully using the archetype approach due to the assumption of a constant geometry within each building archetype. Other work, has generated individual building geometries, for understanding the energy consumption and internal environment, using GIS-based data [216]. This chapter aims to also take a one-by-one approach for whole life carbon modelling, using the methods developed throughout Chapters 3 and 4, assessing both the operational and embodied carbon impacts of retrofit at scale. Devised carbon budgets are used to understand how to limit levels of global warming to acceptable levels by 2050 [40, 278, 279].

The benefits of retrofitting poorly performing buildings first has been demonstrated at scale for residential stock [148, 89] and building portfolios [161]. This chapter aims to continue this work, specifically for the school stock. As non-residential buildings have been shown to have a higher variation in building form we will also quantify the impact of prioritising retrofit of the most inefficient building forms, which have been demonstrated in Chapter 4 to impact retrofit decisions. With this in mind this chapter also aims to provide further answers to the research question - ***What influence does building form have on the lowest whole life carbon intervention for existing buildings?***

It has also been demonstrated that decarbonisation of both electricity [147, 202, 89, 109, 153, 145] and materials [89] is vital to meet government targets. This chapter will include these key sensitivities with three modelled decarbonisation scenarios. Alongside this, changes to post retrofit occupancy behaviour will also be modelled to provide sensitivity analysis. Occupancy patterns have been shown in Chapter 3 to vary widely between schools, with a tendency within the studied schools for newer, more thermally efficient, buildings to have higher than expected energy consumption. Therefore, it is important to understand the potential impact of changes to occupancy, post retrofit, on the total thermal load to the space.

This chapter is structured as follows. First, the study methodology will be outlined, including data collection and modelling methods alongside how the carbon budget was calculated for the English school stock. Following this, results will be presented for baseline operational carbon emissions and post retrofit whole life emissions, with an aim to understand what needs to be done to meet the derived carbon budget. The carbon payback period of the modelled retrofit scenarios will also be provided alongside a comparison against new construction benchmarks and the implications of poor building form on this comparison. These results will be followed by concluding remarks and study limitations.

5.2 Methodology

The following section outlines the key methods undertaken to apply whole life carbon retrofit modelling at scale. In this case we have modelled all English primary, secondary schools and colleges - a total of 20,109 properties according to the school condition survey [15].

Figure 5.1 shows the methodology for assessing the whole life carbon impact of retrofit on the English school stock, including the key scenarios modelled. The next section outlines how the data which is inputted into this model is collected. Further, a description of calculation techniques such as energy modelling and carbon budget calculations is outlined. Finally, further details are provided on the key modelled scenarios and sensitivity analysis undertaken.

5.2.1 English school data collection

The focus of this chapter is primary, secondary schools and colleges which represent 91% of total building floor area within the UK government's school estate [15]. Other properties such as all-through and special schools, pupil referral units, nurseries and alternative provision would likely have different occupancy patterns and potentially retrofit needs which are not accounted for. Therefore, these schools are removed and removal of this is reflected in the carbon budget calculations. For similar reasons, independent schools are also excluded because they have different occupancy patterns such as residential spaces.

Figure 5.2 shows the key methodology stages within the data collection process. As Verisk does not distinguish between different educational stock typologies, the HM Government school database was used which provides the Easting and Northing of every primary, secondary school and college. These coordinates were used to extract relevant schools from Verisk UKBuildings. All educational buildings within the defined search radius of each Easting and

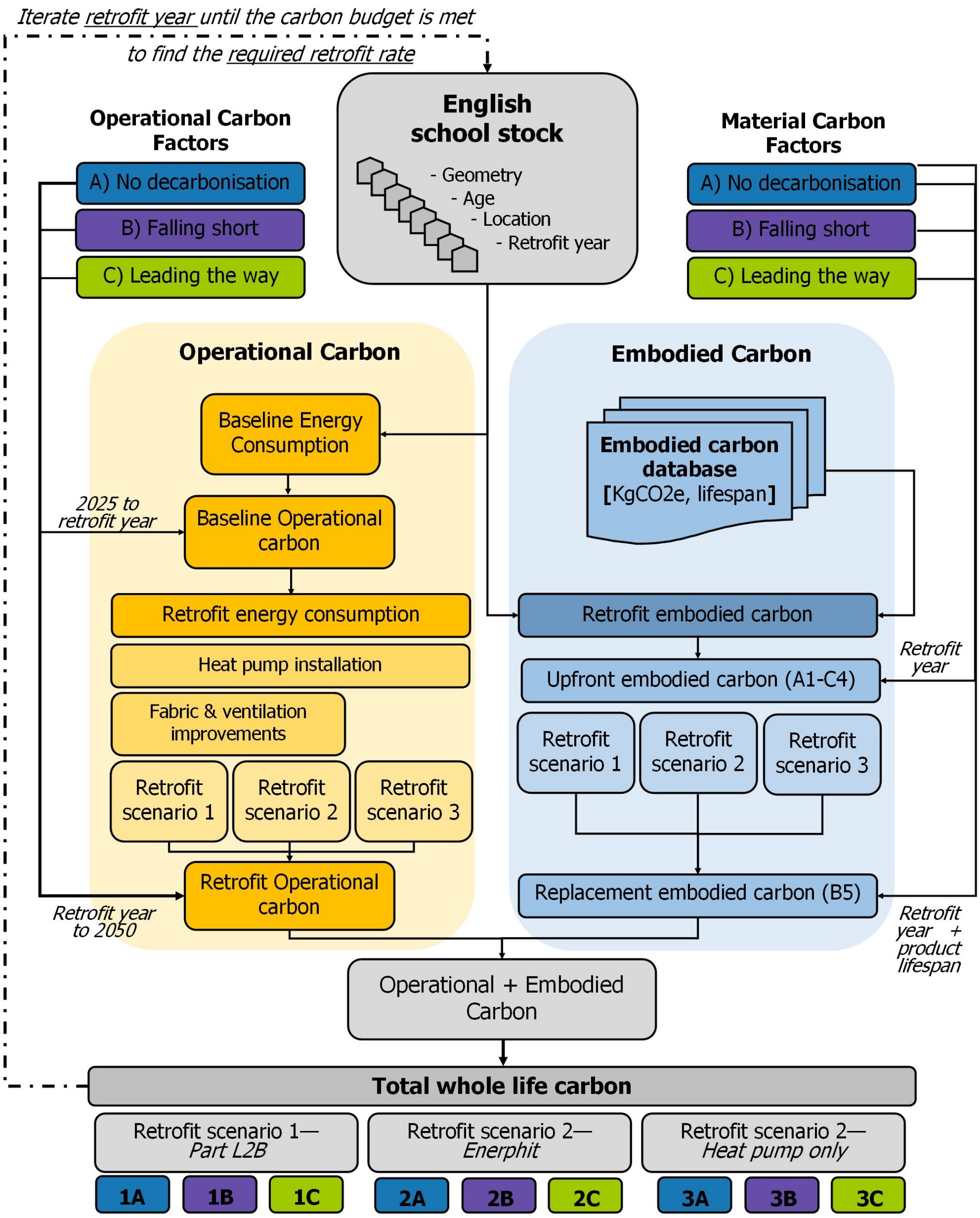


Figure 5.1: Flow chart to show the methodology for whole life carbon retrofit modelling of the English school stock. The three retrofit scenarios all involve replacement of existing systems with an air source heat pump but vary in the level of fabric improvements and efficiency. Building geometry, age and location is used to calculated total operational carbon both before and after retrofit depending on the year retrofit is modelled to occur. Operational carbon is then added to the modelled embodied carbon of retrofit installations. Three different decarbonisation scenarios are modelled for each retrofit scenario which impacts the annual operational carbon emissions of electricity as well as the total embodied carbon of retrofit when it is installed.

Northing point are retained. The Easting and Northing values are also used to define the building location and therefore outdoor temperature (See Table B.5).

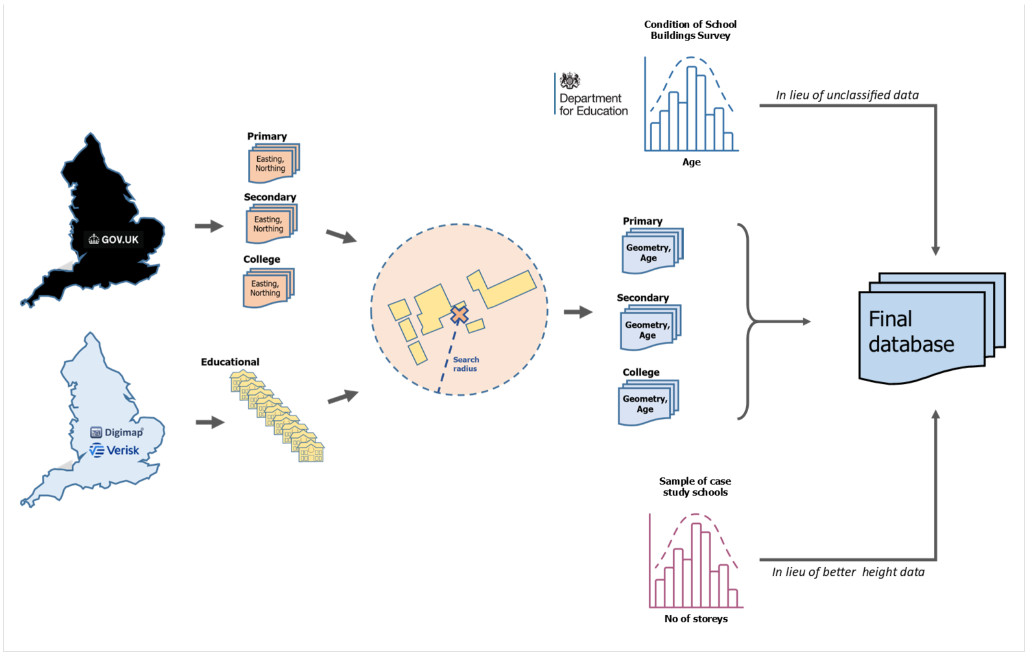


Figure 5.2: Flow chart to show the data collection process for English primary, secondary schools and colleges.

These search radii are based on typical outdoor area guidelines for each typology [17] - 85m for Primary, 175m for Secondary and 85m for colleges. Potential overlap is dealt with, with any duplicates identified and only one retained, designated to the school with the Easting/Northing which is closest to the building.

This left a total of 18702 schools, which is lower than the predicted value of 20,109 properties according to the school condition survey [15]. However when building floor area is calculated, Appendix D.1 shows that the methods undertaken match the same total floor area of all schools within 5% of the school condition survey's predicted total floor area. Possible reasons for this include a slight overestimation of the number of storeys for each school or that multiple schools have been merged into one property. Therefore, when retrofit rates are explored, see Section 5.2.4.1, the total number of schools may in reality be slightly larger than predicted due to the fact that multiple schools have been merged.

As explored in Appendix D.1 Verisk height data will not be used due to a consistent overestimation of heights. Using height modelled from an archetype number of storeys has been deemed most accurate. A distribution of the archetype number of storeys has been applied to the school stock data. For example, over 80% of primary school floor area within case study data is one storey tall, so the same proportion of English primary schools will be modelled as one storey tall, see Appendix D.1 for details. One limitation of this method, especially for secondary schools and colleges whose height varies more than primary, is that building form may not be reflective of actual stock.

Building age is used to define the baseline performance of the building, a method established in past residential [140] and educational building [230] research and shown to be the reflective of building U-Value for non-residential buildings [46] due to the incremental improvements to building regulations over past years. One study into metered consumption of 6 Finnish schools showed considerably higher district heating costs for the oldest unrefurbished building compared to the newer or refurbished buildings [280]. In another study of UK school energy consumption, building age alongside exposure ratio were found to be the two most prominent factors influencing thermal energy use in London schools [215]. When exploring energy consumption patterns within 150 school case studies, thermal energy consumption was found on average to be lower in modern compared to older constructions [214] .

It is also shown in Chapter 3, that using building age to define performance allows for an aggregated baseline energy consumption close to zero for the 234 school case studies.

Appendix D.1 shows that a proportion of the school polygons have unclassified age within Verisk. Therefore, Figure 5.2 shows that a distribution will be applied across any unclassified data based on the proportion of actual ages according to the school condition survey [15]. Though we can understand the aggregated impacts of stock, there are limitations when trying to draw conclusions regarding the whole life carbon impact of retrofit for individual buildings.

This chapter **does not account for the potential additional floor area requirements from schools from population growth as well as carbon emissions related to school maintenance** - with the exception of replacing retrofit measures. Whether there would be significant additional floor area requirements is called into question as the total number of children is predicted to fall by 2045 due to reducing birth rates within the country [281]. However, not accounting for the required maintenance carbon emissions, implies that the modelled baseline operational carbon is an absolute minimum value and in reality would be higher due to the possible required repairs or structural remediation to the stock.

5.2.2 Whole life carbon modelling

Energy modelling will adopt the same methods and inputs outlined within Chapter 3, see Section 3.2. Operational carbon is modelled using the operational carbon factor for each year within the study period of 2025 - 2050. This assumes gas for pre-retrofit modelling, which is a simplification as 12-14% of school's heating systems are found to run on different fuel sources such as biomass, electricity, or oil [218]. Therefore, this assumption may lead to a slight overestimation in baseline operational carbon emissions.

Embodied carbon is split into upfront and replacement emissions. However, as a whole life carbon assessment is undertaken, stages A1 - C4 [2], end-of-life emissions for each retrofit material are also included. As a simplification, all end-of-life, e.g. disposal, and in-use, e.g. refrigerant leakage, emissions from the initial installation of retrofit are attributed to the upfront category. Those end-of-life and in-use emissions from the replacement of retrofit materials are attributed to the replacement category.

Therefore, the whole life carbon for each school [$kgCO_2e$] can then be modelled as:

$$E_{WLC} = \sum_{2025}^{y} E_{ob} + \sum_{n} E_{e_y} + \sum_{n} E_{r_{y+\iota}} + \sum_{y}^{2050} E_{or} \tag{5.1}$$

where E_{ob} is the baseline operational carbon emissions [$kgCO_2e$], E_{or} the post retrofit operational emissions [$kgCO_2e$] and y the year the building is modelled to be retrofit. E_e [$kgCO_2e$] is the total upfront emissions and E_r [$kgCO_2e$] the total replacement emissions depending on the lifespan, ι of each retrofit element, n. The year, y, in which each school is modelled to be retrofit will impact the upfront embodied carbon due as material decarbonisation is modelled (See Appendix C.5). Material decarbonisation, m, is modelled as a proportion of current embodied emissions where $E_{ey} = E_{e_{2025}} m_y$.

Emissions from overall building demolition will not be included as 2025 - 2050 is taken as the study period rather than the building lifespan. Building geometry is modelled as in Chapter 3, but using the archetype number of storeys to calculate building height. Embodied carbon data and retrofit modelling methods, such as required insulation thickness, can be found in Appendix C, see Section C.4.2. The insulation thickness is dependant on the existing U-value of each element. For example, more modern buildings will require a lower insulation thickness due to an already high building performance. If the U-value of the existing element is lower or the same as the target U-value then no retrofit measure is modelled.

A flow chart of all modelling processes and associated input parameters required to calculate whole life carbon is outlined in Appendix E. This provides additional clarity of where each section of modelling methodology can be found.

These methods are applied to three retrofit scenarios of Part L2B, Enerphit and heat pump only with more details provided in Section 5.2.4.2.

5.2.3 Carbon budget calculations

Two estimates for the carbon budget have been calculated using the Climate Change Committee (CCC) [279] and Tyndall reports [278].

The CCC carbon budget calculation is the recommended reduction in greenhouse gases '*placing the UK decisively on the path to Net Zero by 2050 at the latest, with a trajectory that is consistent with the Paris Agreement [279].*' The UK Government has also set its carbon budget in line with this value [282].

The Tyndall budgets '*present recommended climate change commitments for UK local authority areas that are aligned with the commitments in the United Nations Paris Agreement* [278].' Therefore, though both these budgets have similar goals it is interesting that they have very different results for total recommended carbon emissions. In fact, Table 5.1 shows that the predicted school stock carbon budget is 4 times smaller for the Tyndall budget than the CCC.

The Tyndall budget provides its results in $MtCO_2$ compared to the CCC which accounts for emissions in $MtCO_2e$. Though this does imply a smaller result, currently carbon dioxide accounts for 80% of total greenhouse gas emissions and does not explain why Tyndall is significantly lower [283]. The key reason is likely that the Tyndall interpretation states that developed countries deserve a smaller proportion of the total carbon budget which makes it a more stringent interpretation of what is remaining for the UK [50].

Therefore, these two budgets help to provide a minimum and maximum value to strive for within retrofit modelling.

Calculations to apportion each carbon budget were undertaken using literature to estimate the proportion of total carbon emissions currently taken up by English primary, secondary schools and colleges. Appendix D.2 shows exactly how this was undertaken and Table 5.1 shows how the results of this process.

One limitation of this method for carbon budget assignment is that the CCC and Tyndall budget only account for UK territorial emissions, and therefore do not account for any imported material emissions. As this work models whole life carbon, which likely includes some imported goods this infers that both carbon budgets are underestimated.

Table 5.1: Table to show estimated total carbon budget from 2025 - 2050 for primary, secondary schools and colleges.

Carbon budget: 2025 - 2050 (CCC = $MtCO_2e$, Tyndall = $MtCO_2$)						
Budget type	**UK**	**England**	**Buildings** - embodied and operational	**Public sector**	**Educational stock**	**Primary, secondary schools and colleges**
CCC	4533	3677	920	106	38	**20.8**
Tyndall	1126	917	229	26.4	9.5	**5.2**
References:	[278, 279]	[278]	[1]	[284]	[97]	Appendix D.2

The Department for Levelling Up, Housing & Communities [285] show that 75% of UK construction products used in the UK were manufactured in the UK. Further, the UK exports £8559 million worth of construction materials to other countries [286]. Therefore, the vast majority of material emissions should be included within the UK carbon budget, despite a net positive importation of building materials [286].

It should also be acknowledged that some sectors in the UK may be harder to decarbonise than others, meaning that these sectors by right should be apportioned higher levels of the carbon budget than they currently contribute to. This is another limitation to the method but the calculated values still provide a decent estimation of what should be strived for within the schools sector - especially considering that a minimum and maximum value have been derived to understand the sensitivity of using different values.

5.2.4 Modelled scenarios and sensitivities

5.2.4.1 Prioritisation pathways

The current school rebuilding programme aims to carry out major rebuilding and refurbishing projects at a rate of 50 schools per year over the next 5 - 6 years [287].

The school rebuilding programme will be modelled, assuming retrofit of all 50 schools, alongside three key prioritisation pathways for retrofit:

- **Random** - A random selection of schools will be selected to be retrofit each year.
- **Age of buildings** - The oldest buildings will be retrofit first. A random selection within each age category of a certain floor area (m^2) will be retrofit each year. Within each age category - secondary schools and colleges will be prioritised as these have the highest modelled hot water consumption. Instead of modelling retrofit of an entire school, retrofit is undertaken for a certain floor area (m^2) of polygons. This value is converted to equivalent total number of schools, with the average floor area being $3720m^2$.
- **Age and form of buildings** - Using the analytical expression developed in Chapter 4, the buildings with the highest value in terms of total thermal energy consumption will be retrofit first. A certain floor area (m^2) will be retrofit each year. It is shown in Chapter 4 that the developed analytical expression could have been used to model total whole life carbon emissions to the same extent as the degree-days model, as in Section 4.4.2.1. However, this method was not undertaken and instead the analytical expression will be used to prioritise retrofit to further assess how well it can be used to inform retrofit decisions even when non-rectangular form is modelled.

  Again, instead of modelling retrofit of an entire school, retrofit is undertaken for a certain floor area (m^2) of polygons. This has been converted to equivalent total number of schools, with the average floor area being $3720m^2$.

For each pathway the required rate to meet the 2050 carbon budget will be calculated. By randomly selecting schools, slightly different total carbon emissions will be estimated each time the model is run. Therefore, the model will be run three times for each pathway and the required retrofit rate will be calculated to the nearest 25 schools where the carbon budget is always met.

Additionally, the carbon payback period (to the nearest year) is calculated to show at what point the whole life emissions of retrofit would be lower than the baseline building despite the upfront embodied carbon cost. A comparison of total whole life carbon to new construction benchmarks is also undertaken. Both these scenarios will assume retrofit of all stock in 2025. See Table 4.4 for new construction benchmarks.

5.2.4.2 Retrofit scenarios

Three different retrofit scenarios will be modelled to understand the impact of different levels of intervention at scale:

- **Part L2B** - Fabric measures installed to Part L2B levels alongside a medium temperature heat pump.
- **Enerphit** - Fabric measures installed to Enerphit levels alongside a medium temperature heat pump and MVHR with new ductwork.
- **Heat Pump only** - No fabric measures are modelled and only a high temperature heat pump installed.

Details on Part L2B and Enerphit retrofit can be found in Section 4.4.1.1 of Chapter 4. The heat pump only scenario will have the same heat pump efficiency as hot water supply, as it assumes a high temperature system.

In comparison to Chapter 4, a less comprehensive retrofit scenario is modelled for Part L2B and Enerphit. Building emitters will be retained and medium temperature heat pumps will be used in lieu of low temperature. This has been undertaken as past literature shows that existing emitters have potential to allow for lower temperature applications due to improved fabric efficiency. For example, analysis of a refurbished multi family building, to a worse fabric standard than Part L2B, showed that selective replacement of only 7% of emitters would allow for medium temperature applications [288]. Also there is potential that, practically, some systems would be replaced with underfloor heating which when installed in conjunction with the already modelled new floor screed would have a much lower embodied carbon impact than radiators. The embodied carbon values are $9.5kgCO_2e/m^2$ for underfloor heating [289] compared to $150kgCO_2e/m^2$ for radiators [290, 291], though the total required area of each measure would differ. Therefore, Chapter 5 modelling aims to provide a scenario which is realistic and balanced, not having an unfair upfront carbon cost, considering the high embodied impact of radiators. This scenario is also likely cheaper due to the reduction in material consumption, making it potentially more realistic at scale.

One commonly modelled retrofit measure which is not included is renewable energy systems such as PV, hydro-electric or wind power. The operational impact of these systems is assumed to be studied within sensitivity analysis of the carbon factor for the entire electric grid as demonstrated below. It is shown in past literature [109] that decarbonising electricity may have a considerable embodied impact, which is also explored further in Section 5.3.3.1.

One limitation of these modelled scenarios, which will be discussed further in Section 5.4, is that optimal retrofit has not been modelled. This means that the results only reflect carbon emissions if typical scenarios are undertaken rather than that of the lowest potential whole life carbon retrofit scenario.

5.2.4.3 Electricity and material decarbonisation scenarios

Table 5.2: Different materials [14] and electricity [13] decarbonisation scenarios undertaken in this chapter. CCS refers to carbon capture and storage.

	Constant	**Falling short**	**Leading the way**
Electricity	Constant	Falling short (No CCS)	Leading the way + CSS
Steel (MEP)	Constant	Decarbonisation continues at current rate (15% improvement)	Maximum decarbonisation with carbon capture (60% improvement)
Glass (Glazing and Glass wool)	Constant	Continued roll out of technologies (60% improvement)	Maximum decarbonisation with carbon capture (90% improvement)
Refrigerant (Heat Pump)	R513A	R513A	CO_2/R774
Chemical (EPS)	Constant	Continued trends in energy efficiency and decarbonisation (30% improvement)	All technically feasible options are deployed without cost consideration (90% improvement)

The key data for each scenario is provided in Table 5.2. The simplified material and grid decarbonisation scenarios are further explained in Appendix C.5. This aims to provide a worst, best and typical scenario to understand the potential impact of both material and electricity decarbonisation on results.

5.2.4.4 Sensitivity analysis - Occupancy patterns

In Chapter 3 Section 3.4.2.2, we demonstrate that even where data is seemingly accurate in terms of age, geometry and typology the model differs for certain case studies from metered consumption.

This difference has various potential causes ranging from unknown data quality issues or other practical issues, such as poor on-site workmanship [246] or incomplete commissioning [246], causing a performance gap between the building design and actual performance. Another potential cause is the difference in occupancy behaviour to what has been modelled in this thesis. Within Section 3.4.2.2 a pattern was found that newer buildings had a higher tendency for larger than predicted energy consumption, which could be explained as those buildings with lower heating loads can afford higher set point temperatures and usage patterns. Further, when this occurs post retrofit it is known as the rebound effect [248].

Also, reductions in energy consumption due to occupancy behaviour changes have been shown to be beneficial to meeting government targets with a Norwegian study showing reductions in domestic hot water consumption alongside retrofit is important for meeting a 50% reduction target [197].

With these two points in mind, it is important to conduct sensitivity analysis on potential changes to occupancy after retrofit. When it comes to a potential performance gap when installing retrofit, for modelling purposes we have assumed that post retrofit performance matches what is modelled.

The chosen occupancy sensitivity scenarios will be:

- **Minimum:** 17°C average set point temperature with a heating season from November to the end of March. Lower than typical kitchen and hot water energy consumption is also modelled.
- **Typical:** 19°C average set point with a heating season from mid October to mid April. Typical kitchen and hot water energy consumption is modelled.
- **Maximum:** 21°C average set point with a heating season from the beginning of October to end of April. Higher than typical kitchen and hot water energy consumption is also modelled.

See Appendix D.3 for further details.

5.3 Result and discussion

This section provides results and discussions regarding the whole life carbon impact of retrofit at scale on the English school stock. The first section outlines the impact of baseline, pre retrofit, operational carbon emissions. This is followed by retrofit modelling to meet the CCC carbon budget for different decarbonisation scenarios and prioritisation pathways such as by building age and form. A demonstration of whether we can meet the most stringent, Tyndall centre derived, carbon budget is then provided. Sensitivity analysis of different post retrofit occupancy patterns is also explored.

Following this, the carbon payback period is calculated with discussions in regard to the remaining service life of existing buildings. Finally, the retrofit model is compared to different new construction benchmarks over different time periods, followed by concluding remarks.

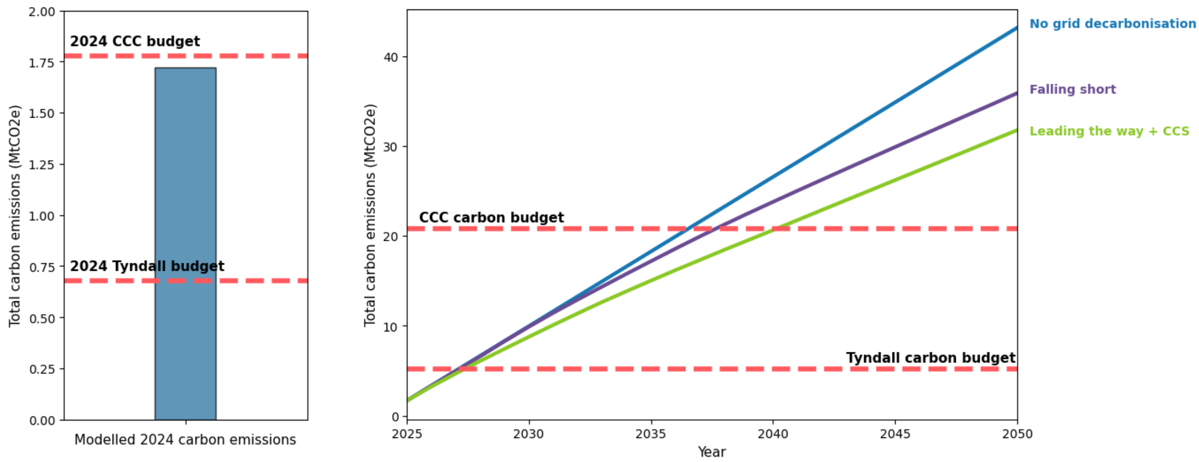
5.3.1 Baseline results

Yearly baseline operational carbon for 2024, shown in Figure 5.3a, has been calculated using the UK governments 2024 electricity carbon factor [271]. Comparing this to the predicted 2024 yearly carbon budget for CCC and Tyndall shows that current operational emissions fall just below the CCC budget.

This is not unexpected as currently we have met every CCC carbon budget to date, with the largest contribution to emission reductions from the phase out of coal and progress in electric grid decarbonisation [292]. It should be noted that as this is operational carbon alone, there will likely be some additional emissions caused by maintenance of school buildings which is not included in this estimation.

Figure 5.3b shows if we continue to use energy at the same rate with no grid decarbonisation then by 2050, schools would have emitted over 8 times the total Tyndall and 2 times the CCC budget.

Depending on which grid decarbonisation is modelled, emissions are reduced from 6 - 7 times over the Tyndall and 1.5 - 2 times over the CCC budgets respectively. This further emphasises that even with the complete decarbonisation of the electric grid, current reliance of fossil fuels



(a) Estimated operational carbon emissions in 2024

(b) Estimated cumulative operational carbon from 2025 - 2050 for different decarbonisation scenarios.

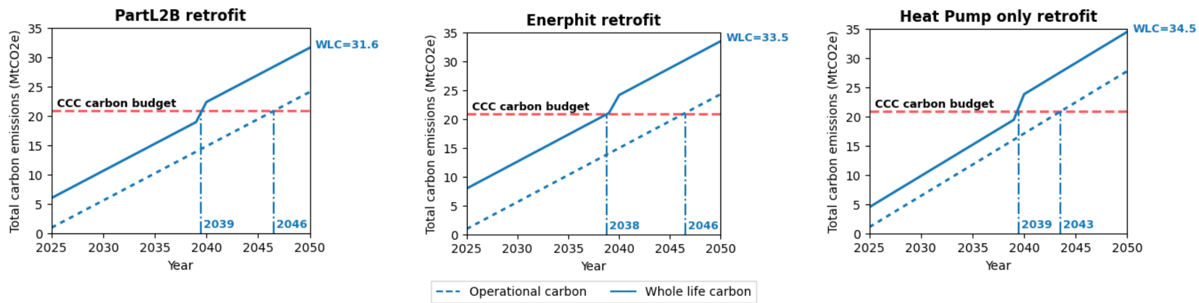
Figure 5.3: Baseline, pre retrofit, cumulative operational carbon emissions for the English school stock. Overshoot of the Tyndall budget occurs after 3 years in 2028 and overshoot of the CCC occurs from 2037 - 2042 depending on the rate of electricity decarbonisation.

for thermal energy does not allow for existing budgets to be met.

Therefore, we need retrofit of our existing school stock to meet the required reductions in carbon emissions.

5.3.2 The importance of grid decarbonisation

Figures 5.4a - 5.4c model retrofit of all stock in 2025, with no electricity or material decarbonisation. It shows, even if all buildings are retrofit in 2025 the CCC carbon budget cannot be met. Even accounting for operational carbon alone would lead to an overshoot of approximately $3.2 - 6.9MtCO_2e$.



(a) Everything retrofit in 2025 to Part L2B standards.

(b) Everything retrofit in 2025 to Enerphit standards.

(c) Everything retrofit in 2025 to Heat pump only standards.

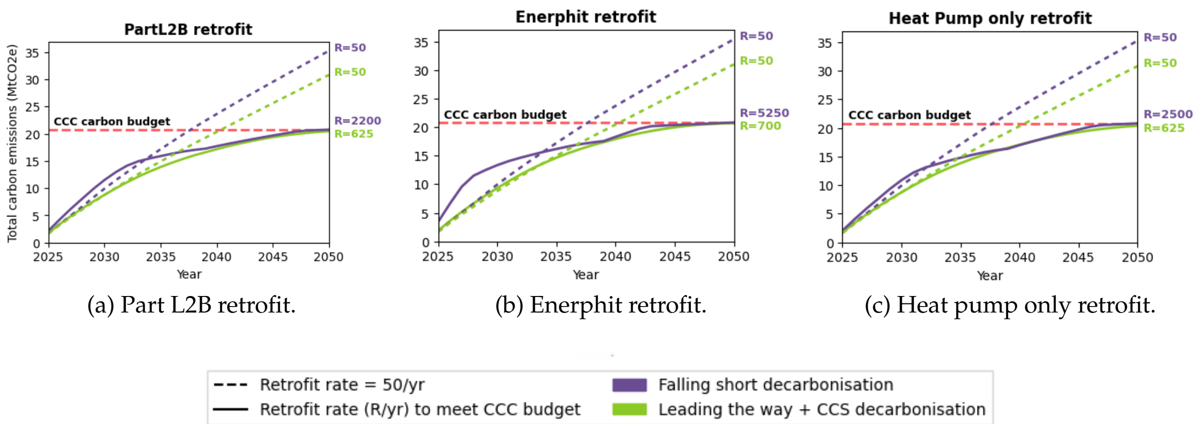
Figure 5.4: Cumulative emissions if every polygon is modelled to be retrofit in 2025, with no electricity of material decarbonisation.

These results show that we need decarbonisation in other sectors if we are to successfully decarbonise our school stock. This is in agreement with other studies [147, 202, 89, 109, 153, 145] which have been applied to different countries and building typologies.

Comparing the three modelled retrofit scenarios, shows higher operational carbon emissions for the heat pump only model caused by a reduction in heat pump efficiency and a lack of fabric improvements. When no decarbonisation occurs this difference is significant, emitting $2.9MtCO_2e$ (nearly 15% of the total CCC budget), more than the Part L2B model over 25 years despite lower upfront embodied emissions.

5.3.3 Meeting the CCC carbon budget

The yearly retrofit rate that is required to meet the CCC budget can be calculated using the falling short and leading the way decarbonisation scenarios. A random selection of schools to be retrofit each year has been modelled.



(a) Part L2B retrofit. (b) Enerphit retrofit. (c) Heat pump only retrofit.

Figure 5.5: The retrofit rates, R, to the nearest 25 schools, required to meet the CCC carbon budget compared to current typical practice. This has been applied for falling short and leading the way decarbonisation scenarios. **The noticeable kinks within the falling short model, are due to the upfront embodied carbon cost of yearly retrofit and the replacement of heat pumps modelled after 15 years. This is less noticeable for the leading the way model as the retrofit rate and the upfront carbon cost of MEP are lower.**

Figures 5.5 shows that the current retrofit rate of 50 schools per year is inadequate for meeting the CCC budget. By 2050 only 7% of modelled schools would be retrofit which leads to just a 1.4 - 2.8% reduction in whole life carbon emissions. This is due to the fact that as retrofit is being implemented so slowly, many of the installed schools would not have paid back the upfront carbon cost of retrofit and the impact by 2050 is reduced.

By implementing a steady retrofit rate, markedly higher than 50 per year, every retrofit scenario can meet the CCC budget for both falling short and leading the way decarbonisation modelling.

The highest required retrofit rate is the Enerphit model. Chapter 4 shows that very inefficient forms would benefit from this retrofit scenario over 30 years which implies that the majority of forms do not fall within this category (See Figure 5.11a for the distribution of modelled building forms). Further, the retrofit scenarios in Chapter 5 are different from Chapter 4 with no replacement emitters modelled. Therefore, the embodied carbon savings from Enerphit retrofit compared to Part L2B is reduced, because the required emitter size would be smaller in the Enerphit model due to a reduced heating load. If replacement emitters were indeed required at scale then the retrofit rate would significantly increase for both Part L2B and Enerphit.

The upfront carbon emissions of Enerphit are significantly higher than the Part L2B model. The key difference in embodied carbon is the installation of MVHR and ductwork which accounts for $1.8MtCO_2e$ due to the high embodied carbon of steel and the large amounts needed in this retrofit measure. Benefits of good ventilation strategies within schools, include improved student performance [99], and health and well-being [100]. In schools, mechanical ventilation has also been shown to improve ventilation quality [101]. Therefore, if it is found that we need mechanical ventilation in certain schools, we need to ensure that high heat recovery and fabric efficiency is achieved to help make up for the higher embodied cost of these MEP systems. Even if high efficiency standards are achieved, the difference between the Part L2B and Enerphit model show that if MVHR was required at scale an increase in retrofit rates would be needed across the stock to meet the CCC carbon budget.

Figures 5.5a - 5.5c show significantly lower retrofit rates for the leading the way scenario, as expected due to the much lower electricity carbon emissions and differences in refrigerant type. Modelling Part L2B retrofit under this decarbonisation scenario means, by 2050, 87% of all schools were retrofit. This is in comparison to the falling short model where all stock would need to be retrofit within 9 years. With the leading the way scenario the continued use of gas boilers in those schools yet to be retrofit means that by 2050, operational emissions are still above zero despite the negative electricity carbon factor of $-0.013kgCO_2e/kWh$, due to the increased reliance on carbon capture and storage.

Both the CCC and Tyndall budget aim to limit global warming to acceptable levels based on the Paris Agreement [278, 279], calculated in the form of a carbon budget. Therefore, each schools carbon budget can technically be met without also meeting the government's goal of yearly net zero by 2050 [293]. To achieve net zero for schools would require a carbon factor of $<= 0kgCO_2e/kWh$, alongside the retrofit of all schools, which is not the case for falling short predictions ($0.016kgCO_2e/kWh$ in 2050). Further, neither falling short nor leading the way scenarios would achieve zero embodied carbon emissions by 2050, meaning that any replacement of retrofit materials would increase overall emissions.

The upfront embodied carbon for the heat pump only model is unsurprisingly significantly lower than that of Part L2B and Enerphit. Interestingly, this is not the case for replacement carbon emissions due to the required increase in plant size to meet less efficient buildings heating load.

Figure 5.5c shows that these higher replacement emissions alongside the increased operational carbon, cause the retrofit rate to be higher for the heat pump only than Part L2B using the falling short decarbonisation scenario. However, this is not the case when comparing the heat pump only model to Enerphit which further highlights the significance of embodied carbon considerations within future refurbishment models.

5.3.3.1 Significance of final energy consumption

Using the leading the way decarbonisation scenario means that the required retrofit rate is the same for Part L2B and the heat pump only model. This implies that if we manage to decarbonise the national grid quickly and use low embodied carbon heat pumps, it would make no difference which retrofit strategy is used.

Table 5.3 shows the final total energy load, including all thermal and electrical consumption, for the Part L2B and heat pump only scenario. The results range between $5.05 - 5.8TWh$ which is in line with UKGBC predicted 2050 energy load, stating a total educational stock load of $10TWh$ [1]. Primary, secondary schools and colleges take up approximately 55% of the total carbon weighted floor area, see Appendix D Section 5.2.3, and England accounts for 81 and 85% of UK current electricity and gas usage respectively [294, 295]. Therefore, $5.05 - 5.8TWh$ is similar to the UKGBC value of approximately $4.5 - 4.6TWh$ for this stock type. Results were not expected to match exactly as the UKGBC retrofit modelling also includes improved lighting and controls which could help explain the slightly smaller predicted number [1].

Table 5.3 shows the final energy load is 15% higher for the heat pump strategy compared to Part L2B. Decarbonising the national grid to negative levels, as has been modelled in the leading the way scenario, would be significantly more difficult with a higher energy load as this needs to be offset by carbon capture and storage. In fact, past work has shown the significant embodied costs from decarbonising the electric grid with a study in Sweden finding that the greenhouse gas emissions from new renewable power plants outweigh those of renovation and new construction of offices and dwellings combined [105].

To further understand the material significance to offset all schools emissions, the total embodied carbon of solar photovoltaic panels (PV) required to produce this total yearly energy load has been estimated. Embodied carbon data for PV [$kgCO_2e/m^2$] was multiplied by typical yearly energy production for PV in England [$kWh/m^2/yr$], as explained in Appendix D.5. The significance of renewable energy embodied carbon is clear as the impact, shown in Table 5.3, is larger than the entire Tyndall carbon budget for schools.

Table 5.3: Total yearly estimated load in 2050 for the English school stock post retrofit and the estimated total embodied carbon to produce this energy in a year with PV. Assuming all stock has been retrofit by 2050.

	Part L2B	**Heat Pump only**
Final total yearly energy load (TWh)	5.05	5.83
Equivalent PV embodied carbon ($MtCO_2e$)	5.69	6.56
Equivalent PV panel area (km^2)	33.05	38.14

This study is a simplified demonstration with clear limitations, such as the consumption profile of a solar panel producing $150kWh/m^2/yr$ which does not necessarily match the usage patterns of a school.

Table 5.3 shows that adopting the heat pump model would lead to nearly $1MtCO_2e$ extra embodied carbon emissions compared to the Part L2B model. This is 4.2% of the CCC carbon and 16.7% of the Tyndall budget. This demonstrates that decarbonisation of the national grid will not come easy and shows the benefits from reducing the additional energy loads as much as possible.

The total area of panels is also higher for the heat pump model. The total predicted plan area of the whole school stock is approximately $54.5km^2$ which is higher than the modelled required area of PV in Table 5.3. However, it is uncertain what proportion of the total roof area would be suitable for panels with evidence within literature showing that this varies widely for PV [296].

There is limited existing data for what is an appropriate area of roof space that is suitable for PV within schools. Gassar and Cha [296] provide a review of this data and show a large range in suitable area for PV in different studies ranging from 30% - 84% [296]. The two educational studies ranged from 36% and 65% [296].

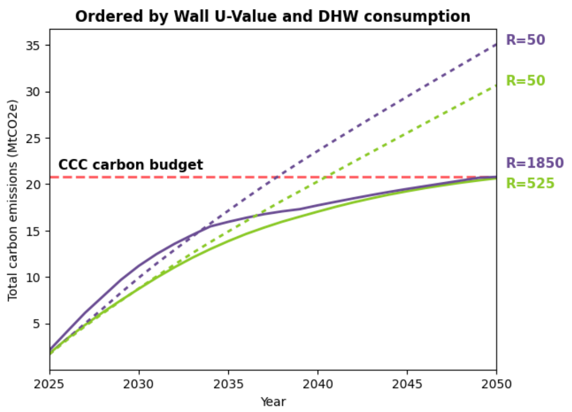
Adopting these educational building ratios infers that the total available area for PV would range from 19.6 - $35.4km^2$. The higher value within this range would allow for complete offset of the Part L2B model but not the heat pump only model.

The yearly operating costs of installing only heat pumps will also be larger compared to Part L2B or Enerphit retrofit due to higher heating energy consumption and reduced heat pump efficiency. Electricity is considerably more expensive than gas and in January 2025 electricity costs were approximately 4 times higher per kWh compared to gas [297]. As high temperature heat pumps are not modelled as 4 times more efficient than gas boilers, Appendix B, Table C.1, the electrification of heat without fabric measures is likely to be more expensive than before retrofit. This increased cost may also create an inequity between schools of different ages, as those that already have a relatively efficient fabric will be less impacted from the increased operating cost of electrification. Future work which looks at retrofit from both a whole life carbon and economic perspective would be useful to provide a more comprehensive understanding of where different retrofit measures should be installed.

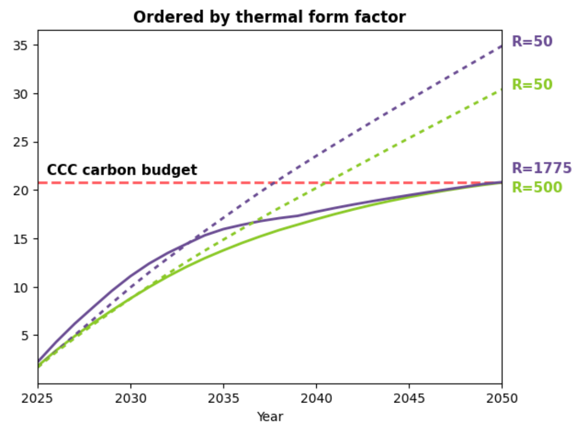
5.3.4 Prioritisation pathways for Part L2B retrofit

As Part L2B modelling is shown to lead to the lowest required retrofit rates of all three scenarios, this is continued with for the following sections. The two key pathways described in Section 5.2.4.1, **Age** and **Age and form**, are modelled and the required retrofit rates to meet the CCC budget demonsrated in Figure 5.6.

For both scenarios, instead of modelling retrofit of an entire school as in Sections 5.3.2 - 5.3.3, retrofit is undertaken for a certain floor area (m^2) of polygons. This has been converted to equivalent total number of schools, with the average floor area being $3720m^2$.



(a) Retrofit is prioritised by age and hot water usage.



(b) Retrofit is prioritised by building age, hot water usage and form using Equation 4.34.

Figure 5.6: Graphs to show the required retrofit rates, to the nearest 25 schools, to meet the CCC carbon budget compared to current practice for two different prioritisation pathways. This has been applied for falling short and leading the way decarbonisation pathways.

Figure 5.6a shows a reduction in the required retrofit rate between randomly choosing which schools should be retrofit compared to prioritisation of the oldest and least thermally efficient. The retrofit rate is reduced by 350 and 100 equivalent schools for the falling short and leading the way decarbonisation scenario respectively. This is a significant amount and demonstrates the benefits from prioritising the least efficient buildings first.

Figure 5.6b shows that inclusions of form further reduces the retrofit rate by 75 and 25 equivalent schools for falling short and leading the way scenarios respectively. Considering that the current strived for retrofit rate of schools is 50 per year, this is an important finding which demonstrates the significance of form when considering retrofit prioritisation.

The retrofit rate still needs to be increase by 10-40 times, depending on the decarbonisation scenario, compared to the current practice of 50 schools per year.

These results also demonstrate a potential usage of the developed analytical expression (Equation 4.34). Not only would it allow form to be included within the discussion for retrofit prioritisation, but it is also a simple method of understanding the impact of different building efficiency levels. For example, in certain building portfolios, there may be higher variation each element's U-value compared to this model. The thermal form factor incorporates all elements of energy consumption in a single value with limited data inputs and computational cost and can be used to understand what needs to be prioritised in terms of retrofit.

If embodied emissions of retrofit could be reduced, it is likely that building form would have a larger impact on overall carbon reductions. This is because inefficient forms would need more material for retrofit due to a larger surface area for the same internal volume. Therefore the effectiveness of retrofit measures would be reduced. The breakdown of embodied carbon for each type of measure is explored in the following section to understand where carbon hotspots are and what materials or products would be most beneficial to prioritise decarbonisation.

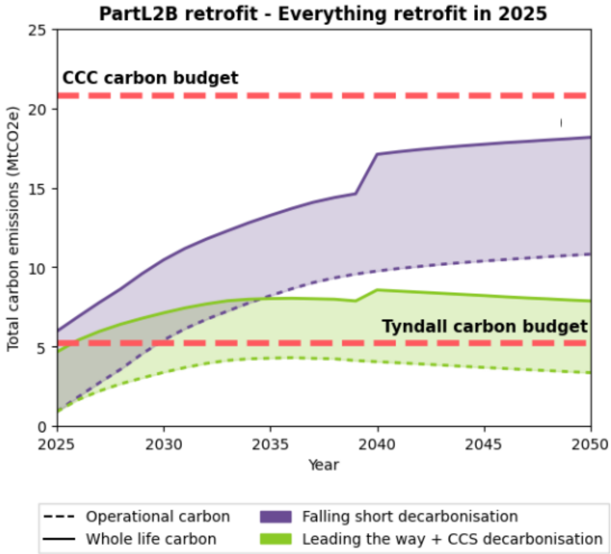
5.3.5 Meeting the Tyndall budget

To understand whether it would be possible to meet the most stringent, Tyndall centre derived, carbon budget, the entire stock has been modelled to be retrofit in 2025 for both falling short and leading the way decarbonisation scenarios. Results are demonstrated in Figure 5.7.

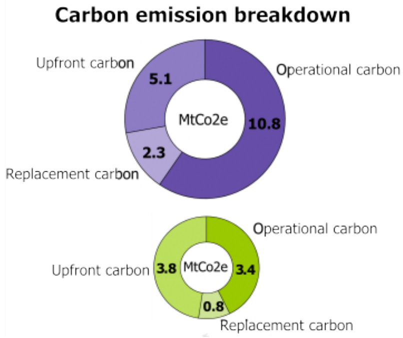
The falling short decarbonisation scenario would not meet the Tyndall budget, even if only operational carbon is modelled. By 2050, whole life carbon emissions are over the double the budget which demonstrates the importance of material and electricity decarbonisation as well as the urgency with which retrofit needs to be undertaken if we are to limit carbon emissions.

Even using leading the way decarbonisation, where by 2037 there are only negative operational carbon emissions, the Tyndall budget is still not met due to the embodied carbon cost of retrofit. The leading the way scenario would reach this budget for operational carbon alone but not when including whole life emissions. Even if replacement of MEP systems is excluded the model would miss the mark by $1.9MtCO_2e$.

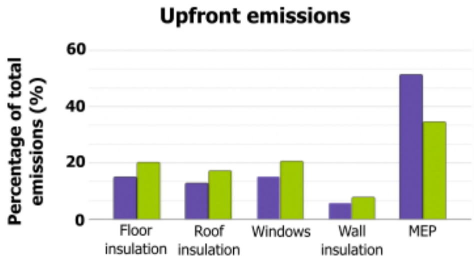
The breakdown of whole life carbon shows that material emissions would need to be $< 1.4MtCO_2e$ to meet the carbon budget with the leading the way scenario which would be equivalent to $< 20kgCO_2e/m^2$. For context, available retrofit benchmarks assume a light refurbishment of a commercial building would have a upfront embodied carbon of up to $30kgCO_2e/m^2$ which does not include any fabric measures. This further emphasises the need for low carbon materials if we are to meet the Tyndall carbon budget, especially considering that this benchmark refers to upfront embodied carbon, stages A1-A3, only. The modelled upfront embodied car-



(a) Total carbon emissions over time.



(b) Breakdown of carbon emissions.



(c) Breakdown of upfront embodied carbon emissions.

Figure 5.7: Cumulative whole life carbon emissions overtime, with all English school stock modelled to be retrofit to Part L2B standard in 2025. This graph also shows a breakdown of total carbon emissions for each decarbonisation scenario. It should be noted that upfront MEP emissions includes refrigerant leakage over the products lifespan.

bon for Part L2B retrofit is equivalent to $50kgCO_2e/m^2$ and $73kgCO_2e/m^2$ for falling short and leading the way respectively. This model is therefore in line with existing embodied carbon benchmarking, where 36 energetic refurbishment projects were found to have an upfront embodied carbon ranging between $20 - 140kgCO_2e/m^2$ [51].

MEP embodied carbon outweighs all other retrofit measures, something which has been found to be the case in literature with CIBSE Guide TM65 stating that MEP can take up 50 - 75% of a refurbishment project's total embodied carbon [94]. Therefore, the need for low embodied carbon MEP is clear. The benefits of adopting lower emission refrigerant is demonstrated here with the R744 model emitting over 1 $MtCO_2e$ less upfront embodied carbon compared to R513A, due to potential refrigerant leakage. However, this section demonstrates that this reduction alone is not enough to meet the most stringent carbon target modelled and further development of low embodied carbon MEP is necessary. This is further emphasised as Appendix C.5 shows the predicted decarbonisation pathways for steel, which makes up the majority of a heat pump's material breakdown, achieves a much smaller predicted reduction compared to that of the glass and chemicals industry. This implies that steel is harder to decarbonise than other retrofit measures and further focus on these systems would be beneficial. Results also show how it would be highly useful to incorporate circular principles within heat pump designs, for example allowing for individual components to be more easily dismantled and repaired/replaced, because the replacement cycle emissions for a whole heat pump are shown to be significant to total whole life carbon.

The embodied carbon estimate for heat pumps in this thesis is a conservative estimate based on the building fabric efficiency and with a typical plant oversize factor applied. Therefore, a study has been undertaken, provided in Appendix D.4, comparing results for schools to that of residential buildings which have more standardised plant size values, to check that the results are reasonable and heat pumps do indeed pose a carbon hotspot.

5.3.5.1 Carbon sequestration and biogenic materials

Throughout this thesis, the most common insulation materials used in industry have been modelled. This includes glass wool and EPS where appropriate for different retrofit measures, as explored in Appendix C.4.2.1, and both these materials also have lower embodied emissions than other typically used materials [264]. Alternative insulation materials are those made from natural/plant-based sources which includes wood fibre and straw bale.

These materials are described as biogenic and have the ability to temporarily store or sequester carbon over their lifespan which makes upfront emissions technically negative. Assessment of these materials must be undertaken with care as at the end of its lifespan a product will re-emit the stored carbon unless carbon capture and storage occurs or another use-case is facilitated. It has also been shown within past studies that biogenic materials only store carbon emissions when taken from sustainably managed forests [298]. For this reason, RICS whole life guidance has stated that if one is undertaking only an upfront carbon assessment, sequestration must be reported separately to avoid misleading results [12].

In fact when excluding sequestration, wood fibre A1-C4 emissions are $62.9 - 86.1 kgCO_2e/m^3$, depending on whether one models flexible [299] or rigid [300] insulation, compared to values of $10.7 kgCO_2e/m^3$ and $67.6 kgCO_2e/m^3$ for glass wool and EPS respectively.

However if the use of biogenic materials was to lead to carbon sequestration, the retrofit of all schools poses a potentially significant store of carbon due to the high amounts of insulation installed over the entire stock. **Assuming the same volume of insulation material as currently modelled** would lead to a total sequestration of $0.2 - 1.9 MtCO_2e$ after excluding other upfront emissions such as manufacturing, installation and transportation. This shows considerable storage potential within schools, likely increased if one accounts for the lower thermal conductivity of wood fibre compared to glass wool and EPS [22, 23, 301, 299, 300].

5.3.6 Occupancy sensitivity

Occupancy sensitivity analysis is included to understand the impact of potential differences in actual compared to modelled occupancy behaviour post retrofit. The minimum, typical, and maximum post retrofit occupancy schedules described in Section 5.2.4.4 have been modelled for all key scenarios. These are demonstrated in Figures 5.8a - 5.8l .

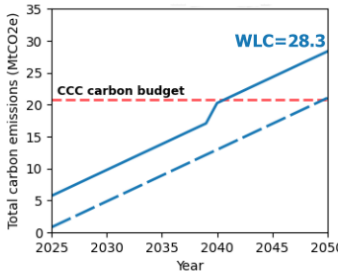
As expected, Figures 5.8a - 5.8l show that reducing occupancy usage reduces overall carbon emissions and increasing usage, the opposite. Decarbonisation scenarios with higher total emissions, e.g. no decarbonisation, have a larger difference between different occupancy patterns due to the higher proportion of emissions which come from operational energy.

The key finding is that overall patterns and conclusions drawn do not change even when taking into account uncertainties in post retrofit occupancy schedule. For example, the CCC carbon budget cannot be met without multi-sector decarbonisation as well as a marked increase in retrofit rates compared to current practise. This retrofit rate is also still benefited by prioritisation of least thermally efficient buildings. The Tyndall budget can not be met once upfront and replacement carbon emissions are considered.

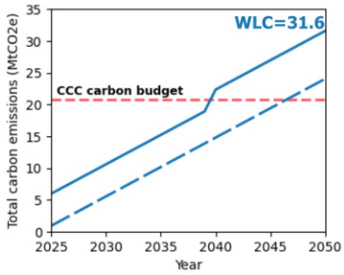
Another potentially significant finding is the marked increase in retrofit rates due to a potential increase in post-retrofit occupancy usage. In fact, the required rate would nearly double under the falling short decarbonisation scenario. As the rebound effect has been evidenced within past work [248], the potential for an increase in post retrofit energy consumption is shown to pose a very real threat for the ability to meet the CCC budget. This should be accounted for in future retrofit decisions, with either an increase in retrofit rates or measures such as the roll-out of improved energy-monitoring within schools. For example, the Energy Sparks scheme [238] uses energy monitoring to alert schools if MEP systems are left on outside of school hours or when usage is very high.

Minimum occupancy pattern | **Typical occupancy pattern** | **Maximum occupancy pattern**

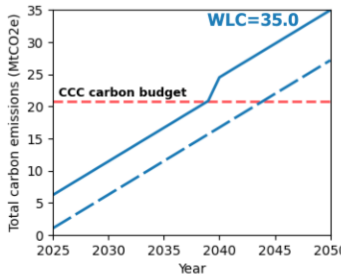
Everything retrofit in 2025



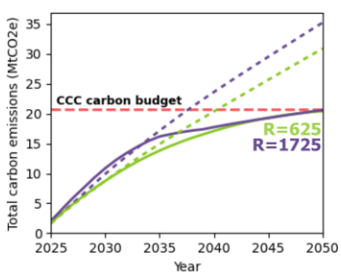
(a) Everything retrofit in 2025 to Part L2B standards.



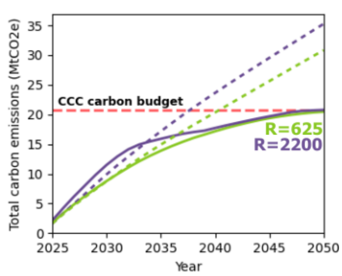
(b) Everything retrofit in 2025 to Part L2B standards.



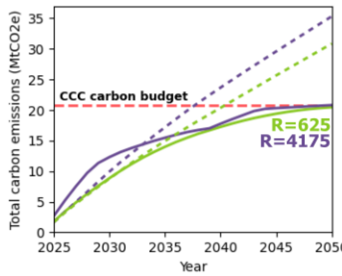
(c) Everything retrofit in 2025 to Part L2B standards.



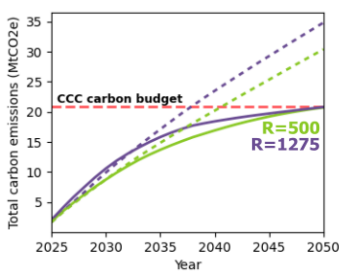
(d) R = Retrofit rate $(X/year)$ to meet the CCC carbon budget.



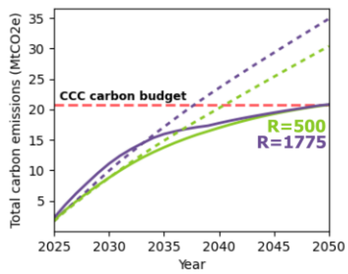
(e) R = Retrofit rate $(X/year)$ to meet the CCC carbon budget.



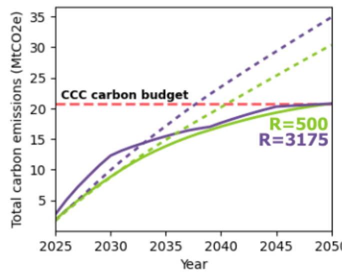
(f) R = Retrofit rate $(X/year)$ to meet the CCC carbon budget.



(g) R = Retrofit rate $(X/year)$ to meet the CCC carbon budget.

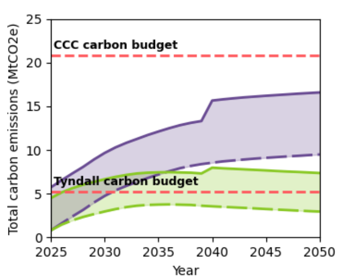


(h) R = Retrofit rate $(X/year)$ to meet the CCC carbon budget.

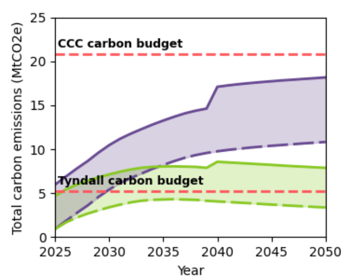


(i) R = Retrofit rate $(X/year)$ to meet the CCC carbon budget.

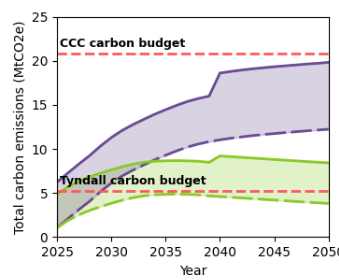
Everything retrofit in 2025



(j) Everything retrofit in 2025 to Part L2B standards.



(k) Everything retrofit in 2025 to Part L2B standards.



(l) Everything retrofit in 2025 to Part L2B standards.

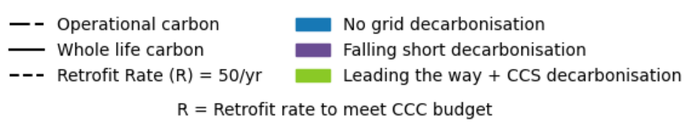


Figure 5.8: Sensitivity analysis to show the potential impact of changes to occupancy schedules - post retrofit.

5.3.7 Retrofit carbon payback period

For each decarbonisation scenario and every building, the embodied carbon payback period was calculated, assuming 2025 retrofit to Part L2B standards. Figure 5.9a shows that all measures are paid back within the 15 year lifespan of the heat pump. This is still the case even in scenarios where the carbon factor of electricity remains the same as that of gas, with no decarbonisation.

The leading the way scenario has shorter payback periods because this would lead to larger carbon savings between the gas heating systems and the heat pumps. Older buildings are shown to have a shorter payback period which further demonstrates the benefits of prioritising the least thermally efficient stock first as they will begin to provide net positive savings quicker than newer buildings.

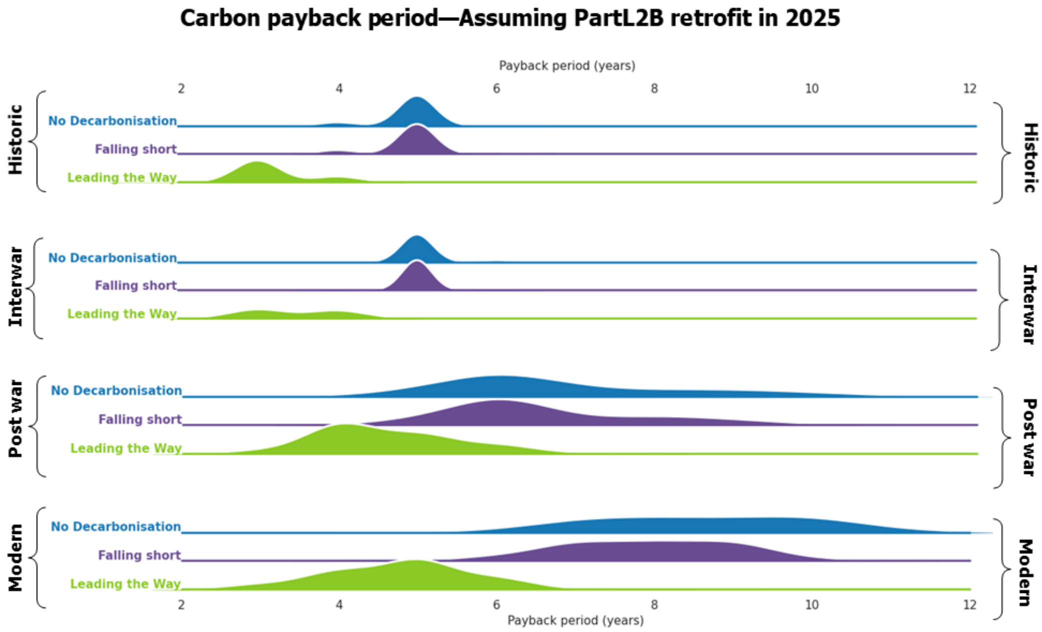


Figure 5.9: Density plots to show the carbon payback period of all buildings for different decarbonisation scenarios, assuming PartL2B retrofit in 2025. For each decarbonisation scenario the total number of schools within that age category have been modelled - historic, interwar, post war and modern. Therefore, the kernel density distribution is relative to the total number of buildings in each age category rather than the total number of English schools.

The results show that older buildings, historic and interwar, would need an extended lifespan more than 7 years and newer buildings, post war and modern, longer than 11 years to justify the embodied carbon investment from retrofit. This is in line with existing benchmark data which predicts a payback period of up to 8 years from cradle-to-gate emissions for medium or deep refurbishment of commercial real estate [51].

With this carbon payback period in mind, there is evidence that structural components of certain schools may not last this period. For example, RAAC is a cheap form of concrete commonly used from the 1950s to the 1990s which was found to have a shorter lifespan than previously expected and therefore risks collapse in certain schools. Discovery of this concrete within many schools in England made national headlines [302, 303], as the material had reached the end of its lifespan in many cases forcing school closures around the country. In England, 234 education settings which is approximately 1% of schools and colleges, have been confirmed to have RAAC [304]. These findings highlight that lifespans of certain schools may not last as long as has been modelled in this study, though this issue impacts a very small proportion of schools.

A crisis such as this shows why it is important to understand the carbon payback period of any future intervention and whether it is short enough to have a positive impact. Potential issues with the structural integrity of the building cause uncertainty on the remaining lifespan of each building. Therefore, though Figure 5.9a shows that the payback period will reduce total carbon emissions by 2050, the carbon payback period also needs to be assessed alongside the remaining service life of a building or element such as the roof.

The requirements for further structural remediation within schools, such as those affected by RAAC, may also have significant embodied carbon impacts which would mean that retrofit rates across the stock would likely need to be increased to meet the budget.

5.3.8 New construction comparison

For context the total internal floor area of school stock is approximately $70km^2$. Multiplying this by the current aspirational embodied carbon target of $540kgCO_2e/m^2$ would be $37.5MtCO_2e$ [11] which is well above the allocated CCC carbon budget for schools, of $20.8MtCO_2e$. If an even more ambitious embodied carbon target is achieved such as LETI A+ band, of $260kgCO_2e/m^2$ this would be equivalent to $18.1MtCO_2e$ [272]. Considering that this is material emissions alone it is clear that replacement of large amounts of our school stock is not possible if we are to meet national carbon targets.

Table 5.4 further supports this point as it shows what would need to be achieved in rebuild to meet the CCC budget for different decarbonisation scenarios. It shows that embodied carbon and/or operational energy would need to be significantly lower than what is currently strived for to meet the carbon budget.

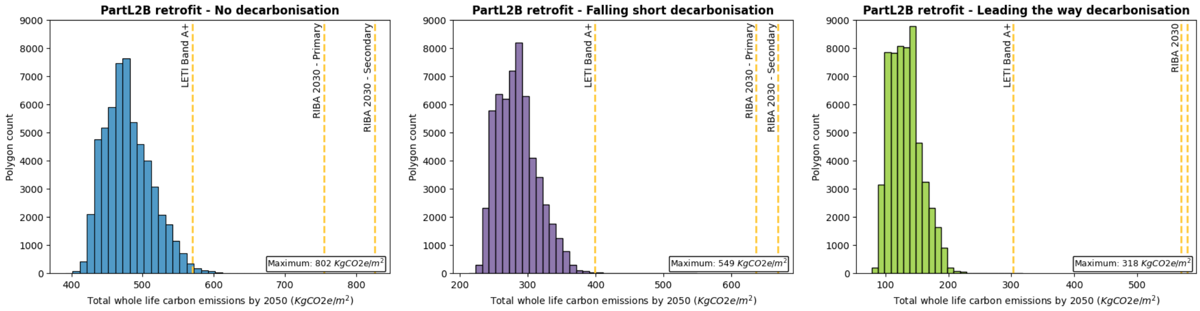
Thus far, this section has demonstrated that mass demolition of our stock is not feasible to meet current carbon targets. However, it may be the case that for certain building types and forms it would be beneficial to total carbon emissions to demolish them.

Table 5.4: Table to show what would need to be achieved for both operational and embodied carbon to meet the CCC budget - if the entire stock were to be rebuilt. Results are compared to current RIBA 2030 standards - the standard that the organisation state industry should be striving to achieve today [11].

Required construction standards to meet the CCC budget ($20.8MtCO_2e$) if the entire school stock was replaced				Current RIBA 2030 standards
	No grid decarbonisation	**Falling short**	**Leading the way**	
Required embodied carbon ($kgCO_2e/m^2$) - Assuming* primary/secondary energy consumption of $45/60kWh/m^2$.	44	184	263	540
Required operational energy (kWh/m^2) - Assuming* LETI A+ embodied carbon of $260kgCO_2e/m^2$.	8.2	18.3	59	45/60†
*These values are the current highest performance targets within literature and do not necessarily reflect currently attainable standards [272, 21, 11]. † depending on primary or secondary school typology.				

Therefore, the school stock is investigated from an individual level with Figures 5.10a - 5.10c showing the total whole life carbon, both operational and retrofit embodied carbon emissions from 2025 - 2050, of all stock, assuming it is retrofit in 2025 to Part L2B standard. It should be noted that as height archetypes have been applied to the stock, individual building forms investigated here may not necessarily be reflective of actual forms in the English school stock.

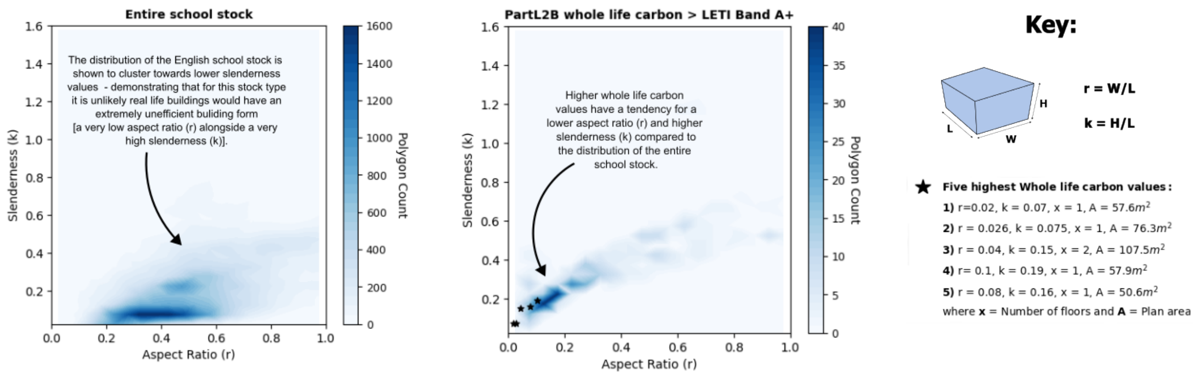
The importance of considering embodied emissions as well as trying to retain our existing stock is demonstrated as no property has a whole life carbon above that of RIBA 2030 standard. This is the level that RIBA claim we should be striving to achieve today [11].



(a) No decarbonisation. (b) Falling short decarbonisation. (c) Leading the way decarbonisation.

Figure 5.10: Whole life carbon of retrofit buildings by 2050, assuming they are retrofit to Part L2B standards. This is compared to different new construction benchmarks for total whole life carbon emissions by 2050. This scenario assumes that the $35kgCO_2e/m^2$ factor for demolition of the existing building would be included in the total new construction benchmark which helps further show the severity in which targets need to be met [12]. New construction benchmarks differ for each decarbonisation scenario as operational carbon is dependant on the level of electricity decarbonisation.

However, within the no decarbonisation and falling short scenarios there are a number of properties whose whole life carbon falls above the LETI A+ target, which is assumed to be possible at some point in the future. Therefore, these values have been explored in more detail. Figures 5.11a - 5.11b shows the distribution of building forms for the entire school stock compared to just those whose whole life carbon is larger than the LETI A+ band.



(a) Distribution of the whole stock.

(b) Distribution of those polygons with a whole life carbon higher than LETI Band A+.

Figure 5.11: The distribution of building forms for the whole stock as well as those whose whole life carbon is higher than LETI Band A+ new construction benchmark for the **no decarbonisation** scenario. Darker colours insinuate a higher polygon count.

Figures 5.11a - 5.11b show that the distribution of forms in Figure 5.11b have a tendency for a lower aspect ratio combined with a higher slenderness compared to the distribution for the whole stock. Figure 4.9 of Chapter 4 also provided examples of different forms for potential extreme values of slenderness and aspect ratio. This highlights that extreme values were perhaps less likely to appear in our stock due to the large differences between width, length and height. Indeed, the distribution of forms for the whole stock, as in Figure 5.11a, is shown to cluster toward a more efficient form, with low slenderness values.

The five highest whole life carbon values [$kgCO_2e/m^2$] are shown to all have reasonably small plan areas. This is because as you reduce aspect ratio and increase slenderness the range of realistic building forms become limited. The range in slenderness values is especially limited as the archetypal number of storeys, x, ranges between 1 and 3 for this stock type. At smaller plan areas a single or double storey building can still have a reasonably high slenderness and are more likely to have this combined with a very low aspect ratio. This is because it is unlikely for a large area building to be extremely long and thin at one or three storeys. Therefore, even if LETI Band A+ was achieved and these buildings replaced it would likely have a small impact on the total floor area of our school stock.

Study limitations include a prescriptive building height of ($H = H_{f_f} * x$) which makes it likely that buildings forms will differ more within the actual English stock. Also, there is a lack of consideration for required structural remediation and retrofit, which would increase embodied emissions.

It should be noted that this study has also not accounted for the fact that new construction and retrofit have potentially different lifespans. Table 5.5 shows the comparison of demolition versus refurbishment over a 60 year period, which is the typical predicted lifespan for a new construction [12]. This therefore accounts for the additional operational carbon emissions from extra years of use, as well as the additional replacement carbon emissions from heat pumps having a predicted lifespan of 15 years and flat roof and glazing systems a predicted lifespan of 30 years. After 2050, decarbonisation is assumed to stay constant.

Table 5.5 shows with no decarbonisation that considerably more polygons would now have lower overall emissions from demolition and replacement to RIBA 2030 standards. Over a longer study period such as 60 years, the increased operational efficiency of new construction outweighs the higher upfront embodied cost for a larger proportion of building forms, especially when no electricity decarbonisation occurs mean operational carbon has a larger impact. Results show the majority of floor area would still be retained. We have already demonstrated that with the no decarbonisation scenario it is not possible to meet the CCC carbon budget.

When the falling short scenario is modelled only 8 buildings in total would benefit from demolition, 0.001% of total floor area. It also should be noted that RIBA 2030 is still an ambitious target and current **business as usual** embodied carbon would be $1000kgCO_2e/m^2$ compared to $540kgCO_2e/m^2$ [11]. Therefore if the required material and electricity decarbonisation is achieved, even over longer lifespans retrofit is clearly the most preferable option from a whole life carbon perspective.

Table 5.5: The percentage of polygons whose whole life carbon falls above the RIBA 2030, $540kgCO_2e/m^2$, new construction standard over a 60 year lifespan.

The total number of buildings whose whole life carbon would be above **RIBA 2030** standards over a **60 year lifespan.**		
	No grid decarbonisation	**Falling short**
Percentage of polygons (%)	47	0.01
Percentage of total floor area (%)	19	0.001

These results do show that the demolition versus refurbishment is a question that should be explored over longer lifespans as there are certain building forms where replacement is preferable, but that at scale demolition should likely be prevented as much as possible. The developed parametric model in Chapter 4 could be highly useful for this as shown in Figures 4.13a - 4.13c. If other sectors, such as electricity and materials, decarbonise successfully in the future, results show there are less benefits from demolition due to the high upfront carbon cost that would occur now.

5.4 Conclusions and limitations

This chapter shows the need for retrofit at scale if England is to meet its carbon budget for schools. Retrofit must occur at markedly increased rates than is currently planned. Not only this, but without decarbonisation in other sectors, such as electricity and materials, even if all stock is retrofit in the next year the carbon budget cannot be met. Carbon budgets can be met through installation of Part L2B, Enerphit or heat pump retrofit as long as it is paired with either falling short or leading the way decarbonisation scenarios. Though the heat pump only scenario requires higher retrofit rates at worse decarbonisation levels, with the leading the way scenario this rate matches Part L2B retrofit. However, the benefits of fabric measures are shown through the reduced embodied carbon to offset final energy consumption with solar PV. Fabric measures are further shown to be beneficial as the carbon payback period of Part L2B retrofit for every building is within the lifespan of a heat pump, even for modern buildings where fabric installations have limited operational impact.

Prioritisation of retrofit for the least thermally efficient buildings is shown to be beneficial to reduce yearly retrofit rates. The largest reduction is caused by prioritising the buildings with worse fabric efficiency but including prioritisation of worse building forms will also reduce retrofit rates further.

The more stringent carbon budget, Tyndall centre derived, is shown to be very difficult to meet through retrofit, electricity and material decarbonisation. Operational carbon does meet this budget through instantaneous retrofit of all stock and if by 2037 the electric grid is actively reducing carbon emissions through use. Once upfront and replacement embodied carbon is incorporated, the budget is not met. As discussed, the carbon budget calculation process is limited in scope as it does not account for any importation emissions and therefore, this budget likely slightly underestimates total acceptable emissions. However, results still show the need for a large increase to retrofit rates as well as the reduction in embodied carbon cost of materials as they are significant for retrofit at scale.

The benefits of using low carbon materials is demonstrated by comparing the carbon cost of scenarios using different refrigerant types. Refrigerant leakage can have significant emissions due to the high greenhouse gas potential of materials such as R513A. The impact from heat pumps is reduced significantly by using a low impact refrigerant type such as carbon dioxide. However, heat pump installation still accounts for the highest proportion of embodied carbon even if low impact refrigerant is used. Therefore, heat pumps are a clear carbon hotspot which may benefit from further focus in future research to reduce upfront costs. Incorporating circular principles into future design could be beneficial as the replacement cycle of heat pumps is shown to lead to significant carbon emissions.

Further research into the usage of biogenic materials is shown to be potentially useful due to the impacts of carbon sequestration. Even when researching only wood fibre insulation, the sequestration potential varies widely between different EPDs. An understanding of what biogenic materials are appropriate at scale for each retrofit measure would be necessary to fully quantify the impact of sequestration. Results here show that if the sequestered carbon were to occur, this has the potential to reduce retrofit emissions significantly.

Changes to occupancy post retrofit, do not change the key conclusions found in this chapter. However, increase in set point temperature and heating season would significantly increase required retrofit rates to meet the carbon budget. An increase in heating energy consumption has been found to occur post retrofit and is known as the rebound effect [248]. Therefore, care must be taken to account for this in future decision making, especially by prioritising good and easy to use building control systems as well as detailed post retrofit handovers which explain appropriate heating temperatures and usage.

One key limitation of this study is that it does not include optimal retrofit. This may especially impact modern buildings which could need less fabric measures to still achieve low carbon emissions. For example, external wall and roof insulation require additional materials independent of insulation thickness such as a protective mesh, render and waterproof membrane. Therefore, for buildings whose U-value already achieves high standards, it could be beneficial from a whole life carbon perspective to not include these measures at all, as the benefits from material input are reduced.

The study assumes that all building's pre-retrofit are naturally ventilated and run on gas boilers. Though this is the case for the vast majority of stock [218], this assumption does not represent all buildings within the English school stock and is therefore a simplification and limitation to the modelling. For example, as a small proportion of schools will already have mechanical ventilation systems in place it is likely that the total whole life carbon impact of installing MVHR systems is overestimated in the model.

Comparisons to demolition and new construction show that over the 25 year study period no schools would benefit from demolition from a carbon standpoint, unless currently unfeasible new construction targets were achieved. If these targets were achieved then buildings of very poor building form would benefit from demolition under the no decarbonisation or falling short scenarios. These buildings typically have small floor areas and therefore a limited impact on the total carbon emissions of the school stock.

Over a 60 year lifespan, it is shown that demolition becomes more favourable, but retrofit is still preferred for the majority of total floor area. This is especially the case if some form of electricity and material decarbonisation is achieved - something which is shown to be necessary to meet the CCC budget. It is acknowledged that these comparisons provide a simplified assumption that lifespans of new construction and retrofit match. This may not be the case, and the carbon payback period that has been calculated, which shows that older buildings must last longer than 7 years to guarantee benefits from retrofit and newer buildings longer than 11.

This chapter shows the scale of the problems faced by the building sector if we are to meet carbon budgets. Retrofit rates must increase dramatically and the demolition of our existing buildings must not occur at scale. Considering building form, it is shown that the form of individual buildings matters when making future retrofit decisions, both in terms of prioritisation of retrofit for those inefficient forms and comparisons to new construction.

Chapter 6

Discussion

Retrofit or replacement of our existing stock is pivotal to reducing the impacts of global warming due to current reliance on fossil fuel heating systems which cannot be decarbonised without intervention. In Chapter 2 we showed the importance of considering the emissions from a building over its entire lifespan, not only those emissions related to energy consumption, but also those caused by the materials used within a building.

Within current literature, the vast majority of publications which examine the whole life impacts of retrofit focus on individual case studies. It is very difficult to make comparisons between each case study due to the large variation in the system boundaries adopted by different researchers. With mass intervention shown to be necessary, the benefits of studies which assess many building types and forms is clear as this allows for an understanding of how different intervention considerations impact total emissions, as well as how government targets can be met through these interventions. However, current studies are limited in scope and at a stock level these studies typically focus on residential buildings and also commonly focus on fabric only retrofit measures.

The presented work in Chapters 3 - 5 demonstrates methods and an understanding of how retrofit impacts the total whole life carbon of the existing English school stock. Alongside this, due to the increased variation in non-residential form compared to residential [150, 151], this thesis quantifies the influence of these key building geometric characteristics on future whole life carbon decisions.

The following section discusses the required increase in retrofit rates to meet the devised carbon budget, with results of this thesis put in context of other publications globally. Further, discussion on the impact of this thesis regarding whole life carbon assessments is provided alongside UK industrial and policy implications. Finally, limitations and scope for future work are outlined.

6.1 Retrofit pathways to meet carbon reduction targets

In Chapters 3 and 4 we developed a method to understand both energy consumption and whole life carbon of retrofit, at scale, for many different building forms. In Chapters 4 and 5 we applied this method to show that retrofit has the potential to dramatically reduce a stock type's energy consumption and related carbon emissions. However, Chapter 5 also demonstrates that retrofit rates need to increase by 10-50 times from current practice alongside significant decarbonisation in electricity and material sectors if UK climate targets are to be met. This is in agreement with other publications conducting analysis of residential buildings across different spatial scales in Ireland, Sweden and Portugal which advocate for retrofit rates to be scaled up by 20, 2.5 and 8 times respectively, alongside multi-sector decarbonisation [147, 89, 145]. In Sweden, more than half of residential homes already have a heat pump installed [305], a much higher proportion than UK buildings [43, 44], which helps to explain the lower required increase in retrofit rates in the Swedish case study [147].

Unlike Sweden, over 80% of UK heating systems for all typologies are currently fuelled by fossil fuels [43, 44], making it likely that mass retrofit of these systems is required for all stock types as well as in many countries all over the world as fossil fuel systems are prevalent globally [82]. Considering that the retrofit rate of the English school stock alone must be increased by approximately 10-50 times from the current level, this highlights the huge challenge that government's face when trying to decarbonise the entire building stock. Though the method developed in Chapter 3 has only been validated against and applied to the English school stock, as there are many buildings with similar construction systems, fabric efficiency and mechanical systems [46] this method can be applied to other naturally ventilated stock types in heating dominated climates. It is clear that these results, though comparable with past work, are dependent on core assumptions made within the whole life carbon modelling, a fact which is discussed further within Section 6.5.

6.2 Discussions regarding whole life carbon assessments

Chapter 3 and 4 demonstrate a method for understanding the energy consumption and whole life carbon of retrofit at scale, while including the influence of many different building forms. Importantly, this work has demonstrated that building form impacts both the energy consumption and whole life carbon of retrofit of a building. The importance of form considerations is demonstrated in different ways, such as in Chapter 4 where an analytical expression quantifies the parametric contribution of key form factors to total consumption. Further, in Chapter 5 prioritising retrofit of those buildings with the most inefficient form is shown to reduce the required retrofit rate to meet current carbon targets. However, Chapter 2 shows the archetype method for stock level assessments is commonly adopted within research, where a prescribed geometry is used to represent many buildings. Therefore, the importance of form demonstrated in this work presents a challenge for future studies, especially those of non-residential typology which vary more widely in shape and size [150, 151]. Energy use intensity [kWh/m^2] of one building form cannot necessarily be used to represent the energy consumption of many buildings, even if they have the same fabric efficiency. This is especially the case where demolition versus refurbishment cases are assessed, as it is shown that over longer lifespans or as new constructions are able to achieve lower upfront embodied carbon targets the retrofit versus new construction comparison becomes more reliant on building form.

Assessments of current whole life carbon retrofit studies, in Section 2.3.1, demonstrate a range of carbon payback periods for different retrofit measures which are typically within the predicted 50 year lifespan of a building. Findings in Chapter 5 are in agreement with this, as the maximum payback period for Part L2B retrofit is 11 years for newer and 7 years for older constructions. This payback period is also within the typical lifespan of a heat pump, 15 years, showing that all modelled installations of retrofit have an overall positive impact on total carbon emissions. However, the importance of material choice becomes evident when one applies whole life carbon assessments at scale. For example, by adopting low carbon heat pumps one can save $1.7MtCO_2e$ in upfront emissions, nearly a third of the total devised Tyndall carbon budget for schools. This sentiment has already been demonstrated by other work for fabric measures where insulation material choice is shown to be pivotal to meeting the most stringent carbon budget for residential buildings [50]. Within Chapter 5 the importance of insulation choice has also been further emphasised, with the potential impact of adopting biogenic materials shown to sequester up to $0.2 - 1.9MtCO_2e$ over the insulation material's lifespan. However, as mechanical systems typically account for the majority of a refurbishment project's total embodied carbon [94], results in this thesis highlight the importance of reducing embodied carbon of heat pumps within future retrofit installations. The significance of mechanical system's embodied carbon is further shown in Chapter 5 by the dramatic required increase in retrofit rates for adopting Enerphit standards, due to the high embodied carbon of ventilation systems, over Part L2B. This increase is caused by the high embodied carbon of installing ductwork and MVHR systems, and is in spite of a more efficient fabric and decreased ventilation losses due to heat recovery systems compared to Part L2B. Future work needs to take a holistic approach to whole life carbon assessments, with considerations of all retrofit measures, rather than merely fabric measures, and the impacts of potential sensitivities, such as electricity decarbonisation, to understand exactly what the best future intervention for our stock is.

Even with the choice of low carbon mechanical systems, heat pumps still pose a carbon hotspot within retrofit installations. Decarbonisation of heat pump embodied carbon is advisable, especially when one considers that heat pumps are the centre point of different national governments' decarbonisation strategies [98, 96]. Material decarbonisation of steel, the main material used within a heat pump, see Appendix C.5, poses various technical challenges and will require a significant investment in new infrastructure. For example, though pilot studies have demonstrated the potential for hydrogen based systems to decarbonise the steel making process, creating renewable and low carbon hydrogen at a commercial scale poses a huge challenge [49]. Further to this, the case study in Chapter 5, among others [147, 202, 89, 109, 153, 145], demonstrates that electricity decarbonisation is pivotal to meeting the carbon budget, something that will also require huge infrastructure investments. In fact, Chapter 5 demonstrates the significant embodied impact of offsetting the English school stocks energy consumption using PV. Whether this occurs at the supply point or at the individual building level, a significant investment in new renewable infrastructure needs to occur. The above points further emphasise the importance of a 'whole-house' approach to retrofit. Fabric measures such as insulation systems and airtightness improvements allow for not only smaller required heat pumps due to lower overall heating loads but also a reduction in the required renewable systems to decarbonise heat pumps to net zero levels. Reducing the increase in electricity consumption may also reduce the required level of upgrades that are planned for the electric grid to allow for increased electrification [306], which in itself will hold an embodied carbon cost.

Therefore, fabric retrofit measures should help reduce the required secondary infrastructure to decarbonise the electric grid, which whilst not accounted for in this thesis, is still likely to be pivotal to meeting the government's net zero targets. Comparisons of different retrofit measures within Chapter 4 shows we can potentially limit this input of fabric retrofit measures as much as possible, as more efficient building forms are shown to require less intervention to still achieve similar low carbon emissions. Reducing the required interventions from a carbon standpoint will also likely reduce the economic cost of installing retrofit at scale, a cost that will be considerable, the magnitude of which is discussed in the following section.

This thesis provides analysis, at scale, of demolition versus retrofit for schools, which builds upon work, explored in Chapter 2, where existing case studies have found conflicting results. Results in this piece of work show that demolition of our existing stock should not be taken lightly, due to the significant embodied impact of replacing our stock. The embodied carbon cost of replacing the entire school stock with constructions built to currently aspirational embodied carbon targets, of $540kgCO_2e/m^2$, would cause emissions well above the current CCC carbon budget for schools [11]. The work in this thesis therefore adds to existing work that highlights that, whole life emissions cannot be ignored within future decision making.

Chapter 4 also shows, that over the 30 year lifespan, the building forms where demolition would be preferable are extremely limited, even where a high glazing ratio limits the possible operational efficiency reductions of the existing building. As new construction targets become more ambitious the number of forms where demolition is preferable increase, but within the English school stock the actual forms where this occurs are typically of a small floor area and therefore replacement would have a small impact on total carbon emissions. Even over a 60 year lifespan, if electricity and material decarbonisation takes place, which is shown to be necessary to meet carbon targets, a very small proportion of buildings would benefit from demolition, despite the modelled superior operational efficiency of new construction.

6.3 UK industrial and policy implications

This thesis also has several key findings with direct implications for the UK built environment sector and policy practice.

Assessment of the English school stock shows that we need a significant increase in retrofit rates compared to the current rate of 50 schools per year, for which intervention is planned to occur within the 'School rebuild programme' [287]. There is also evidence that we are already missing these targets, with current forecasts showing that fewer projects than initially planned will be completed [307]. The challenge of meeting current carbon budgets is further demonstrated when one considers the required increase to retrofit rates, combined with the current retrofit skills shortage of trained workers. In fact, the Green Jobs Taskforce predict a need for 230,000 more skilled workers by the end of the decade to meet rising retrofit demand [308]. Looking at retrofit drivers for English schools also shows the crucial role of local authorities to drive retrofit [64], something which may be difficult due to a large funding and skills gap that the local government are currently facing [157]. With the uptake of academies within the UK, a proportion of schools are now directly funded by the government [309] who also currently face a budget deficit [310].

The government has explicit social goals [212] and carbon targets that need to be met [282], making the decarbonisation of public sector buildings essential. Further, without a skilled workforce, it is unlikely that retrofit in the private sector will be attractive to residents and building owners. Therefore, if the retrofit rates for schools and social housing can be increased, the retrofit sector within the UK can be expanded, helping to improve key elements of the sector, such as an increase in the trained workforce, and making it more attractive for the private sector to also increase retrofit uptake.

Though one limitation of this thesis is that economic cost of retrofit has not been explored, the high cost is evident when one considers existing cost benchmarks for retrofit measures. There is limited data for the cost of retrofit of schools, but existing benchmarks for other typologies, show a large spread in the expected cost of deep retrofit. Analysis of 200 residential homes showed a cost of £$870/m^2$ - £$1100/m^2$ [311] and office benchmarks give a range of £$152/m^2$ - £$1150/m^2$ (The minimum and maximum values for wall insulation/façade replacement, window replacement, roof insulation, airtightness and heating system upgrades within Table 1 of [56]). Applying the extremes of these ranges to the total floor area of the school stock leads to a potential cost of £10.5 billion - £80 billion. There is a clear need for a significant increase in funding within the field of retrofit if carbon targets are to be met. By applying retrofit at scale through policy implementation there is also potential to reduce retrofit costs though bulk procurement. Economies of scale are evidenced within case study analysis of healthcare buildings where the refurbishment of buildings with a smaller floor area have a tendency for a higher cost per floor area [£/m^2], and a larger spread in costs, compared to those of a larger floor area [312]. It should be noted that different healthcare buildings will have varying and specialist design requirements [312].

Evidence of disrepair within the school stock further emphasises why this typology is a great starting point for driving the retrofit industry. The school condition survey claims the modelled cost of remedial work to replace or repair defective elements in the English school estate is £11.4 billion [15]. This value averages at £500,000 per school, with the costliest required repairs at stock-level being electrical services, mechanical services, walls, windows, doors, and roofs [15]. This shows that many building elements within the school stock which require retrofit to meet carbon targets, also already require replacement or upgrades. Therefore, the government has the potential to improve the conditions for pupils and the sustainability of these buildings simultaneously. The school condition survey also shows that older buildings are in a higher state of disrepair [£/m^2] [15], meaning that prioritisation of retrofit for the least efficient buildings will not only assist in meeting the CCC carbon budget, as demonstrated in Chapter 5, but improve those buildings in the worst condition.

When considering demolition versus refurbishment, results show the significance of including whole life carbon within future comparisons. Successful decarbonisation of the electric grid makes demolition less appealing, something shown to be pivotal in the UK plan for meeting net zero [279]. Therefore, mandating whole life carbon measurements, within building regulations or future planning proposals, within future building projects would be highly useful to ensure each project must consider sustainability in a comprehensive manner.

Regulating these assessments would also help ensure that all whole life carbon calculations are fair and standardised, something shown not to be the currently the case within industry as different undertakers of whole life carbon comparisons have reached different conclusions for the same building [58]. More monitoring of embodied carbon within both future new construction and retrofit projects is highly important as it would also help us to understand and identify any potentially hidden hotspots of carbon which in turn may influence required retrofit rates and future intervention decisions.

The developed analytical expression demonstrates the connection between building form and total energy consumption. This not only has implications for retrofit decision making but also applications for future new constructions and planning approvals. For example, a system which flags new designs with very poor slenderness and aspect ratio combinations, would be highly useful as future new constructions also need to be as efficient as possible to reduce their whole life carbon footprint. Any designs which have highly inefficient forms should be justified, and ensured that their operational carbon is still below acceptable levels.

6.4 Limitations and recommendations for future work

The quality of building data at the national scale limits the conclusions that can be made for individual buildings within the English school stock. For example, though Chapter 5 demonstrates the importance of building form for retrofit prioritisation, due to inaccuracies in Verisk height data, archetype data is used implying that the building forms assessed are not fully reflective of actual buildings within the English school stock. We demonstrate that the developed model can achieve low average error across a set of 234 school case studies, but there is still very high error for individual schools, which again limits the level of detail for which conclusions can be made.

Embodied carbon data also varies widely between different sources. In Chapter 4, the differences between Part L2B and Enerphit total whole life carbon were found to be very small over a 30 year lifespan. Therefore, it is likely that using different embodied carbon data may impact the lowest whole life carbon retrofit solution for different forms. This finding further emphasises the importance of embodied carbon modelling within future work as the balance between operational savings and additional embodied carbon is shown to impact the final total carbon emissions. It should be noted that using different embodied carbon data is less likely to impact demolition versus retrofit comparisons, as the differences between the benchmark new construction values and retrofit whole life carbon is higher.

This thesis uses a process-based method for calculating embodied carbon which is shown to underestimate total emissions where comparisons are made to the Hybrid Input-Output method [122]. It would be useful to explore other methods of embodied carbon data collection, to understand what impact this may have on required retrofit rates for the English school stock.

Chapter 2, demonstrated the large focus of current case studies on countries in Europe, for which this piece of work has continued. The methods developed here can only be applied to currently naturally ventilated spaces, with mechanical ventilation only included as a retrofit measure. This makes the tool limited in scope to certain typologies and countries of a certain climate where mechanical ventilation and cooling is commonplace [313, 221]. Adapting the methods to include cooling energy consumption could be highly useful to make it applicable for countries all over the world.

The form of the developed analytical expression is shown to quantify energy consumption to the same extent as the established degree-days model. However, the simplifications made in this piece of work, when estimating the analytical constants (C_1, C_2 and C_3) are demonstrated to limit accuracy when estimating energy consumption of highly efficient buildings, such as those retrofit to Enerphit standards. Therefore, future work could create constants that can estimate consumption, to the same extent as the degree day's model, for all levels of energy efficiency.

Within Chapter 5, the significance of the embodied impacts of heat pumps is demonstrated. There is a need for lower upfront carbon solutions to make the most of the limited carbon budget. The considerable impact of replacement emissions, due to a heat pumps 15 year lifespan, also shows the benefits of research to incorporate circular design principles within future heat pump designs such as improved re-usability of individual components [314].

One limitation of this piece of work is the assumption that MEP requirements within building will remain steady between now and 2050. In fact, due to impacts of global warming there may be increased cooling needs which would have a significant embodied cost considering that the vast majority of schools are currently naturally ventilated [218]. Further research into whether we should be designing in-built adaptability into our retrofit installations could therefore be highly useful. For example, with the limited carbon budget for schools, it may be important to install measures which can be easily adapted for cooling, such as reversible heat pumps, rather than having to update all our stock again in the near future. This is dependent on many factors such as the predicted levels of warming in the future and at what point schools may require cooling systems.

It is also noted that this work does not account for installing retrofit scenarios which are optimal from a whole life perspective, for example the exact thickness of insulation for each building which would lead to the lowest total emissions. Chapter 5 demonstrates that prioritising retrofit of the least efficient buildings first can reduce the required retrofit rates for the English school stock, when trying to meet the CCC carbon budget. Using optimal retrofit scenarios would likely reduce this rate further, but to what extent is unclear and the influence of building form on these findings is also unknown. Chapter 4 demonstrates the delicate balance between improving efficiency and airtightness standards and the requirements for mechanical ventilation with the increased embodied cost of this measure.

The financial impact of retrofit has also not been considered in this piece of work. Therefore, though this study has shown the necessity of retrofit to limit the impacts of global warming, the extent to which the financial cost of this retrofit will act as barrier toward uptake is unclear. Future work which finds the most economically attractive pathway to decarbonising the English school stock could therefore be highly useful to help make this necessary retrofit as feasible as possible. This could include exploration of multi-objective optimisation which attempts to find the best reduction in carbon emissions for the lowest possible cost.

When it comes to demolition versus refurbishment, there are several limitations for the studied comparisons. This thesis does not account for potentially different lifespans of existing buildings versus new constructions, which was deemed acceptable as over 25 - 30 year study period, as the vast majority of Europe's current stock is predicted to still be standing [55, 56]. However, as it has been shown that demolition becomes a more favourable option over a longer lifespan, further research into the impact of this assumption would be useful. For example, past work which develops a durability based service life for an individual case study, demonstrates that large difference in lifespan between the existing and new construction [108].

Also, this thesis does not account for any required structural remediation measures, such as roof replacements, within existing buildings. 1% of the English school stock is found to be affected by RAAC concrete [304], which has a limited structural lifespan, showing why this may be necessary when making improvements to existing buildings. Accounting for this, where required, would undoubtedly increase the embodied carbon of a refurbishment project, and future work which accounts for changes to the building structure may lead to a more well-rounded view of when different building forms may require demolition.

6.5 Modelling assumptions and associated limitations

This thesis does not use real life metered data, but instead takes a modelling approach. Therefore, it is important to highlight that the conclusions within this thesis are dependent on core assumptions which are outlined and discussed as follows:

- **Energy modelling approach**. Heating energy consumption is modelled using CIBSE TM41: Degree days methodology [135]. Calculations are undertaken on an average monthly basis, with modelled heat losses balanced against heat gains for each month to estimate the total space heating required. As a comparison, these core assumptions are very similar to other existing models such as SBEM which also balances heat gains and losses on a monthly basis [222]. Hot water consumption is also calculated on a monthly basis by estimating the quantity of water used and the extent it is required to be heated [222]. Kitchen gas usage is modelled using CIBSE TM50:2021 [224] benchmark data and typical occupancy patterns to estimate the number of meals consumed and their associated energy consumption. Electricity consumption is calculated using a constant benchmark of $40kWh/m^2$. This simplified methodology is assumed acceptable as the focus of this thesis is on thermal retrofit, not lighting and equipment upgrades.
- **Inputs to calculate both baseline and retrofit energy consumption**. This includes assumptions on the efficiency of the building, such as the efficiency of existing and replacement mechanical systems (Table 3.1 and C.1) and the U-Value of existing and upgraded fabric elements (Table 3.1 and C.1). Further, assumptions have been made to calculate the total air leakage within the building, including both background infiltration and ventilation from opening windows during occupancy (Table 3.1, C.1 and 3.2). Occupancy itself has been modelled as constant between different typologies of school, which in turn assumes certain values such as total internal heat gains, the occupancy period, hot water usage and number of meals consumed (Table 3.2 and B.2 - B.4). These values will all impact energy consumption.
- **Embodied carbon assumptions for retrofit installations**. Embodied carbon data has been used which is aimed to be representative of each modelled retrofit material. Further, assumptions have been made on which retrofit measures are installed, aiming to be representative of school retrofit (Table C.2 - C.3). This includes the assumption of a 15

year replacement cycle for air source heat pumps, which is shown in Figure 5.7 to hold a significant proportion of whole life carbon emissions. In a critical review [264], the embodied carbon of different insulation types is compared using a functional unit (FU), designed to make comparisons over the same given thermal performance. Variations in embodied carbon are $1 - 5kgCO2_e/FU$ for EPS and $0.3 - 1.8kgCO2_e/FU$ for glass wool [264]. Therefore, as embodied carbon data can vary widely even for the same material and performance, changing the assumptions made may impact results.

- **Future scenario assumptions**. Three different future scenarios have been modelled for electricity and material decarbonisation, which demonstrates the large impact these assumptions can have on results. For example, Sections 5.3.2-5.3.3 shows that the the CCC carbon budget can only be met with some form of decarbonisation in these sectors. There is a multitude of other future variables which are assumed to be constant, one notable example being the temperature which is likely to change within the study period [40].

A full breakdown and description of these core assumptions and model input parameters is provided in Appendix E in the form of a flow chart.

Sensitivity analysis has been made on a proportion of the core assumptions, such as the three discussed material and electricity decarbonisation scenarios. Further, occupancy sensitivity analysis was conducted in Section 5.3.6 which altered the final energy load of the retrofit stock by $\pm 13\%$. Results show that the key conclusions within Chapter 5 remained the same, despite this change.

It has also been shown in Section 5.3 that baseline and retrofit energy consumption results are in line with other at scale modelling [134, 1] and embodied carbon data is in line with benchmark data [51]. However, demonstrating similarities to other modelling approaches does not necessarily solve the limitations of core model assumptions. The models that this thesis compares to could also have made similar assumptions that may not be accurate or have made different assumptions, in error, that still lead to the similar results. This potential issue is not a focus within this body of work. However, it should be acknowledged that this is a limitation of the work undertaken, and that all results are reliant on the assumptions made. The reader may want to ensure that they agree with all model inputs and assumptions before they agree with conclusions made.

Chapter 7

Conclusions

Mass retrofit of educational buildings is essential due to the current fabric inefficiencies and reliance on fossil fuel systems. In this piece of work, the impact of retrofit, for the English school stock, has been demonstrated while accounting for emissions over the entire lifespan of the building. This thesis advances our understanding on the impacts from including both whole life carbon and building form considerations within retrofit decision making.

This work presents a novel analytical expression, which can be used to present whole life carbon decisions graphically for many building forms. As new construction is not constrained by the existing form of the building, this provides an interesting comparison between demolition and new construction, which comes at a high embodied cost, and retrofit of the existing building, where highly inefficient forms are less able to achieve acceptable operational efficiency. Using this expression is shown to reduce the required retrofit rates to meet government targets by enabling prioritisation of retrofit of those buildings with the least efficient form and fabric.

The methods developed allow for time-efficient whole life carbon assessment of retrofit for many naturally ventilated buildings. It allows for a more comprehensive understanding of non-residential stock as current individual studies vary widely in system boundaries.

By applying these methods to the English school stock, insights into the impact of retrofit are provided. A dramatic increase in retrofit rates, by 10 - 50 times from current practice, alongside decarbonisation in other key sectors is required to meet government targets. Results also reveal that demolition and reconstruction at scale is not feasible if targets are to be met, emphasising why whole life carbon comparisons should be undertaken.

7.1 Summary of key findings and contributions to knowledge

Research question 1 - ***What influence does building form have on the lowest whole life carbon intervention for existing buildings?***

- This research question seeks to understand the key characteristics of a building which drive retrofit decisions from a whole life perspective. As non-residential buildings are shown to vary more widely in size and shape than residential [150, 151], the influence of building form varies more widely within this stock type. Therefore by answering this question, this work aims to provide a comprehensive understanding of how whole life carbon decision making changes between a wide range of different buildings, addressing the lack of standardisation between current whole life case studies in a computationally time efficient manner.
- The research question has been answered through the development of an analytical expressions which demonstrates the parametric contribution of building form to both energy consumption and whole life carbon. By expressing the value as an analytical expression rather than a single value, the influence of different fabric element efficiencies can also be accounted for.
- It is shown that those buildings of a high slenderness combined with a low aspect ratio are the least efficient in form, causing an increase in thermal energy consumption. Buildings with a worse fabric efficiency have a wider relative variation in energy consumption due to building form than those that have been retrofit to a higher standard.
- The analytical expression has been applied to typical future intervention decisions, to understand how building form influences future decision making. It is shown that only a small proportion of the most inefficient forms would benefit from demolition, over the 30 year lifespan, and that more efficient forms require less intervention from a retrofit perspective to still achieve low total whole life emissions. If the upfront embodied carbon of new construction can be reduced then the demolition versus refurbishment comparison becomes more influenced by building form.
- It is also shown, when applying whole life carbon retrofit modelling to the English school stock, that prioritising retrofit of buildings of the worst efficiency can reduce the required

retrofit rate to meet the CCC carbon budget. This includes accounting for not only fabric but form efficiency, showing the importance of building form in future decision making.

Research question 2 - ***What intervention is required to the existing building stock when considering a stock's carbon budget?***

- This research question seeks to address the whole life impact that retrofit can have on the total carbon emissions of the English school stock. Existing past work has focused on residential buildings [50] or only from an operational perspective [134]. By answering the question, this piece of work aims to provide comprehensive insights into the barriers and the pathways in which these government targets can be met.
- This question has been answered through the development of a method which can apply retrofit modelling to a wide range of different building forms, at scale. The model has been demonstrated through validation to 234 metered energy consumption case studies and application to approximately 20,000 equivalent schools.
- Retrofit modelling of the English school stock shows that, though retrofit can be used to meet the CCC budget, retrofit rates must increase significantly from current government targets. This must also be paired with significant decarbonisation in other sectors such as electricity and materials.
- Results show that meeting our most stringent carbon budget would be very difficult. Even with instantaneous retrofit, the use of low carbon heat pumps and extreme decarbonisation of the electric grid, the embodied impacts of retrofit push whole life emissions over this limit.
- Heat pumps pose a whole life carbon hotspot, even if low carbon refrigerants are used. Therefore, future research aiming to develop low embodied carbon heat pumps would be highly beneficial with far reaching impacts, especially considering that different national governments put heat pumps at the centre of their decarbonisation plans [98, 96].
- Comparing demolition versus refurbishment at scale, over a 25 year period, showed that no school would benefit from demolition unless currently unrealistic building standards are achieved, an embodied carbon of $260kgCO_2e/m^2$. If these standards are achieved then those with poor building form may benefit from demolition. However in the case of the school stock, these buildings typically have small floor areas so would make limited

difference to total carbon emissions.

- Making the same comparison, but over a 60 year period, showed more buildings may benefit from demolition. However, the majority of the total stock's floor area should be retained. This is especially the case when some form an electricity decarbonisation occurs - something which is shown to be necessary to meet the CCC carbon budget.

Appendix A

Chapter 2 supporting information

This appendices outlines the methodology for the systematic collection of literature, used within Section 2.1 to define and understand the key characteristics of relevant building retrofit case studies.

A.1 Methodology of systematic literature review

First, both Scopus [66] and Web of Science [67] are used to retrieve literature, based on the following key word search:

(Retrofit OR renovation OR Refurbishment or renovate or refurbish) AND (building OR dwelling OR office OR school OR hotel OR house OR property OR 'non-residential' OR residential) AND ('embodied impact' OR 'embodied carbon' OR 'embodied energy' OR 'whole life impact' OR 'LCA' OR Life-cycle assessment').

All data was collected on the 15th of April 2024. Only publications from international peer-reviewed journals, which are published in English were analysed. Dissertations, theses, datasets, awarded grants and conference papers or proceedings are not included within the dataset. This leaves a total of 1019 journal papers for analysis.

A keyword search is then conducted on journal article titles to remove any publications which are not related to occupied buildings:

Bridge, highway, ship, vehicle, wastewater, boat, water treatment, furniture, laptop, railway, coastal, offshore, mine, marine, streetlight, embankment, vessel, WEEE, stormwater, carbon capture equipment, *aviation fuel, road, Dam, civil infrastructure*

It should be noted that the entire title of the article is read when undergoing this filtering process to ensure that the paper is actually irrelevant. A total of 977 papers remained. At this stage bibliometric analysis is undertaken to ascertain progress in the field as a whole.

A.1.1 Case study analysis

Within the systematic review, analysis of case studies of the whole life impacts of building refurbishment are focused upon. Therefore, manual screening of each paper is undertaken to isolate only building case studies and their key characteristics. To be classified as a **case study** the publication must meet the following criteria:

- Apply the methodology within the paper to a building case study. Building case studies were identified as occupied buildings with a defined location or climate. For example, those papers which assessed only the impacts of an individual retrofit measure were not counted, but those which assessed the impacts of that retrofit measure when it is applied to a building were included.
- Assess the impact of both materials and energy consumption within the retrofit case study results. Therefore, to be considered, a publication must have quantified the impacts from retrofit using system boundaries which do not merely calculate the operational impacts. As a minimum, both the cradle to gate (stages A1 - A3) and the operational impacts (B6) of retrofit material use were included. Those case studies where it was unclear whether both stages A1-A3 and B6 were included were excluded from the study.
- As long as this criteria was met the impact category used within each publication was not critical to being included as a whole life retrofit case study. However, these impact categories must relate to environmental impacts and therefore purely economic studies would not be included. A list of the environmental impacts within each case study is provided:
  - Carbon emissions [$kgCO_2$]
  - Carbon equivalent emissions [$kgCO_2e$] - also referred to as greenhouse gas emissions and global warming potential (GWP).

- Total energy consumption [MJ or kWh]
- Other environmental impact categories which are commonly undertaken within LCA assessments such as:
  * Particulate matter [PM]
  * Ecotoxicity (Freshwater/Marine) [$CTUe$]
  * Eutrophication (Freshwater/Marine/Terrestrial) [$kgPeq./kgNeq./molNeq.$]
  * Ozone Depletion [$kgCFC11eq$]
  * Acidification [$molH + eq.$]
  * Photochemical ozone formation [$kgNMVOCeq.$]
  * Depletion of Abiotic Resources [$kgSbeq.$ or MJ]
  * Human Toxicity (Cancer/Non-Cancer) [$CTUh$]
- Measures of environmental impact which brings together many impact categories into a single value. A notable example is the ReCiPe method where environmental indicators are classed as 'Damage to human health', 'Damage to ecosystems' and 'Damage to resource availability' [315].

In reality, even if other environmental indicators are analysed they are often modelled alongside either carbon or carbon equivalent emissions or embodied energy consumption. In fact 95% of publications gave either explicit carbon or carbon equivalent emissions or embodied energy consumption. The impact category is dominated by carbon or carbon equivalent emissions with 86% of case studies containing assessment of this impact category.

• Each case study must also include some form of energy retrofit within the assessment. Energy retrofit is defined here as any form of intervention on an existing building which is designed to reduce the operational environmental impact of the building.

This can be in the form of fabric measures (such as insulation, airtightness improvements or window replacements), mechanical systems replacements (such as replacing existing systems with more efficient ones or installing new systems to improve efficiency) or renewable energy systems (such as solar PV). Other types of retrofit, renovation and refurbishment will be excluded. For example, assessments of renovation and maintenance that only include minor decorative elements such as painting and varnishing or changes to interior furniture do not count within this study. By isolating only retrofit studies which have included stages A1-A3 and B6 - these study boundaries should help keep the focus on the energy retrofit. For example, structural retrofit studies, unless undertaken alongside energy retrofit, typically only include upfront emissions as the retrofit itself does not impact operational emissions.

- The intervention described in the publication must have been applied to an existing building. If a paper only assessed new constructions it was not classed as a retrofit case study.

A total of 289 publications with appropriate case studies are found. The following characteristics of each case study are then studied

- Country/countries of case study.
- Time frame of the case study. This has been split into three categories, defined as follows:
  - **Building lifespan** is defined as the remaining modelled lifespan or service life of the refurbished building.
  - **Study period** is the assessment period of the whole life impact assessment when building lifespan is not provided.
  - **Not stated** refers to studies where no building lifespan or study period is provided with enough clarity to be counted.
- The building typology.
- The system boundaries of the whole life carbon assessment. This refers to the scope of whole life assessment undertaken by publications (where clearly explained), split by LCA stages as defined by BS EN 15643-4:2021. Stage B5, titled refurbishment, was not included in the results as each case study has already been found to be a refurbishment case study.
- The scale of the case study. To be seen as an 'at scale' case study the publication must meet the following criteria:

- Investigate the impact of multiple buildings within a defined geographical scope, such as through the use of representative archetypes, while also demonstrating the level of representation of those buildings, such as total number of buildings or total conditioned area, within the geographical boundaries of the study.
- Some level of 'at scale analysis' must be included in the study. At scale analysis in this study is defined as providing analysis or understanding of the total impacts for the described system boundaries (both typology and geographical). This means that studies must go beyond separately analysing different buildings and understand the impact for the entire stock that is being analysed. These results can still be normalised as long as the proportional impact of each building type assessed is accounted for. Also, different archetypes can be assessed separately as long as the number of buildings within each archetype is provided for the system boundaries, to allow for understanding at scale.

Therefore, assessment of a single archetype which merely claims to be typical or representative of large amounts of stock or studies which assess archetype buildings individually without providing their relative representation within the system boundaries would not be classed as at scale. Each case study could focus on one typology within each region and still be classified as assessing impacts for that geographic boundary.

The scale category is also split into several more precise categories:

Campus - studies which assesses the impacts of a whole educational campus.

Sub-urban - studies which look at geographical boundaries within an urban area, but not to an entire sub-national extent. This includes analysis of districts, neighbourhoods or streets within an urban area such as a city, town or village.

Sub-national - studies which look at geographical boundaries within a country, but not the entire national stock. This includes analysis of an entire city or region within a country.

National - studies which assess the impacts of an entire country.

Continental - studies which assess the impacts of an entire continent.

Global - studies which assess the impacts of the entire world.

These studies are then isolated for further analysis leaving **47 publications**.

Appendix B

Chapter 3 supporting information

This appendices provides supporting information regarding the energy modelling of the 234 case studies which were used to validate the developed method.

Firstly, all inputs used within the energy model are outlined, followed by an assessment of outlier results within the dataset. Finally, the rationale for classifying shed-like buildings which are then excluded from the total heated floor area of the stock.

B.1 Inputs

Energy modelling at scale depends on gathering an appropriate set of input data which can be used to represent large amounts of stock. Tables B.1 - B.6 provide details of all the inputs used within the energy modelling. This information has been gathered from various sources, which provide typical building, occupancy and weather information for UK school buildings.

Where each model input is provided, this section also includes a description of each input and a reference for where each value was sourced.

B.1.1 Building Inputs

Calculating the thermal time constant, τ, is required to account for thermal mass within the degree-days energy model [135], as it helps to define the response time of a building to temperature changes. To estimate τ, the thermal capacitance , c, must first be calculated based on the characteristics of each exposed material, n, within a building:

$$c_n = \rho_n cp_n d_n. \tag{B.1}$$

where the density $[kg/m^3]$ is ρ, the specific heat capacity $[kJ/kg.K]$ is cp, and the exposed thickness $[m]$ is d.

In this piece of work c is assumed to be constant between buildings, based on the typical exposed materials within a school, with data provided in Table B.1. It is assumed that the wall has a plasterboard finish, ceiling is a suspended ceiling system and floor has a carpet/lino finish [131].

Table B.1: Properties of the first insulating layer, or exposed material, of each internal element. These in turn are used to estimate the thermal time constant of each building.

		Value	Unit	Symbol	Notes	Ref
Wall	Density	700	kg/m^3	ρ_w	Plasterboard finish	[131]
	Heat capacity	1	$kJ/kg.K$	cp_w		
	Exposed thickness	0.0125	m	d_w		
Window	Density	2500	kg/m^3	ρ_g	4mm panes	[131]
	Heat capacity	0.84	$kJ/kg.K$	cp_g		
	Exposed thickness	0.004	m	d_g		
Ceiling	Density	700	kg/m^3	ρ_c	Suspended ceiling	[131]
	Heat capacity	1	$kJ/kg.K$	cp_c		
	Exposed thickness	0.0125	m	d_c		
Floor	Density	800	kg/m^3	ρ_f	Lino/Carpet finish	[131]
	Heat capacity	1.1	$kJ/kg.K$	cp_f		
	Exposed thickness	0.0085	m	d_f		

B.1.2 Occupancy inputs

Occupancy inputs, refers to those which are directly controlled by occupants. The set-point temperature is set as 19$°C$. This value is chosen as the minimum internal temperature in schools should be $18°C$ [316] and CIBSE internal temperature guidance ranges between 19-21$°C$ [316, 131]. Therefore $19°C$ is deemed sensible.

Internal gains within the degree-days model must be averaged over 24 hours. Using typical occupancy schedules (χ_{oc}, χ_e and χ_l as provided in Table B.3) and the maximum occupancy internal gains for each zone, (q_{oc}, q_e and q_l as shown in Table B.2) average daily internal gains can now be estimated for each zone within the school ($q_o = \frac{1}{24}\sum_{hrs}^{24}(q_e\chi_e + q_l\chi_l + q_{oc}\chi_{oc})$).

Internal gains, as well as hot water usage, not only change throughout the day but also between different zones within the school. The proportion of each key zone within each type of school is provided in Table B.2, based on typical area guidelines [17]. Typical internal gains and hot water usage were calculated using an area weighted average of an aggregated space breakdown for a school [17].

For hot water consumption, typical daily usage for each zone is found [L/m^2] [131, 24]. Kitchen water usage is included in within the typical kitchen gas usage, κ [224]. Therefore any kitchen hot water usage is excluded from the calculations.

A relatively high occupancy density is predicted for each space. This leads to area weighted values of 0.36-0.38 $people/m^2$ which is equivalent to that of a classroom [317]. In fact, area guidelines shows a typical pupil to floor area ratio of 0.07 - 0.21$pupils/m^2$, which is a much smaller value [17]. The high occupancy density value will be used to estimate ventilation losses due to the modelled natural ventilation. Therefore the value has been kept high to make a simplified assumption of the same ventilation patterns, to that of a classroom, throughout the entire school. This also helps account for any scenarios where windows remain open throughout unoccupied hours or the school is used out of hours for different purposes. This value is also used to predict kitchen gas usage and therefore assumes a reasonably wasteful use of gas in each school.

The model is also dependant on defining key monthly data, including the total occupied days, the total heated occupied days and the monthly average temperature difference between incoming cold water and outgoing hot water which are shown in Table B.4.

Table B.2: Table to show the area weighted proportion of water usage [L/m^2], occupancy density [$people/m^2$], and occupant, lighting and equipment internal gains [W/m^2] for each educational typology. This calculation is calculated using typical area guidelines for schools [17], which defines the proportion of total space taken up for specific purposes.

	Primary	Secondary	College	l_z [L/m^2]	o_d [p/m^2]	q_{oc} [W/m^2]	q_{eq} [W/m^2]	q_{li} [$W m^2$]
Zone:	p_z	p_z	p_z					
Teaching	0.5	0.46	0.46	1.35	0.67	53	10	12
Hall	0.07	0.1	0.09	0$\star$	0.1	9	5	12
Library	0.02	0.02	0.06	1.35	0.08	9	15	10
Staff and Admin	0.05	0.03	0.03	0.19	0.08	6.7	15	10
Changing rooms*	0	0.04	0.04	30	0	0	0	0
Float**	0.04	0.06	0.04	0.19	0.23	18.9	11.3	11
Non-net	0.33	0.24	0.29	0.06	0.1	9	5	12
*Changing Rooms: Provided for 50% of a single year group at $1.6m^2/person$ [17, 318]. **Float: Average of all areas. $\star$ Kitchen hot water usage accounted for in $F_{kitchen}$								
References: [17, 131, 24]								

Table B.3: Typical occupancy, lighting and equipment schedule for a school [18]. Data is provided hourly and averaged over 24 hours for the purposes of inputting into the degree-days model, using equation 4.14. χ is the sum of total occupied hours over 24 hours provided as a fraction in this table.

	Gains fraction		
Time period	Occupancy	Equipment	Lighting
00:01 - 07:00	0	0.05	0
07:01 - 08:00	0	1	1
08:01 - 09:00	0.1	1	1
09:01 - 10:00	0.75	1	1
10:01 - 12:00	1	1	1
12:01 - 14:00	0.5	1	1
14:01 - 16:00	1	1	1
16:01 - 18:00	0.5	1	1
18:01 - 21:00	0	1	0
21:01 - 00:00	0	0.05	0

Table B.4: Key monthly data which includes the total and heated occupied days for school buildings and temperature difference between incoming cold and heated water. The heated occupied days, or heating season, is assumed to be from mid October to mid April.

Month	Occupied days	Heated occupied days	Hot water $\Delta\theta_m$
Jan	23	23	41.2
Feb	15	15	41.4
Mar	13	13	40.1
Apr	12	6	37.6
May	18	0	36.4
Jun	22	0	33.9
Jul	17	0	30.4
Aug	0	0	33.4
Sep	22	0	33.5
Oct	18	9	36.3
Nov	22	22	39.4
Dec	13	13	39.9
References:[223, 236, 237]			

B.1.2.1 Occupancy comparisons to metered energy consumption

To calculate electricity consumption $[kWh]$, $F_{electricity}$ a constant benchmark $[kWh/m^2]$ of $\epsilon = 40$ is used. This has advantages over modelled data, as it is based on actual in-use metered energy consumption and has also been validated against recent metered data in Section 3.2.1.4.

In contrast, to calculate internal heat gains, typical occupant, lighting and equipment gains values and occupancy schedules have been used to estimate the 24 hour average internal gains to the space (kW/m^2). This was undertaken instead of using metered data as it allowed for the heat gains from occupants to be accounted for. Within heating consumption calculations, a gains utilisation factor is then calculated to understand the useful gains e.g. the extent to which these internal gains are heating the space [135].

CIBSE Guide A states that all electrical energy used by a lamp is ultimately released as heat and that, for computers and office equipment, the total internal heat gains are equal to the total power input [46]. As we average all internal gains over 24 hours, this value could be used to make a simplified estimate of total electricity consumption [kWh], $F_{electricity}$ as follows:

$$F_{electricity} = 24q_{e+l}n_{(o)} \tag{B.2}$$

where q_{e+l} is the 24 hour average internal gains for equipment and lighting [kW/m^2] and n_o is the total occupied period in a year [$days$].

Therefore, we can compare this result to metered data, to ensure that internal gain calculations are in a similar magnitude.

Results provide a value of $47kWh/m^2.yr$ in comparison to the $\epsilon = 40kWh/m^2.yr$ that is based on metered results. These values are similar and within the correct magnitude which implies that internal gains values and occupancy schedules do reflect a typical school building.

B.1.3 Weather inputs

Table B.5: Average Met Office monthly outdoor temperature data [$°C$], for the different regions [19]. NI = Northern Ireland, SN = Scotland North, SE = Scotland East, SW = Scotland West, EE, England East and North East, EN = England North West and Wales North, M = Midlands, EA = East Anglia, ES = England South West and Wales South and EC = England South East and Central.

Month	NI	SN	SE	SW	EE	EN	M	EA	ES	EC
Jan	5.5	4.8	4.1	5.2	4.3	4.7	4.3	4.5	5.2	4.8
Feb	5.7	3.4	3.6	4.8	5.7	6	6.5	6.8	7	7.1
Mar	6.6	5	5	5.9	6.9	7	7.4	7.8	7.8	8.1
Apr	8	6.4	6.4	7.4	8.2	8.1	8.8	9.3	8.9	9.4
May	11.8	9.7	10.3	10.8	12.2	11.8	12.8	13.5	12.3	13.3
Jun	13.3	12.2	12.6	12.8	14.4	13.6	14.8	15.7	14.2	15.5
Jul	15.5	13.4	14	14.6	17.6	16.23	18.1	19.3	17.1	19
Aug	15.5	13.2	14.3	14.5	17.2	16.5	18.3	19.7	17.9	19.5
Sep	13.1	11.6	11.9	12.5	13.7	13.4	14.1	15.1	14.1	14.9
Oct	11	9.3	9.5	10.4	11.7	11.7	12.4	13.4	12.8	13.6
Nov	8	6.7	6.5	7.6	8	8.3	8.6	9.4	9.3	9.8
Dec	3.4	1.5	1.1	2.4	2.9	3	3.2	3.7	4.1	4.1

Table B.6: 24-hour averaged monthly solar irradiance from the National Renewable Energy Laboratory - averaged over North, South, East and West facing walls [W/m^2], for the different Met Office regions [20].

Month	NI	SN	SE	SW	EE	EN	M	EA	ES	EC
Jan	18.4	18.9	18.9	18.9	20.8	16.9	21.1	22.9	21.1	25.3
Feb	34.1	37.3	37.3	37.3	36.3	35.8	38.8	37.9	38.8	36.4
Mar	53	60	60	60	55	53.1	62.1	55.5	62.1	51.1
Apr	70.7	74.5	74.5	74.5	76.4	80.8	84.7	80.7	84.7	77.2
May	98.8	90.6	90.6	90.6	92.6	94	99	99.7	99	95.2
Jun	89	96.8	96.8	96.8	94.8	92.1	104.4	95.8	104.4	89.1
Jul	82.3	94.8	94.8	94.8	97.2	85.6	105.8	98.5	105.8	94.1
Aug	76.4	79.8	79.8	79.8	85	82	93.3	90	93.3	89
Sep	64.1	63.3	63.3	63.3	65.2	67.7	72.2	73.6	72.2	71.1
Oct	41.3	38.3	38.3	38.3	36.4	41.5	47.6	50.5	47.6	50.4
Nov	22.8	23.2	23.2	23.2	23.2	23.6	26.3	24.9	26.3	30.3
Dec	13.1	12.5	12.5	12.5	15.9	14	18.5	15.4	18.5	17.6

B.1.4 Additional case study information

This section outlines the investigations into anomalous results, see Chapter 3 Section 3.3.1, and the reasons why alternative data was used. This section also includes the overall study results if anomalous data were used. Following this, the system boundaries for polygon classification is outlined, with the rationale for which polygons are to be classed as unheated sheds.

B.1.4.1 Outlier schools investigations

As referred to in Section 3.2 the most recently available DECs data is used in all results, Section 3.4, for all schools except for 9 secondary schools that were all built under the same scheme, using biomass fuel.

Different data points were used for these 9 schools as it was found that from 2021 (after all schools had already been constructed), every school built within the same scheme had a 'Renewable thermal energy production' above zero. Alongside this change, the total measured thermal energy consumption for each school dramatically increased.

With biomass being the adopted thermal fuel, it would make sense for the 'Renewable thermal energy production' to equal that of the total thermal consumption. However, this is not the case. In fact it is unclear where this 'Renewable thermal energy production' is coming from or why after 2020, the total thermal energy consumption increases so dramatically, as demonstrated in Table B.7.

Potential reasons for this jump in thermal energy consumption include some form of double counting happening within the DECs assessment, or that these schools have started producing renewable heat for other buildings.

As this pattern cannot be explained, 2020 data has been adopted for these schools. However, for the sake of transparency, the results using most recent DECs are given below in Tables B.8. This shows a slight increase to average absolute error and a large impact on the R^2 value reducing from 0.85 to 0.69 for the manually (MM) data collection method. This implies using more recent DECs data for these schools causes much higher spread in results.

Table B.7: Metered thermal energy consumption data over the past 5 years for the nine anomalous schools. Where data is not available for a certain year, the cell is left blank.

	DECs thermal energy consumption data [kWh/m^2] [Renewable Fuel Thermal [kWh/m^2]]				
School	2023	2022	2021	2020	2019
S1	134 [34]		163 [25]	91 [0]	88 [0]
S2	186 [29]		198 [24]	128 [0]	107 [0]
S3	204 [28]	195 [29]	171 [33]	120 [0]	120 [0]
S4	147 [28]	169 [30]	103 [40]	78 [0]	
S5	188 [25]	177 [0]	135 [29]	74 [0]	113 [0]
S6	192 [21]	178 [25]	171 [28]	68 [0]	
S7	209 [29]		194 [5]	98 [0]	102 [0]
S8	125 [27]	111 [19]	129 [31]	93 [0]	85 [0]
S9	187 [27]	165 [25]	153 [25]	95 [0]	125 [0]

Table B.8: Percentage error and linear regression results. See Section 3.3.3, Table 3.3 for a breakdown of each data collection method Verisk only (VO), Using both Verisk and manual methods (VMN and VML) and manual methods (MM).

		Average percentage error	Absolute average percentage error	Maximum error	R^2
Excluding properties with pools	VO	97.6	111.5	1344.4	0.4
	VMN	2	31.7	265.3	0.69
	VML	7.3	32.3	265.3	0.68
	MM	6.2	29.5	259.1	0.69

B.1.5 Shed-like building classification

This section aims to distinguish between Verisk polygons which are heated and which are unheated spaces such as sheds. Smaller buildings are more likely to be sheds or polygons created in error.

To estimate the cut off value for which sheds are classified, the entirety of the Verisk UK educational building stock was analysed. An assessment of the distribution of total building plan areas (m^2) is demonstrated in Figure B.1. Figure B.1 shows that there are several peaks within the distribution of total plan area.

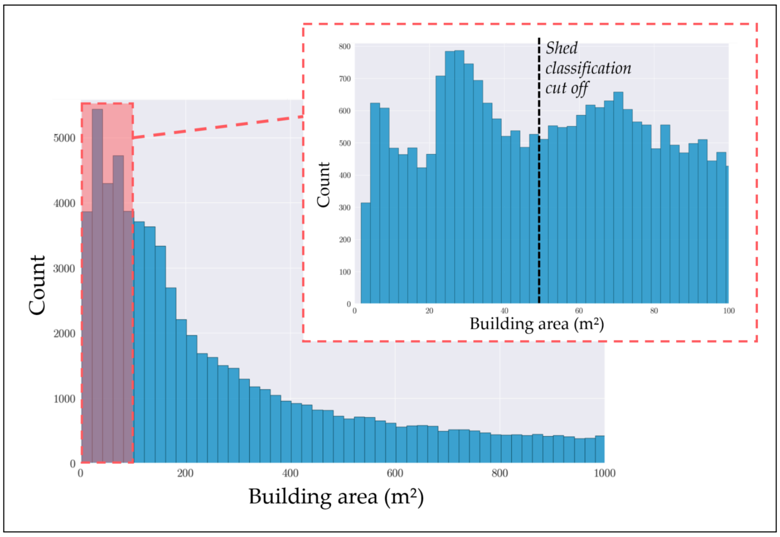


Figure B.1: Distribution of building areas within UK educational buildings, as defined by Verisk UKBuildings.

It is assumed that the first peak within the distribution would likely be shed-like buildings and the second peak value the distribution of occupied buildings. Zooming in further into the smaller plan areas shows two smaller peaks. One has an average value of $2.5 - 5m^2$ and the other $27.5 - 30m^2$. Both these distributions, cut off at the black line in Figure B.1, are classed as shed-like buildings as the standard classroom size is between $43 - 60m^2$ so even a single classroom is likely to be larger than these values [260].

This was also corroborated through assessment of the 234 case study during manual data collection of the number of floors, See Section 3.3 for methodology.

For both these reasons, a cut-off polygon size of $<= 50m^2$ was adopted and will continue to be adopted in future work, such as the developed energy model for all English schools.

Appendix C

Chapter 4 supporting information

This appendices provides supporting information for Chapter 4. This begins with the evidence of unrealistic forms within the Verisk polygon database. This evidence provides further discussions regarding where the assumption of rectangular form is appropriate within the educational building stock.

Following this, sensitivity analysis is provided analysing the impact of the simplifications made to solar gain analysis. From these results we can infer it is acceptable to assume an equal glazing ratio, g, and solar gain factor [kWh/m^2], q_n, for each wall within a building for the English climate. The next section analyses the differences between the degree-days model and the analytical expression, when using the simplified constants (C_1, C_2 and C_3). From this, a transition period is created defined as the results where inaccuracies in the simplified constant calculation impact which intervention measure provides the lowest whole life carbon solution.

Finally, data is provided which allows for whole life carbon modelling to be undertaken for different typical intervention scenarios. This includes fabric efficiency inputs, embodied carbon data of retrofit measures and different material and electricity decarbonisation scenarios.

C.1 Evidence of unrealistic forms within Verisk

This section provides examples of building forms within Verisk which are not realistic.

When assessing the top 100 highest residuals, there is evidence of inaccurate polygons within the Verisk database, leading to unrealistic building forms. These classifications have been found through analysis of each high error Verisk polygon, alongside Google map satellite view.

Examples of these unrealistic forms are demonstrated in the Figure C.1, where non-building structures have been classed as polygons. This has caused highly complex forms through either joining together buildings that are in fact separate or classification of attached walls as polygons. from Figure C.1 we can infer that if you removed those inaccurate connections

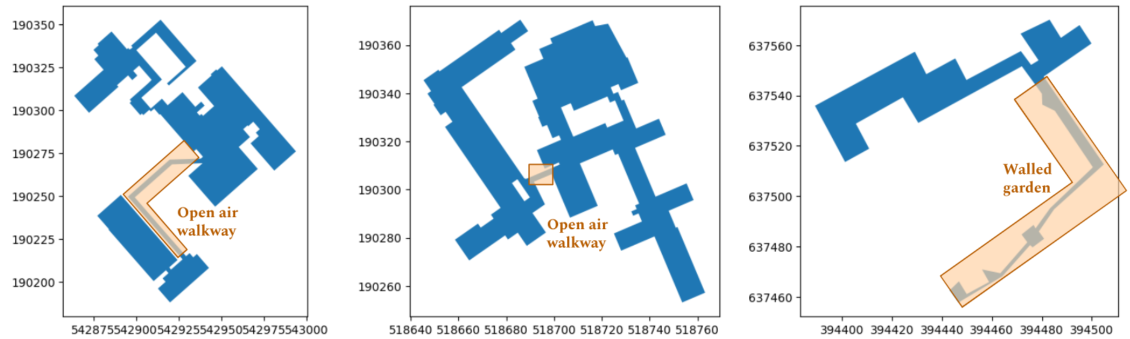


Figure C.1: Examples of unrealistic or inaccurate forms within the UKBuildings Verisk database. The inaccurate section of the polygon is labelled, which has been verified using Google map satellite imagery.

this would lead to a much more rectangular form than is currently present. Therefore, there are likely even more forms within the Verisk database for which rectangular form can be assumed.

C.2 Solar gain sensitivity analysis

The degree-days model assumes all solar gains are averaged over a 24 hour period as demonstrated in Table B.6. Further simplifications have been made in this model where an average value of solar gain, q_{sol}, has been estimated assuming a south facing square box with equal glazing ratio on each face:

$$q_{sol} = \frac{1}{4}(q_{north} + q_{east} + q_{south} + q_{west}) \tag{C.1}$$

A constant value of solar heat gain, q_{sol}, and a constant glazing ratio, g, for each wall of the building are assumed. In reality these differ between buildings with different orientations and glazing ratio between walls of each building. Therefore, sensitivity analysis is required to quantify the difference this makes while using the degree-days model.

Assuming rectangular form, both solar heat gain and glazing ratio can be expressed as a function of the building aspect ratio, r:

$$q_n = \frac{q_{(n)}g_{(n)} + q_{(n+180)}g_{(n+180)}}{2(r+1)} + \frac{(q_{(n+90)}g_{(n+90)} + q_{(n+270)}g_{(n+270)})r}{2(r+1)} \tag{C.2}$$

where n is the reference angle [°], defined as the position of the longest wall of each building, with 0° representing a north facing wall. Therefore, q_n can be estimated for every wall of each building for the UK educational stock. Each wall also has its own glazing ratio, g_n.

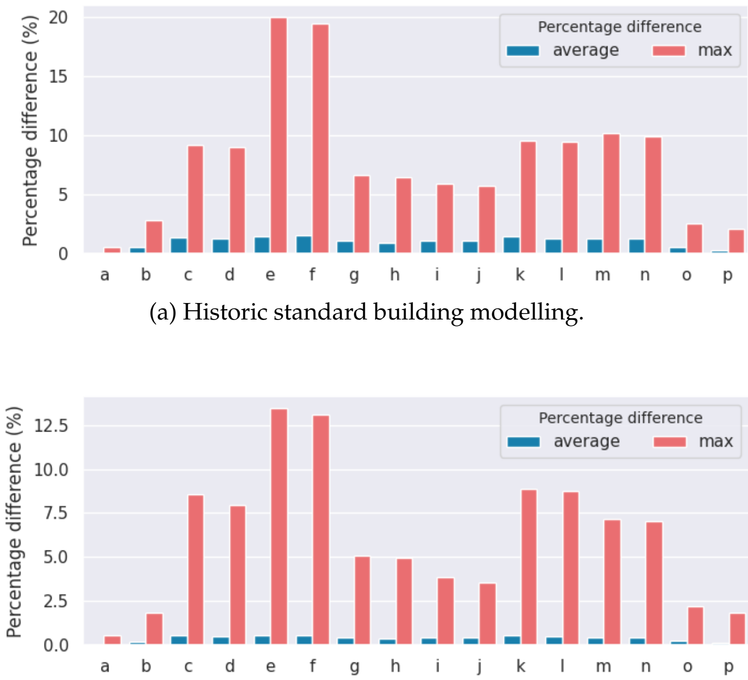
The reference angle for every polygon within the UK Verisk polygon database is calculated to the nearest five degrees. Average daily solar gains are also calculated for each possible angle of wall.

Each polygon is run through the degree-days model twice, the first assuming a constant glazing ratio and solar gain factor and the second adopting methods outlined above. The glazing ratio was altered for each wall, ranging between a minimum value of 10% and 80%. This provides 16 combinations of glazing ratio which were all explored as shown in Figure C.3. Results are provided for historic and Enerphit building performance levels.

As expected, Figure C.2 shows there is a larger difference between results at higher glazing ratios. The maximum percentage difference is high, especially for the scenarios where the glazing ratio differs widely between each wall. This maximum value is 20% from a building which has a Length of 39.9m and a Width of 1.9m, a particularly thin and possibly unrealistic shape. However, the difference between using average and individual glazing ratios is on average still very small for all combinations, never being above 2%.

	Wall – glazing ratio (%)			
	n	n + 90	n + 180	n + 270
a	10	10	10	10
b	10	10	10	80
c	10	10	10	80
d	10	10	80	80
e	10	80	10	10
f	10	80	10	80
g	10	80	80	10
h	10	80	80	80
i	80	10	10	10
j	80	10	10	80
k	80	10	80	10
l	80	10	80	80
m	80	80	10	10
n	80	80	10	80
o	80	80		10
p	80	80	80	80

Figure C.3: Table to show the glazing ratio, g, of each wall for every scenario that has been modelled in Figures C.2a - C.2a. Each letter refers to the same letter along the horizontal axis of each figure. Yellow boxes highlight a 10% glazing ratio and blue 80%.



(a) Historic standard building modelling.

(b) Enerphit standard building modelling.

Figure C.2: Maximum and average differences in results when accounting for changes in glazing ratio and solar gain factor between different walls (See equation C.2), compared to using average values (See equation C.1).

This result demonstrates that for cool-temperate climate, the differences in glazing ratio and solar heat gain ratio for different walls make a minimal impact on the average results, allowing for the exploration of building form without the inclusion of these differences. In fact, where a large impact has been found at high glazing ratios, likely relates to unrealistic and uncommon polygons within the built environment. In different climates these results may change and an additional factor that is described in Equation C.2 can be used to adapt the model. This factor still only relies on aspect ratio, so the analytical expression could be adapted.

C.3 Analysing the transition period

Section 4.4.2.3 shows that, at very high fabric and ventilation efficiencies, the model begins to overestimate values as building forms become more inefficient. To understand the impact of this, this section aims to understand the patterns between overall fabric efficiency and differences between the analytical expression and degree-days model.

The heat loss coefficient, U', will be used to represent the fabric efficiency of each scenario. As this value typically changes between different building forms a constant value, U'_c has been estimated which aims to provide an indicator of fabric performance which is independent of form:

$$U'_c = \frac{1}{1000} 2U_{av} + \frac{2N}{3S_c} \tag{C.3}$$

where U_{av} is the area weighted U-Value $[W/m^2K]$, N the total ventilation rate $[hr^{-1}]$, and S the typical surface area to volume ratio $[\frac{1}{m}]$. Though this value is a simplification of the actual heat loss coefficient, the following results show that, despite simplifications, this value is still analytically connected to the transition period, for many different building forms.

A range of heat loss coefficients have been plotted against the comparison between degree-days modelling and the analytical expression:

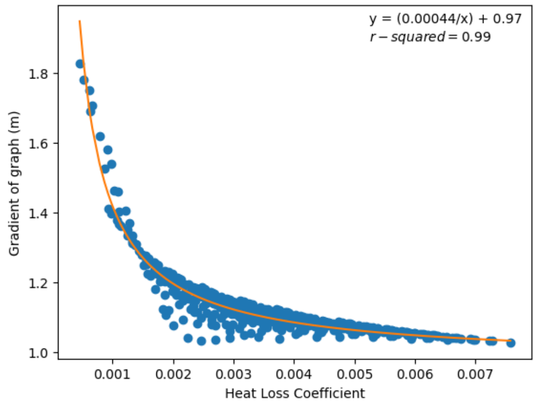
1. For each heat loss coefficient, the heating energy consumption is calculated using the degree-days model, for a sample of 1000 polygons.
2. For each heat loss coefficient, the heating energy consumption is calculated using the analytical expression, for the same sample of 1000 polygons.
3. Both these results were used to find the equation of best fit between these two values ($y = mx + c$). If $y = x$, this would infer that the degree-days model and the analytical expression retrieve are exactly the same results.
4. The gradient (m) and the constant (c) were then plotted against the heat loss coefficient as demonstrated in Figure C.4 for a building with a heating system efficiency of 1. Therefore, results will show how the building heat loss coefficient influences the extent to which the analytical expression varies from the degree-days model.

These Figures show that m can be expressed as the following function:

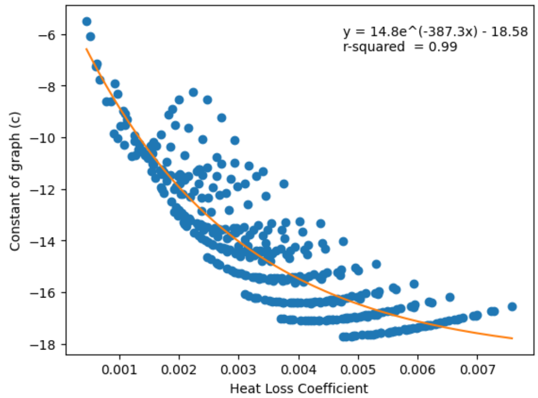
$$m = \frac{0.0004424}{U'_c} + 0.973 \tag{C.4}$$

Within Figure C.4b the values of c are shown to have an additional discrete relationship within the data alongside the overarching trend of the heat loss coefficient. However, as we want to estimate the relationship we can express c as:

$$c = 14.48e^{-(387.3U'_c)} - 18.58 \tag{C.5}$$



(a) Gradient (m)



(b) Constant (c)

Figure C.4: The relationship between the constant heat loss coefficient, U_c', and the equation $y = mx + c$ when comparing the degree-days model and the analytical expression.

It was found that value of m do not change even if the building systems efficiency changes, but the value of c does. This is logical as the value of c will be dependant on the magnitude of the total energy consumption of the buildings.

Building system efficiency (η) will be the only thing to change between retrofit scenarios other than the values which inform the heat loss coefficient (e.g. U-values, Infiltration and ventilation rates). Therefore, once we have result assuming a heating system efficiency of 1 we can calculate c as:

$$c = \frac{14.48}{\eta} e^{-(387.3 U_c')} - \frac{18.58}{\eta} \tag{C.6}$$

It should be noted that this transition period calculation will change if other factors that impact total energy consumption changes.

These can then be used to adjust the analytical expression to be in line with the degree-days model for heating energy consumption as follows:

$$f_{degree-days} = \frac{f_{analytical} - c}{m} \tag{C.7}$$

Therefore, using both $f_{degree-days}$ and $f_{analytical}$ to estimate the lowest whole life carbon solution we can understand the range of building forms where inaccuracies in the analytical expression would impact results. **This is defined as the transition period**.

C.4 Whole life carbon modelling data

This section outlines the key performance data used for whole life carbon modelling, including operational efficiency standards, embodied carbon data and the predicted decarbonisation of both electricity and retrofit materials.

Within Chapter 4, whole life carbon retrofit modelling is applied to two different baseline buildings - post war and historic. Three different retrofit scenarios are also modelled - Part L2B which runs off gas, Part L2B which runs off a air source heat pump and an Enerphit model.

C.4.1 Operational efficiency

This section provides the fabric, ventilation and systems performance of both the baseline and retrofit buildings. The key building performance inputs can be found in Table C.1.

Historic buildings assume a very poorly performing building with uninsulated walls, roof and floor and single glazing [25]. Post war also assumes the building was built before building regulations. However, it now assumes a flat instead of pitched roof in comparison to historic buildings.

The first retrofit scenario, Part L2B, refers to UK building regulatory standards [228]. Enerphit is an extremely high level of refurbishment equivalent to Passivhaus but for existing buildings [16].

The typology of the building is assumed to be a primary school for which occupancy data is provided in Appendix B. Weather data, outdoor temperature and monthly average solar gains, have been taken from historical data [19] for a central UK location - see Tables B.5 - B.6.

Table C.1: Key building performance metrics for each modelling scenario. U-value for Enerphit wall assumes internal insulation as the chosen refurbishment method. Historic buildings glazing is assumed too be single glazed with timber frame.*Heat pump efficiency is dependant on required output temperature (Low/Medium/High). In Chapter 4 low temperature efficiency is assumed for heating consumption and high temperature for DHW production. If gas boiler upgrade is ever assumed for retrofit modelling, the efficiency of the boiler is 0.95. Heat recovery is provided through an MVHR system with a Specific Fan Power of $1.2W/L.s^{-1}$ [21]

Input	Historic	Post war	Part L2B	Enerphit	References
Wall U-value $[W/m^2K]$	1.7	1.7	0.35/0.3	0.35/0.15	[25, 228, 16]
Glazing U-value $[W/m^2K]$	4.8	4.8	1.6	0.6	[131, 228, 257, 258]
Roof U-value $[W/m^2K]$	2.3	2.4	0.16	0.15	[131, 228, 16]
Floor U-value $[W/m^2K]$	1.0	1.0	0.25	0.15	[131, 228, 16]
Infiltration rate $[hr^-1]$	0.675	0.675	0.3	0.05	[131, 259]
Heat recovery efficiency	-	-	-	0.9	[21]
Heating system efficiency, η	0.8	0.8	4.25/3.5/2.3*	4.25/3.5/2.3*	[230, 319, 320]
Glazing solar gain factor, s_g	0.62	0.62	0.62	0.62	[135]
Glazing frame factor, α	0.3	0.3	0.3	0.3	[275]

C.4.2 Embodied carbon data

A1 - C4 whole life carbon boundaries will be adopted for the study. The main source of data are Environmental Product Declarations (EPDs) which provide a full system boundaries. However, transport values (Stages A5 and C2) are replaced with more UK specific data using typical values from the Institute of Structural Engineers [321]. Also, where data was missing for other stages, industry guidance was used to make estimates. This includes, the disposal stage (C4) where a typical landfill emission factor of $0.013kgCO_2e/kg$ was included where data was missing [321].

One limitation of the data collected, is that only basic fit out data is included in each retrofit scenario. For example, where internal insulation is modelled this would include the addition of new plasterboard. However, no other fit-out would be included such as paint and decoration or any changes to interior partitions. Therefore, results may be a slight underestimation of actual total embodied carbon.

C.4.2.1 Fabric measures

Past research has shown a range of data for the embodied carbon of different insulation materials [264]. Within this thesis glass wool has been chosen as the main material due to its low combustibility [265], making it appropriate to be applied at scale. Also, Graziechi et al. [264] show that glass mineral wool has the lowest average embodied carbon making it a suitable low carbon choice.

However, industry data shows that the properties of glass wool do not make it appropriate for certain retrofit measures, including external wall, solid floor and warm flat roof systems [322]. Therefore, the second lowest average embodied carbon and most commonly installed insulation material [264, 172] EPS is modelled for these systems.

The lifespan of all insulation materials is assumed to be longer than 50 years which is disputable. For example, analysis of 25 year old glass wool wall insulation shows a 12% degradation in thermal conductivity from installation [323]. This highlights a limitation of the study as any potential required replacement of insulation has not been accounted for.

Total embodied carbon for each insulation system is demonstrated in Table C.2. The insulation thickness is dependant on the required thermal resistance of insulation to achieve the target U-Value. This can be calculated by subtracting the total required thermal resistance by the resistance of the existing materials, R_e, and the internal, R_{in}, and external surfaces, R_{ex}.

$$R_{ins} = \frac{1}{U_{element}} - R_{ex} - R_{in} - R_e \tag{C.8}$$

Window values are taken from two different EPDs published by the same company [324, 325], which allows for hopefully comparable values between triple and double glazing. However, values of double and triple glazing vary widely between EPDs. A past study [275] shows that the embodied carbon of double compared to triple glazing can have a much smaller difference. These values have been used as sensitivity analysis within Chapter 4 - Double glazing = 68 $kgCO_2e/m^2$ and Triple Glazing = 76 $kgCO_2e/m^2$ [275].

Table C.2: Embodied carbon for different fabric retrofit measures (A1 - C4 boundaries excluding stages B6, B7 and B4). Lifespan of each element is provided to understand the typical number of replacements (B4) that would occur over the study period or building lifespan. A typical thermal conductivity of 0.04W/mK is assumed for all insulation materials [22, 23].

Retrofit measure	Material(s)	Embodied carbon	Unit $[kgCO_2e/unit]$	Lifespan $[years]$	
Loft insulation	Glass wool - roll	10.9	m^3	> 50	[22]
Flat roof insulation	EPS insulation	67.1	m^3	> 50	[23]
	Roof waterproof covering	6.6	m^2	30	[326]
Floor insulation	EPS insulation	67.1	m^3	> 50	[23]
	Screed and VCL	20.4	m^2	> 50	[327, 328]
External wall insulation	EPS insulation	67.1	m^3	> 50	[23]
	ETICs components	4.8	m^2	> 50	[328, 329, 330]
Internal wall insulation	Glass wool - slab	19.8	m^3	> 50	[301]
	Timber frame	4.6	m^2	> 50	[328, 329, 330]
Double glazing	PVC frame	58.3	m^2	30	[324]
Triple glazing	PVC frame	78.2	m^2	30	[325]

C.4.2.2 MEP measures

Two key MEP measures are modelled - air source heat pumps and MVHR. The majority of data is taken from the same source to allow for a fair comparison [331] and can be found in Table C.3.

The refrigerant of heat pumps is modelled as R513A because this is a standard material used in industry but does also offer a lower embodied carbon than other typically used refrigerants [213].

Due to the high predicted embodied carbon emissions from ductwork and its accessories, this value was also corroborated with existing literature where a range of values between 9.9$kgCO_2e/m^2$ - 19.9$kgCO_2e/m^2$ was over an A1-C4 boundary was found [332].

Table C.3: Embodied carbon (A1 - C4 boundaries excluding stages B6, B7 and B4) data for MEP measures modelled. Lifespan of each element is provided to understand the typical number of replacements (B4) that would occur over the study period. *Calculated by finding the embodied carbon per m^2 of emitter ($kgCO_2e/m^2$) and the total heat output at low temperature ($875W/m^2$) [24].

Retrofit measure	Material(s)	Embodied carbon	Unit $[kgCO_2e/unit]$	Lifespan $(years)$	
Air Source Heat pump	Type: R513A	188	kW	15	[333]
Air Source Heat pump	Type: R774	90	kW	15	[331]
Heating distribution	Heating systems only	0.7	m^2	45	[334]
Low temperature emitter	Steel	155*	kW	60	[290, 291]
MVHR	MVHR	3.74	$L.s^{-1}$	15	[331]
	Ductwork	14.8	m^2	40	[335, 336]

C.5 Material and electricity decarbonisation

Within the scenario modelled in Chapter 4, decarbonisation of the electric grid has been modelled. This would not only directly impact the embodied carbon of different materials but also implies a level of national decarbonisation which would likely also occur in industry and manufacturing. Therefore, electricity and material decarbonisation have been identified at different levels of sensitivity. Within Chapter 4 a typical value has been assumed, as shown in Section 4.4.4.3, and in Chapter 5 all sensitivities have been explored in further detail.

Electricity decarbonisation has been taken from the UK national grid's future energy scenarios [13] with Figure C.5 showing two different potential decarbonisation pathways. Falling short is assumed to be the typical scenario, which is adopted in Chapter 4. No decarbonisation and leading the way scenarios provide a worst and best case scenario respectively.

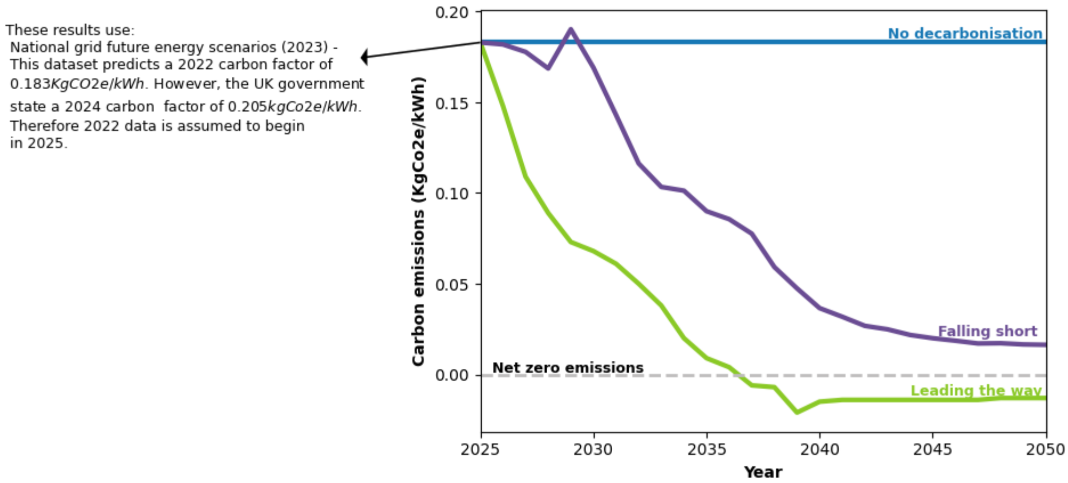


Figure C.5: Different decarbonisation scenarios of the electric grid [13].

Alongside this, simplified **material decarbonisation** will also be modelled. Material decarbonisation is hard to quantify as it relies on many different factors, including electricity decarbonisation and the implementation of material specific, low carbon strategies. Decarbonisation measures differ widely between different materials [14] and there are many different materials used in construction. Past research has overcome these challenges through various methods such as modelling of individual materials to estimate a material reduction factor per floor area [%] [202], assuming a constant embodied carbon factor with no decarbonisation [197] or assuming a blanket reduction in embodied carbon for all materials [89].

For this piece of work, the decarbonisation pathways for 4 key materials within retrofit installations are accounted for. These materials are steel, refrigerant, glass and insulation. Decarbonisation data is gathered from the government's industrial decarbonisation pathways [14], which outline different levels of success in decarbonising these 3 materials. Each pathway has been matched to the scenarios outlined for electricity decarbonisation, as described in Figure C.6.

Therefore, three scenarios are developed each with defined levels of both electricity and material decarbonisation. The falling short scenario is adopted in Chapter 4.

Each retrofit element will follow the decarbonisation pathway for the material which takes up the majority of that element's total mass. For example, EPDs show that Steel and Iron take up 44 - 78% of heat pump's and 66 - 80% of MVHR's total mass †. Therefore, MEP decarbonisation,

†A sample of all available commercial data from the PEP database [34]. Air to water heat pumps from brands Aldes, Ariston, CIAT, Panasonic, and Mitsubishi. MVHR systems from brands Atlantic and Vim.

with exception of refrigerant choice, will be based on the predicted decarbonisation pathway of Steel and Iron in Figure C.6a. This is a clear simplification, showing why different sensitivities of this assumption are required and explored within Chapter 5.

C.5.1 Steel

As discusses, within MEP systems Steel and Iron typically take up a large proportion of the entire system. Therefore, MEP decarbonisation, with exception of refrigerant choice, will be based on the predicted decarbonisation pathways for Steel and Iron [14] (See Figure C.6).

Decarbonisation rates a predicted to linearly decrease from current levels to a 2050 level predicted by the Industrial Decarbonisation & Energy Efficiency Roadmaps to 2050 [14]. This includes:

- BAU (Business as usual) which assumes decarbonisation continues at current rates. *15% improvement by 2050.*
- Max technical which assumes *60% improvements by 2050.*

C.5.2 Refrigerant

Currently refrigerants are often highly polluting with typical greenhouse gas emissions of 547-4750 $kgCO_2e/kg$ depending on the refrigerant type [94]. Low emission alternatives to this include CO_2 or propane which have developed, with greenhouse gas emissions of 1 - 4 $kgCO_2e/kg$ [94].

Both the **no decarbonisation** and **Business as Usual** scenario assume no attempts are made to use low carbon systems and R513A will be modelled with an embodied carbon of $188kgCO_2e/kW$ [333]. The **Max technical model** will assume that CO_2 heat pumps are used for all systems which have been found to have an embodied carbon of $90kgCO_2e/kW$ [331].

C.5.3 Glazing

The Industrial Decarbonisation & Energy Efficiency Roadmaps to 2050 [14] also predicts typical scenarios for the decarbonisation of glass :

- BAU model assuming continued roll out of technologies combined with grid decarbonisation. *60% improvement by 2050.*

- Max technical model assumes *90% improvement by 2050.*

As with Steel, the simplification is assumed that the rest of materials within the glazing systems will follow the same linear trend.

C.5.4 Insulation

Insulation is found within EPDs to have a lifespan the same as that of a building [22, 23]. Therefore no decarbonisation pathways are modelled in Chapter 4. However, in Chapter 5, retrofit is modelled from present day to 2050 meaning insulation decarbonisation needs to be understood:

- Glass wool is a glass product and therefore follows the same pathways as the glazing scenarios [14].
- EPS is made from plastic and therefore the chemical decabonisation plans will be adopted [14]. This category includes many different chemicals which makes it a clear simplification:
  - *BAU leads to a 30% reduction.*
  - *Max technical leads to a 90% reduction.*

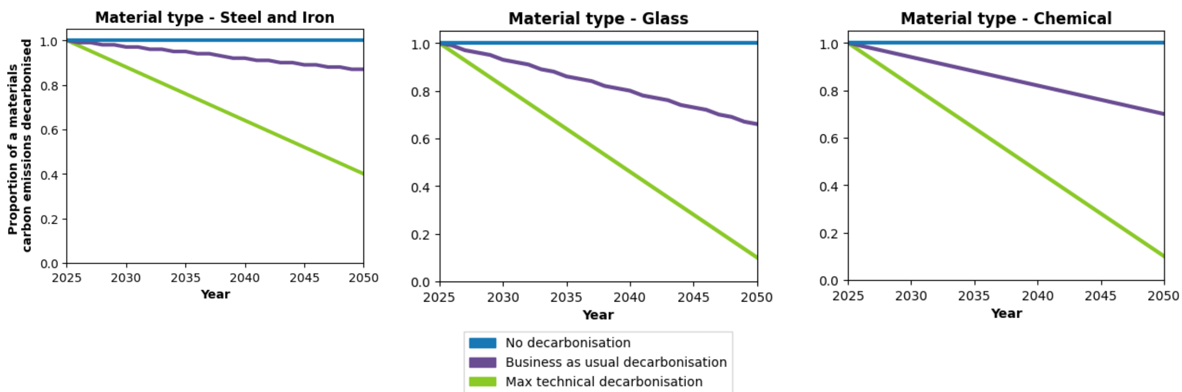


Figure C.6: Graphs to show how material decarbonisation was modelled for key retrofit materials [14]. The business as usual scenario will be modelled alongside falling short electricity decarbonisation (titled the falling short scenario). The max technical decarbonisation will be modelled alongside leading the way electricity decarbonisation (titled the leading the way scenario). There will also be a no decarbonisation scenario which assumes constant electricity and material emissions. **Values, m, range from zero to one as they are a proportion of current embodied carbon emissions.**

Appendix D

Chapter 5 supporting information

This appendices provides supporting information for Chapter 5. This begins with further exploration, continuing with the work in Chapter 3, of the current available data and how best to utilise it for applications of retrofit modelling at scale. Further, detail on carbon budget and occupancy sensitivity analysis calculations is provided.

Finally, validation of plant size estimations for air source heat pumps is undertaken followed with the adopted embodied carbon data used to assess the potential impact of solar PV.

D.1 Data collection and validation

Within this Chapter 3 several key issues with Verisk data quality are highlighted.

Therefore this section aims to explore the potential impact of these data availability issues when trying to model the carbon emissions for the entire English school stock. Where these issues would negatively interfere with the final results, a different solution is found.

Where data is incorrect, the yearly operational carbon both pre and post retrofit as well as the total quantity of required materials for retrofit is impacted. Therefore, for several key comparisons, using the 234 case studies outlined in Chapter 3, the total whole life carbon both pre and post retrofit is modelled. This assumes falling short electricity decarbonisation over a 30 year lifespan. All retrofit will be modelled to Part L2B standard.

D.1.1 Building height data

Height data has a direct impact on total carbon emission calculations due to its influence on the total heat losses as well as the amount of materials required for retrofit.

We demonstrate in Chapter 3 that height data provided by Verisk posed a key barrier toward energy modelling at scale. Figure 3.2 shows that the archetype height of 17.8m which is commonly used within the 234 case studies, despite the majority being one storey tall. In fact, even if 17.8m data points are removed the average Verisk height of the primary school case studies is 7.9m. This is taller than a typical two storey residential house [245], despite only 17% of the primary schools being more than 1 storey tall.

D.1.1.1 Whole life carbon analysis

Figure D.1 shows that, of the 234 case studies, the vast majority of primary schools are 1 storey tall, in line with archetype predictions [244]. However, there is larger variation in height for secondary schools and colleges.

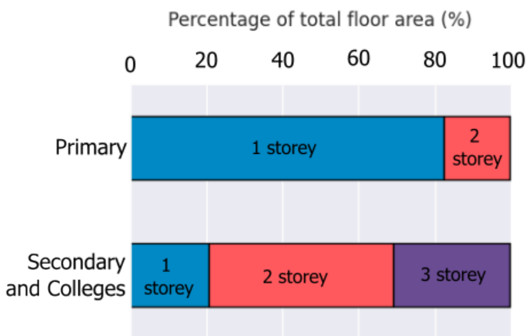


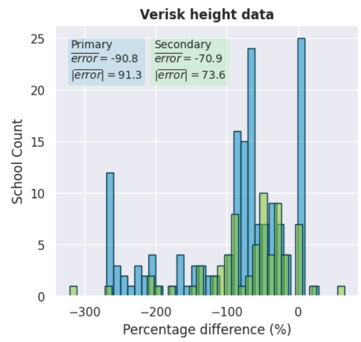
Figure D.1: The number of storeys in each building within the case study as a percentage of total floor area.

Therefore, to understand the impact of Verisk height, three different methods for predicting the building height are used within the whole life carbon modelling:

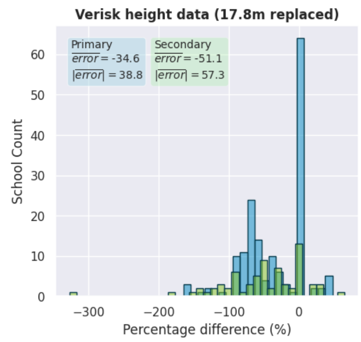
- Using Verisk height data. See Section 3.2.2 for method.
- Using Verisk height data but 17.8m are replaced with a constant archetype height.
- Using a constant archetype height where primary are assumed to be one storey [244] and secondary two storey.

The percentage difference, when modelling whole life carbon, between these methods and adopting the actual building height data (using the actual number of storeys collected from Google Street View) is shown in Figures D.2a - D.2f.

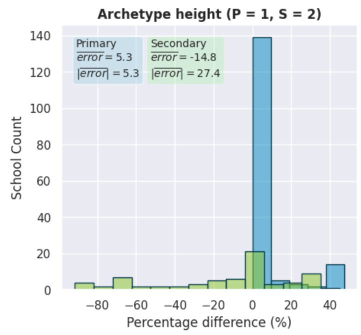
These results show a consistent overestimation of total carbon emissions when using Verisk height data even if values of 17.8m are replaced. This method still leads to a 34 - 51% over-estimation pre retrofit and 42 - 56% post retrofit which would have a considerable impact on carbon budget.



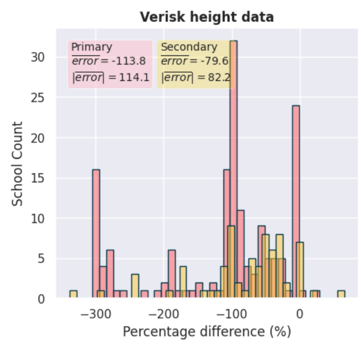
(a) Pre Retrofit (Baseline)



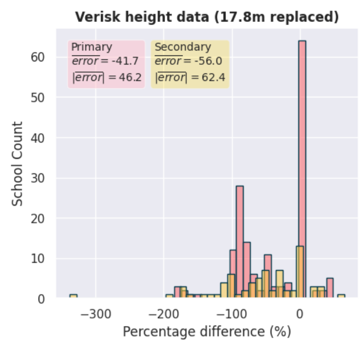
(b) Pre Retrofit (Baseline)



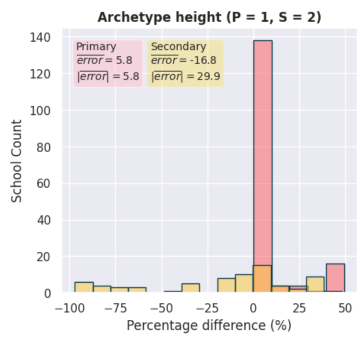
(c) Pre Retrofit (Baseline)



(d) Post Retrofit (Part L2B)



(e) Post Retrofit (Part L2B)



(f) Post Retrofit (Part L2B)

Figure D.2: Percentage error in whole life carbon when using actual height data compared to predicted height data. Percentage error is calculated as $\frac{100(Height_{actual}-Height_{predicted})}{Height_{actual}}$ meaning that negative values insinuate an overestimation in results. Whole life carbon is calculated over a 30 year period.

Adopting an archetype method leads to an average error much closer to zero. Therefore, this method will be adopted within Chapter 5. This is shown to be especially important as, when assessing the Verisk heights of the entire English school stock, 23% of polygons have a height of 17.8m. This implies that the same issues that impact the 234 case studies would impact results for the entire English school stock.

For secondary schools, a much higher average error was found, compared to primary schools, likely because building height within secondary case studies varies more widely. Therefore, to ensure representation of the school stock a distribution of archetype number of storeys, x, will be applied to the database of Verisk polygons. This distribution is based on the data shown in Figure D.1 and will be applied randomly to each school typology. For example, over 80% of primary school floor area within case study data is one storey tall, so the same proportion of all English primary schools will be modelled as one storey tall. It is shown in the following section, that the modelled total assessed floor area from making this assumption is in line with existing data for the total floor area of the English school stock.

D.1.2 Building floor area data

To ensure that this study does not miss out on large amounts of data, the total floor area of data collected is compared to the floor area of schools as attained by the school condition survey. The school condition survey presents total floor area defined as *measured off Ordnance Survey (OS) based information using the external face of the perimeter walls at each floor level, and which also includes areas such as those occupied by internal walls and partitions*. Therefore, this can be compared directly to the building area data collected which is shows in Figure D.3.

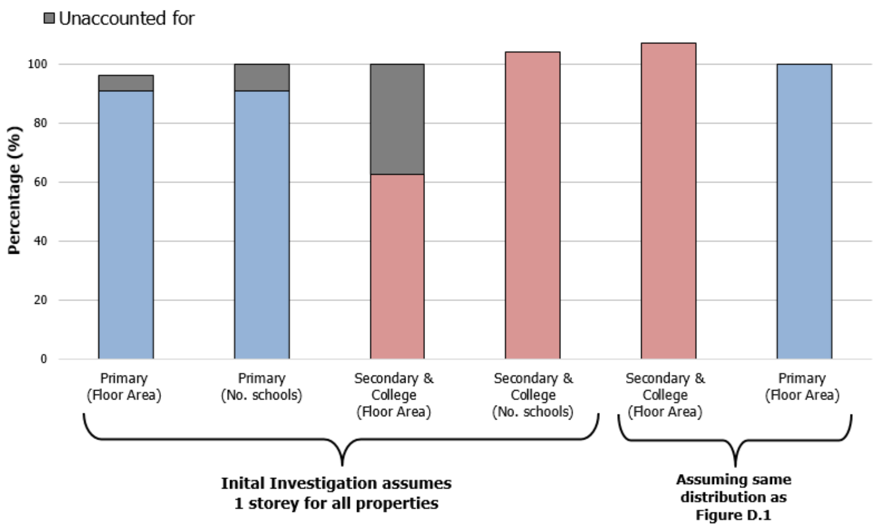


Figure D.3: The total floor area and number of properties from the database compared to the school condition survey results (Government estate only). The final results show that assuming the same number of storeys as in Figure D.1 is in line with the total predicted floor area by the school condition survey [15].

When assuming 1 storey, there is a 9% underestimation of total floor area for primary schools which helps further confirm that an assumption of 1 storey buildings is correct for the majority of forms. Secondary schools and colleges would have a significant floor area underestimation if you assumed 1 storey, despite a 5% overestimation in number of properties. By assuming the same distribution as Figure D.3 leads to a 7% overestimation of floor area for secondary schools and a 0% of overestimation in total floor area for primary schools compared to the school condition survey.

Considering the school condition dataset allows for a $\pm 10\%$ tolerance in total floor area these values for both secondary and primary are deemed acceptable within the model, with an acknowledgement that they may likely lead to a slight overestimation of carbon emissions due to increased floor area of secondary schools [15].

D.1.3 Baseline building performance data

Baseline building performance data refers to the efficiency of the existing building, such as the U-value and infiltration rate. These impact both the operational carbon of the baseline building as well as the embodied carbon required to bring the building up to the correct standard.

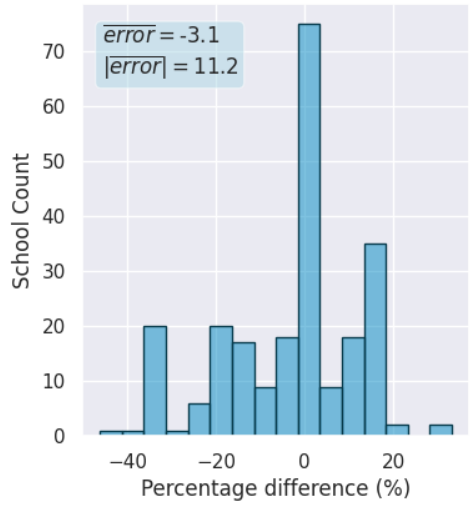
Building age has been chosen to define this building performance. Chapter 3 shows that age data from Verisk can lead to differing results compared to using actual age data attained from historical maps. For comparison, in this section historic digimaps data has been taken as ground truth because it is based on actual historic maps and is shown to lead to a decrease in absolute error compared to Verisk data (See Section 3.4.2.1, Chapter 3).

D.1.3.1 Case study analysis

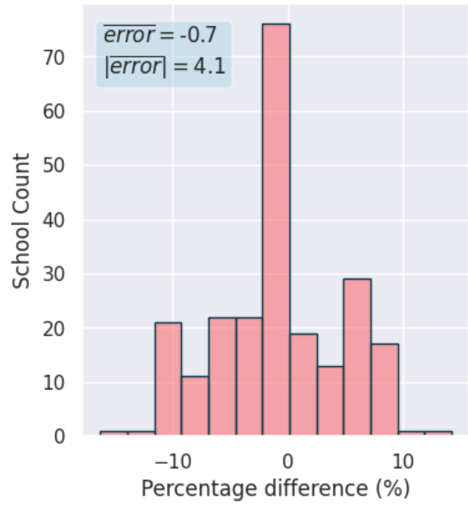
Figures D.4a - D.4b show the difference in total whole life carbon for all 234 case studies when using historic map compared to Verisk age data. This has been undertaken both pre and post retrofit as above.

Results show that, especially at baseline level, there is a reasonably large average absolute error of over 10%. There is also some high error in post retrofit comparisons which can be explained by the differing levels of required embodied carbon depending on the age. For example, those buildings built post 2021 would not require new double glazed units as these already perform to the specified level.

However, the aggregated average error is low for both pre and post retrofit analysis, inferring



(a) Pre Retrofit



(b) Post Retrofit

Figure D.4: Percentage error of whole life carbon over 30 years comparing historic digimap data against Verisk age. Percentage error was calculated $\frac{100(Age_{actual} - Age_{predicted})}{Age_{actual}}$ meaning that negative values insinuate an overestimation in results.

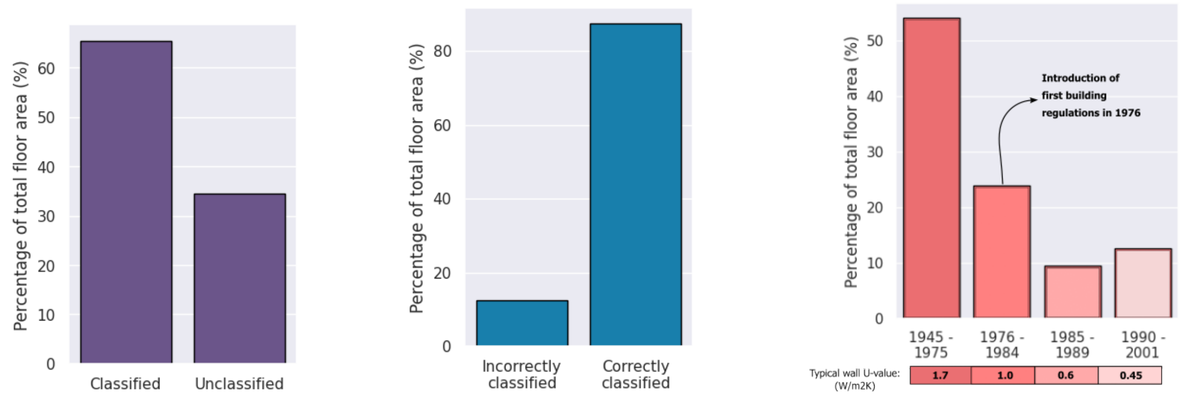
Verisk age data is a reasonable data point. This implies that the incorrect data balances each other out and the impact of data availability issues will be reduced at scale. The total difference in whole life carbon is a 0.7-3.1% difference in total carbon emissions depending on the whether pre or post retrofit is modelled.

We can attribute differences in results between Verisk and historical maps for the case studies for 3 reasons:

- Unclassified polygons, where no age data is provided.
- Incorrect classification of building age.
- Verisk post war classification which has a large possible date range in which several building regulations were introduced making a large range in performance levels.

Figures D.5, demonstrate where these inaccuracies have occurred for the 234 case studies. This shows a large proportion of the total floor area is unclassified in age by Verisk, alongside a number of incorrectly classified polygons. Figure D.5c shows that the wall U-value within the post war category is predicted to range between 1.7 and 0.45 W/m^2k which is a large difference in performance.

To reduce the impact of poor age classification by Verisk for the entire school stock the school condition survey's breakdown of building ages will be used [15], see Table D.1. **This distri-**



(a) Proportion of unclassified data.

(b) Proportion of incorrectly classified data (where data is classified).

(c) Distribution of ages within the post war category (where data is correct). These ages have been split for the key changes to building regulations during this period [46].

Figure D.5: Examples of incorrect Verisk age data, when assessing the 234 case studies.

bution will be applied to any unclassified, post war and modern data so that building age will be representative of the entire English school stock. Verisk data is also now tested for a sample of the English school stock to check that where data is available it is representative of the aggregated stock.

Table D.1: The breakdown of the English school stock ages according to the school condition survey [15].

Age	Percentage of total floor area (%)	**Age**	Percentage of total floor area (%)
Pre 1900	6.2	1961 - 1970	17.7
1901 - 1910	3.0	1971 - 1980	11.7
1911 - 1920	1.3	1981 - 1990	4.6
1921 - 1930	1.8	1991 - 2000	6.0
1931 - 1940	3.9	2001 - 2010	15.1
1941 - 1950	1.7	2011 - 2020	15.9
1951 - 1960	11.2		

The database of English primary school data will be used as a case study to ensure that the Verisk age data is actually representative of the aggregated stock. Figure D.6 shows that over 20% of polygons are completely unclassified within the dataset. Therefore, these unclassified polygons will be assigned an age based on the same distribution of floor area breakdown as in Table D.1, to ensure they are still representative at scale.

Figure D.6 also shows that the Verisk age distribution follows that roughly of the school condition survey.

The Verisk age categorisation follows the same pattern as the School condition survey with exception of slightly larger proportion of buildings assigned to be historic and interwar and fewer to post war. However, these older buildings have a very similar predicted performance to the vast majority of post war buildings, as the largest time period within post war is also pre building regulations (1945 - 1976), which implies a reduction of the impact from this inaccuracy.

Another limitation of this method is that we cannot know whether a building has already undergone some form of refurbishment. It should be acknowledged that this may lead to an overestimation in both baseline emissions as well as embodied carbon.

Results in Figure D.6 imply that the verisk age categorisation is representative of the entire English school stock when applied at scale, despite occurrences of inaccurate classification.

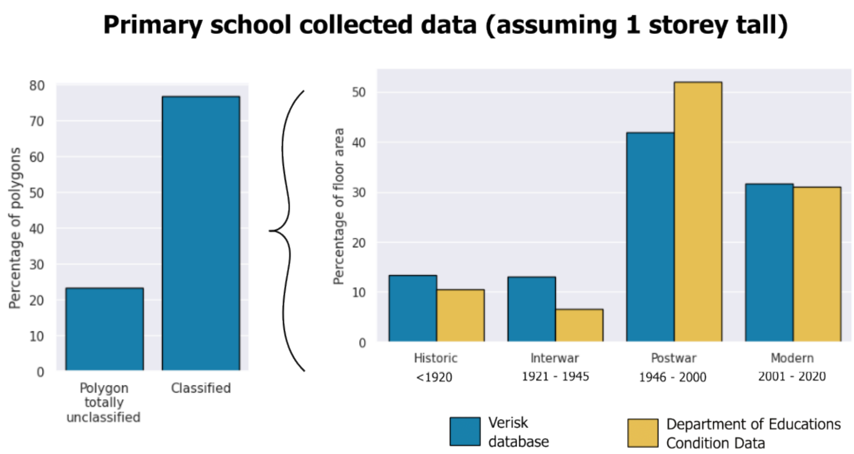


Figure D.6: The distribution of Verisk ages for the entire English primary school stock, assuming a single storey tall. This is compared to the distribution of ages defined by the school condition survey. The polygons shown in Figure D.6 are only those which are assigned a single age by Verisk as it is unclear how mixed age buildings are dealt with in the school condition survey.

The post war category will be assigned performance based on the the distribution of post war schools within the condition survey results. This aims to overcome the limitation of such a large U-Value range, as it should still be representative of the actual stock. This will also be completed for the Modern buildings.

D.1.4 Roof type

The roof type must also be estimated from available data and this will be undertaken using building age data. This section explores whether age data does represent the roof type as predicted by literature as well as the potential impacts from incorrect roof assignment.

D.1.4.1 Case study analysis

Table D.2 shows that the archetype roof type would be correct for the majority of the 234 case studies. Research is limited on archetype roof types for modern buildings which this is understandable as Table D.2 implies an approximately 50/50 split between flat and pitched roofs.

Table D.2: The breakdown of roof types for different age categories, for the 234 assessed case studies. Actual roof data was taken from Google map satellite imagery. Archetype roof types are taken from literature regarding typical school construction [25].

Age	Archetype Roof type	Percentage of Flat Roof polygons (%)	Percentage of Pitched Roof polygons (%)
Pre 19191	Pitched	9	91
1919 - 1945	Pitched	28	72
1945 - 1976	Flat	70	30
1976 - 1985	Flat	77	23
1985 - 1990	Flat	75	25
1990 - 2002	Pitched	30	70
2002 - 2010	No Data	46	54
2010 - 2024	No Data	61	39

As Table D.2 shows that assuming a constant roof type will lead to some inaccurate classifications, the impact of this is calculated. A typical $1000m^2$ square plan historic building was modelled, with the whole life carbon calculated for pre and post retrofit. Pre 1919 was chosen as it has the largest difference in U-value between roof types and would require the largest retrofit intervention.

Figure D.7 shows a very small difference in whole life carbon between the two results. In fact, this would be 4-6% depending on whether pre or post retrofit is modelled.

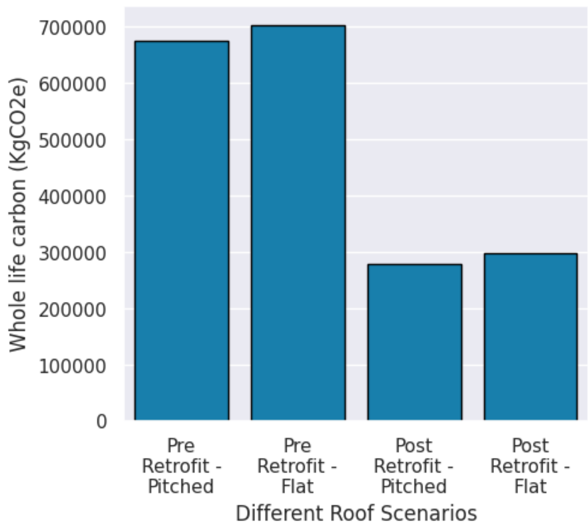


Figure D.7: The impact of different roof types on whole life carbon results for a typical square plan historic primary school. Whole life carbon modelling was undertaken over 30 years for a Pre and Post retrofit scenario.

Modern buildings (post 2002) will be assumed to be flat roof to provide a worst case, conservative assumption in embodied carbon.

D.1.5 Concluding remarks

This section has shown how various limitations in Verisk database are overcome with an aim to reduce its impact on total carbon emission accuracy. As in Chapter 3, we show that Verisk height data has a systematic overestimating impact on total consumption which would make a significant difference to the total carbon emissions both pre and post retrofit and its comparison to the carbon budget. **Therefore, a distribution of the number of storeys is applied to the dataset in lieu of height data**.

Using this distribution, the total floor area is shown to be within 5% of the value predicted by the school condition survey. The school condition survey will also be used to ensure that building age data is representative at scale for the English school stock **by again applying a distribution of building age where Verisk data is limited**. Finally, it is shown that incorrect roof classification has limited impact on total whole life carbon emissions.

D.2 Carbon budget calculations

Two estimates for the carbon budget have been devised using the CCC calculations and the Tyndall budget [278, 279].

Each carbon budget, B, is provided over several 5 year periods which must be aggregated to understand the allowable emissions between 2025 - 2050:

$$B_{2025-2050} = \frac{3}{5}B_{2023-2027} + B_{2028-2032} + B_{2033-2037} + B_{2038-2042} + B_{2043-2047} + \frac{3}{53}B_{2048-2100} \tag{D.1}$$

The data in Table D.3 demonstrates the results of this calculation. Table D.3 also shows how the CCC carbon budget was estimated for only England, using the ratio of the total UK to England Tyndall budget.

Table D.3: Total UK and England carbon budgets using CCC [$MtCO_2e$] and Tyndall data [$MtCO_2$].

	CCC - UK	**Tyndall - UK**	**Tyndall - England**	**Proportion - $\frac{England}{UK}$ [%]**	**CCC - England**
2023 - 2027	1950	742	601	80.8	1575
2028 - 2032	1725	367	298	81.0	1398
2033 - 2037	965	181	148	81.3	785
2038 - 2042	491	89.6	73.2	81.6	400
2043 - 2047	182	44.3	36.3	81.7	148
2048 - 2100	15.5	43.3	35.7	82.2	12.7
2025 - 2050	4533		917	-	3677
	This data was interpolated directly from Figure 1 of the CCC 6th carbon budget using the 'Balanced Net Zero Pathway'. These values assume linear reduction of yearly total carbon emissions within each period [278, 279].				

Results in Table D.3 are then multiplied by different factors to get the estimated carbon budget for English primary, secondary and colleges - excluding independent schools. This is based on the current estimated proportion of total English emissions attributed to English schools, see Table 5.1, in Chapter 5 for final results.

The following factors were used:

- 25% of UK emissions are directly caused by buildings - both operational and embodied

[1].

- 11.5% of Building emissions are public sector [284].
- 36% of Public sector emissions are caused by educational stock [97].

This 36% includes Universities and spaces such as special schools and nurseries which were excluded from this study. Therefore, Table D.4 shows how a proportion of the total emissions caused by primary, secondary schools and colleges has been developed based on the total floor area of each space weighted by the typical benchmark carbon emissions. **This value is 54.7% which is all applied as a factor to the CCC and Tyndall budgets**.

Table D.4: Calculation procedure for the carbon and floor area weighted proportion of primary, secondary schools and colleges. *Area of University stock estimated - 141/168 universities including the 50 most populated universities in the country [26, 27, 28, 29, 30, 31].

School Type	**Floor Area** [m^2]	**Carbon benchmark** [$kgCO_2e/m^2$]	**Proportion [%]** (Carbon and area weighted)	References:
Primary	33272454	50.5	54.7	[88, 15]
Secondary	37157716	50.5		
Colleges	1559110	50.5		
Special	3766418	50.5	45.3	[88, 15]*
All-through	2054922	50.5		
PRU	334130	50.5		
Nursery	300030	50.5		
Alternative provision	221457	50.5		
University stock*	29866350	89.6		

D.3 Occupant behaviour - sensitivity analysis

Within Chapter 3, there is evidence of inaccurate modelling at the individual building level despite no obvious issues with data quality, see Section 3.4.2.2. The various possible reasons for this are discussed in Chapter 3 but one potential reason is occupancy behaviour.

If we can assume that results from all 234 case studies are representative of the entire stock, we can infer that baseline/pre-retrofit modelling would not have a huge error (3.7% in Chapter 3) using current occupancy schedules. However, we cannot be sure that post retrofit behaviour will follow this same pattern. For example, in Chapter 3 we show that modelling newer buildings has a higher tendency to underestimate results, which may be due to increased fabric efficiency leading to the lower heating costs and an increase in set point temperature. This is something that has also been found for retrofit buildings and is called the rebound effect [248]. There is also evidence of attempts to actively reduce energy consumption in schools through occupant behaviour. Initiatives, such as Energy Sparks [238], encourage and educate schools on how to run more efficient buildings and aims to improve occupant behaviour to reduce energy consumption.

With the demonstrated evidence of differing occupancy patterns, especially post retrofit, it is important to understand the potential impact of changing occupancy inputs on the total carbon budget. The parameters used within the sensitivity analysis have been chosen as they have a direct impact on energy consumption and are deemed to be easily varied by the occupant.

The sensitivity analysis values alongside the references and justification are shown in Table D.5. These values will be modelled for all retrofit buildings, to understand the impact of any potential post retrofit changes to behaviour.

Table D.5: Different modelled changes to occupancy behaviour during sensitivity analysis.

Value	Typical	Sensitivity	Notes
Set point temperature ($°C$)	19	$\pm 2°C$	CIBSE Guide A provides a range of 19 - 21$°C$ [131] while the NEU stipulates a minimum temperature of 16$°C$ for a school and 18$°C$ for a classroom [260].
Heating season ($month$)	Mid Apr. - Mid Oct	±1 month	Literature shows the heating season is likely to vary [236], with data claiming half a month different on each side of the heating season (**1 month total**).
Hot water usage (L/day)	0.73/1.99	$\pm 15\%$	Domestic hot water usage is shown to vary typically by 15% which has been used in lieu of more specific data [255].
Kitchen gas usage ($kWh/meal$)	0.41	$\pm 33\%$	CIBSE TM50:2021 [224] claims school kitchen use varies between 6-12kWh/m^2 so we assume a 33% variation.

D.3.1 Application of occupancy sensitivity to case studies

To ensure that the range of occupancy sensitivity analysis appropriately reflects actual variations in occupancy, it has been applied to the 234 case studies.

Baseline thermal energy consumption is calculated for the minimum and maximum sensitivities. The minimum percentage error, see Section 3.3.2, is then calculated with any crossover between metered and modelled, classed as zero error using equation 3.16.

Results show that the average absolute minimum percentage error, $|\overline{error}|$, [%] would be 5.7% using this sensitivity analysis for all 234 results.

This result contains all of the data, including those properties with swimming pools, which is excluded from the scope of this study, and those data points which were found on an individual basis to be limited in their data availability. **Excluding these points with a known cause for inaccuracy (See Figure 3.8) would reduce the absolute average percentage error to significantly below** $< 5\%$.

These results show that using these occupancy sensitivity results, we can represent the behaviour of the 234 case studies for the vast majority, over 95%, of properties.

D.4 Model validations - embodied carbon of air source heat pumps

A key result within Chapter 5, includes the significant embodied impact of air source heat pumps within retrofit projects. To estimate the embodied carbon of heat pumps, a conservative estimate of each school's post retrofit plant size [kW] was undertaken, which was multiplied by manufacturers data for embodied carbon [$kgCO_2e/kW$] of air source heat pumps.

While it is assumed that manufacturers data is accurate, it needs to be ensured that the plant size estimates are not causing an overestimation of the predicted impact of the heat pump. The validation undertaken in this section allows for further confirmation that air source heat pumps pose a carbon hot spot within retrofit installations.

Therefore, as assessment of the predicted embodied impact of switching all residential buildings to heat pumps will be undertaken. This is completed because residential buildings have a much more standardised heat pump size compared to schools as they vary less widely in floor area and building form [150, 151]. In fact, case study analysis of different heat pump installations shows a limited variation in the size of heat pump installed for residential buildings [337]. The total embodied carbon of switching all residential buildings to heat pumps will undoubtedly be higher than that of schools due to the significantly larger floor area of this stock type [338, 15]. However, by understanding the extent that this floor area differs, we can compare the predicted percentage difference in embodied carbon of new heat pumps to the percentage difference in total floor area for schools and residential buildings. As the total plant size is easier to predict for residential buildings, this comparison should allow us to understand whether the plant size calculations undertaken for the English school stock are sensible.

There are approximately 25.2 million dwellings in England with an average size of $94m^2$ which is a 2 - 3 bedroom house [338]. With the total floor of schools predicted to be $69,529,500m^2$, this means that the school floor area is approximately 2.9% of the total residential area as demonstrated in Table D.6. Estimating the total plant size of an average home, of similar efficiency to Part L2B, is undertaken using case study data [337]. 2 -3 bedroom new builds, built to Part L standards, are found to range between $8.5 - 11.2kW$ [337]. The refurbishment case studies show installations up to $14kW$ [337].

Therefore, a range of $8.5 - 14kW$ total plant size is assessed. Table D.6 shows that the ratio of predicted school carbon emissions to residential carbon emissions is similar to that of the total floor area. However, this ratio is slightly larger than the ratio of total floor area, likely due to differences in occupancy patterns and also building construction. For example, schools are modelled to have a higher glazing ratio than the typical residential home [339].

From this assessment, we can infer that the total estimated plant size for schools is in the correct magnitude and air source heat pumps do indeed pose a carbon hotspot for future retrofit installations that should be accounted for in future research.

Table D.6: Study of total modelled embodied carbon for air source heat pumps for both English schools and residential buildings. This is compared as a ratio to the total floor area for the two building typologies. This study has been undertaken as residential building plant size is more standardised than that of schools. Therefore, we can understand whether school plant size calculations are as expected.

MEP embodied carbon comparison (Using the same manufacturers data)	
Ratio of $\frac{Area_{school}}{Area_{residential}}$	0.029
Typical Heat pump capacity per dwelling (KW) [337]	8.5 - 14
Number of dwellings in England [338]	25,200,000
Embodied carbon of heat pump ($kgCO_2e/m^2$) [333]	188
Estimated upfront carbon emissions to replace English residential stock ($MtCO_2e$)	40 - 66
Estimated upfront carbon emissions for English school stock	2.6
Ratio of $\frac{Carbon_{school}}{Carbon_{residential}}$	0.04 - 0.065

D.5 Embodied carbon of solar photovoltaic panels

Within Chapter 5, a simplified estimation of the total embodied carbon to offset every school's energy consumption using solar PV is undertaken. This section outlines the data collection process for embodied carbon data and predicted energy production.

From the data collected, and presented in Table D.7, an average value can be assumed as the embodied carbon of PV of $172kgCO_2e/m^2$ and yearly solar production of $152kgCO_2e/m^2.yr$ The total required area [m^2] of solar PV to offset the yearly energy consumption is calculated as:

$$A_{solar} = \frac{F_{total}}{P_{solar}} \tag{D.2}$$

where F_{total} is the total yearly energy demand of the English school stock [kWh] and P_{solar} is the average yearly solar production of a solar panel [$kWh/m^2.yr$].

From the total area, the embodied carbon can now be estimated by multiplying this area by the average embodied carbon of a solar panel [$kgCO_2e/m^2$].

Table D.7: Embodied carbon and solar production data from available EPD sources. Embodied carbon provided on a A1 - C4 boundary. Transport emissions estimated from an average solar panel weight of $11kgCO_2e/m^2$ [32]. Solar production data based on typical UK solar irradiance of $\approx 1000kWh/m^2.yr$ [33]. The average embodied carbon per production company available is provided, taken from all available EPDs within the PEP Ecopassport database [34] alongside other available sources [32, 35, 36, 37, 38, 39].

Solar PV	**Embodied carbon** $[kgCO_2e/m^2]$	Typical solar production $[kWh/m^2.yr]$	Reference
SunPower (*Average*)	151	148	[32, 34]
Clearline (*Average*)	162	N/A	[35]
JA Solar (*Average*)	80	N/A	[36]
Longi (*Average*)	137	N/A	[37, 38]
IRT (*Average*)	122	N/A	[39]
DualSUN (*Average*)	145	161	[34]
Edelians (*Average*)	267	125	[34]
DMEGC (*Average*)	145	151	[34]
JAM69 (*Average*)	255	167	[34]
Photowatt (*Average*)	100	129	[34]
JINKO Solar (*Average*)	235	166	[34]
REC SOLAR (*Average*)	180	158	[34]
SOLIPAC (*Average*)	143	154	[34]
Sunstyle (*Average*)	319	N/A	[34]
SYSTOVI (*Average*)	251	183	[34]
Terreal (*Average*)	290	N/A	[34]
Voltec Solar (*Average*)	136	133	[34]

Appendix E

Thesis modelling and inputs flow chart

E.1 Flow chart description

This Appendix provides a description of all modelling inputs and procedures within this thesis. Figures E.1-E.2 provide a double page spread flow chart of how all input parameters are used for each section of modelling.

All developed models in this thesis are used to provide key contributions to knowledge. Contributions include - the influence of building form on whole life carbon retrofit decisions and the impact of retrofit on the total whole life carbon emissions of the entire English school stock.

The following Figures E.1-E.2 show that energy modelling is described in Chapter 3, with further explanation of the contribution of building form to energy consumption provided in Chapter 4. Key input parameters to energy models are provided in Chapter 3 with further details found in Appendix B.

Chapter 4 also provides methodology for operational, embodied and whole life carbon calculations. Embodied carbon and retrofit performance data is provided in Appendix C.

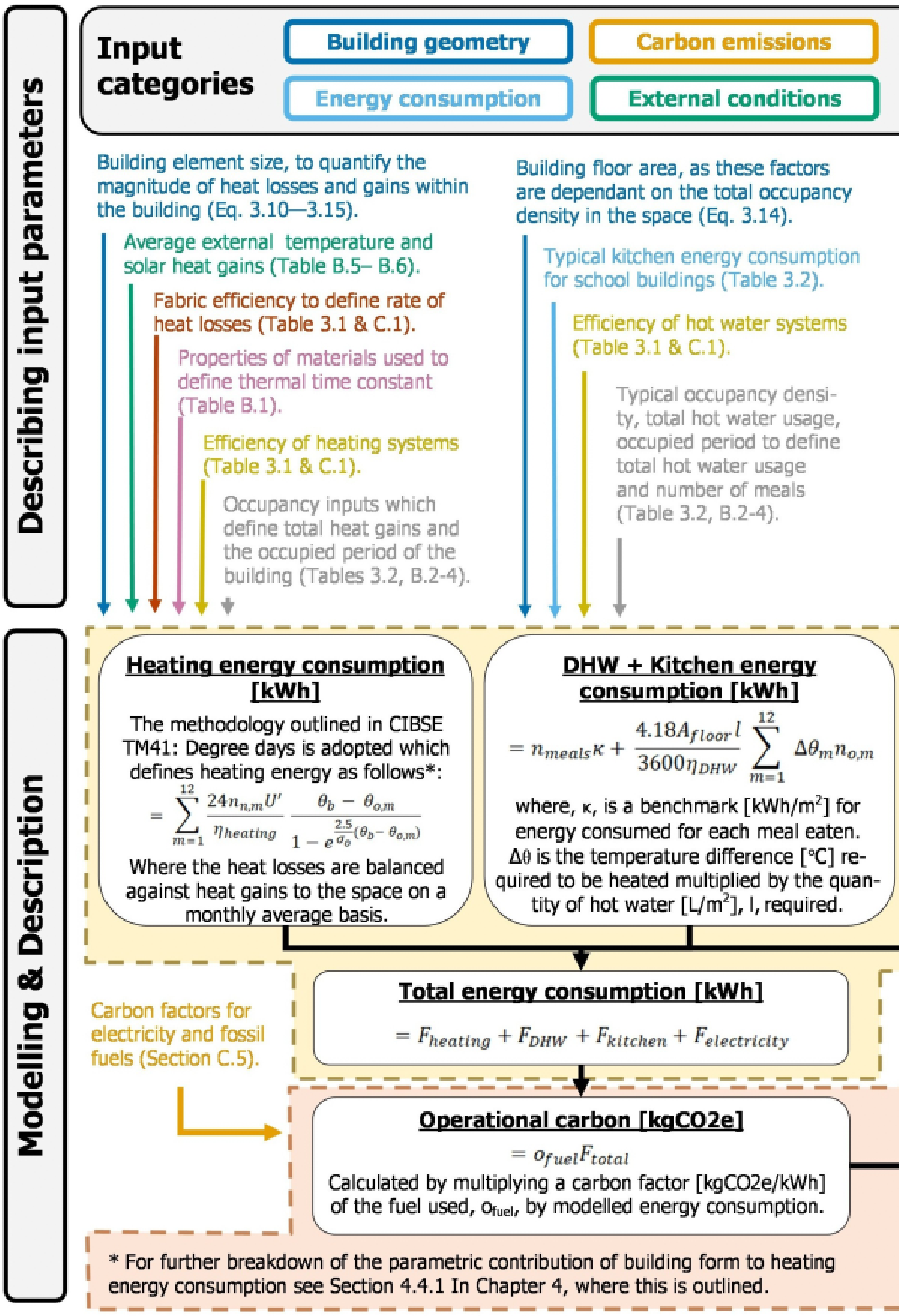


Figure E.1: Double page spread figure to describe all modelling and input parameters within this thesis. This includes the location of all input parameters and methodologies. Though not all nomenclature is expressly described here, within the preamble section a full list of nomenclature is outlined. The input categories described in this flow chart also match that of the nomenclature section.

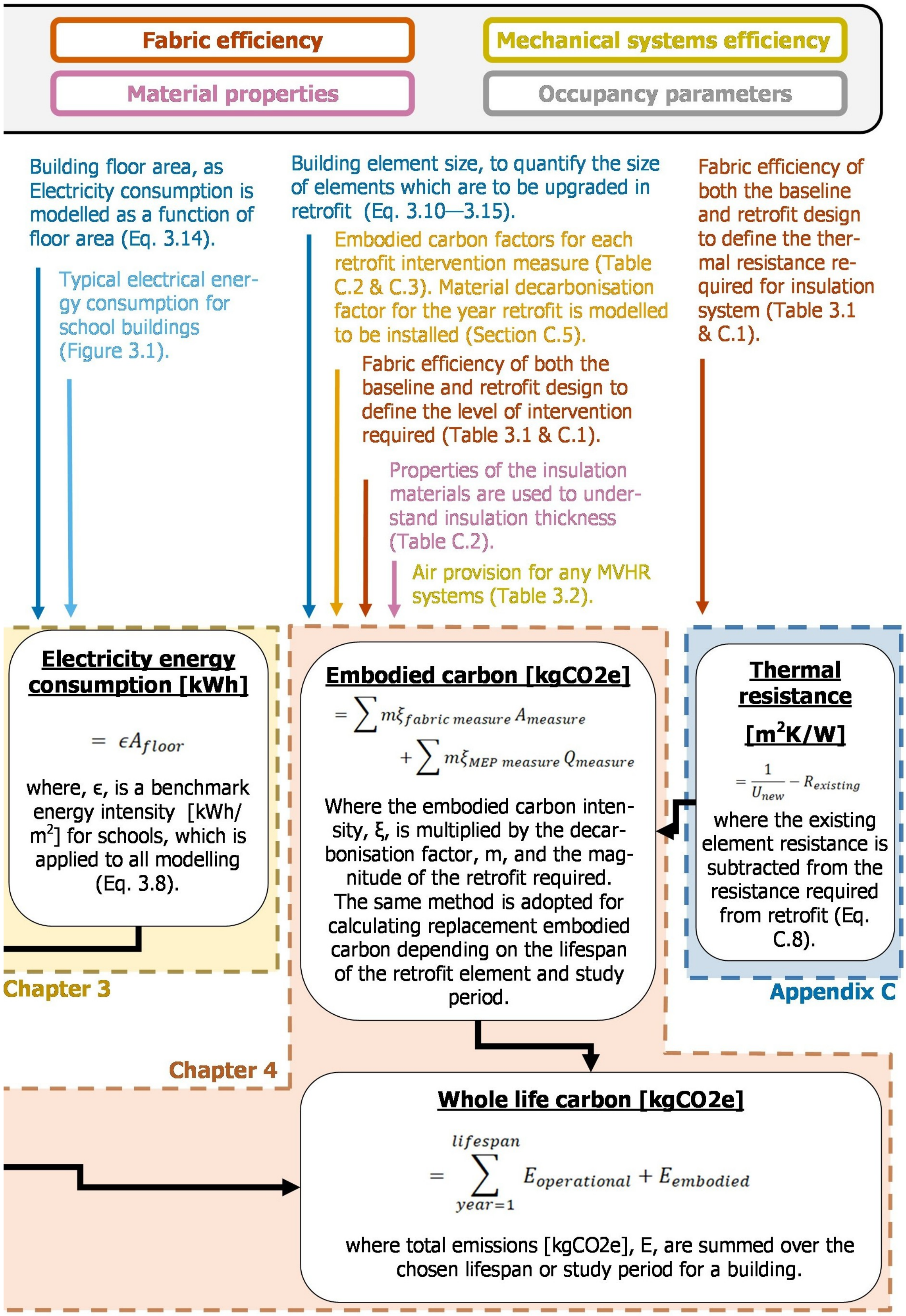


Figure E.2: Double page spread figure to describe all modelling and input parameters within this thesis. This includes the location of all input parameters and methodologies. Though not all nomenclature is expressly described here, within the preamble section a full list of nomenclature is outlined. The input categories described in this flow chart also match that of the nomenclature section.

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