University of Sheffield

Potential for the Vertical Extension of Existing Buildings

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Doctor of Philosophy
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December 2022

Not everything that can be counted counts, and not everything that counts can be counted.

- William Bruce Cameron, 1963

Declaration

I hereby certify that all work contained within this thesis is my own, except where specific reference has been made to that of others.

C Gillott

December 2022

Statement of collaborative work

Elements of work forming part of jointly authored publications have been included within this thesis. Details of these publications, and the candidate's contribution to each, is explicitly indicated below.

1. **Gillott, C.**, Davison, B. and Densley Tingley, D. (2022). Drivers, barriers and enablers: construction sector views on vertical extensions. *Building Research & Information*, 50(8), 909-923.

   In this publication the candidate conceived and planned the investigation, collected and analysed all data, and authored the manuscript.

2. **Gillott, C.**, Davison, B. and Densley Tingley, D. (2022). The potential of vertical extension at the city scale. *IOP Conference Series: Earth and Environmental Science* 1078 012079

   In this publication the candidate conceived and designed the investigation, collected and analysed all data, and authored the manuscript.

3. **Gillott, C.**, Davison, B. and Densley Tingley, D. (2022). The Potential of Vertical Extensions: A Case Study Analysis. *IOP Conference Series: Earth and Environmental Science*. (in print – included in Appendix 4)

   In this publication the candidate conceived and designed the investigation, collected and synthesised all data, and authored the manuscript.

4. **Gillott, C.**, Densley-Tingley, D. and Davison, B. (2021). Sustainable Housing Provision: A Case for the Vertical Extension of Steel Framed Buildings. ce/papers, 4: 2425-2433.

   In this publication the candidate conceived and designed the investigation, conducted all analyis, and authored the manuscript.

Acknowledgements

I would first like to thank my supervisors, Danielle Densley Tingley and Buick Davison, for the opportunity to undertake this work. Your continued guidance has been invaluable in achieving the outcomes herein and to my development as a researcher.

My deepest gratitude goes to my parents and the rest of my family for their support. Thank-you Dad for sharing with me your love of construction and Mum your passion for everything else. Without you this would not have been possible.

Finally, I would like to thank K.P. and my friends. You have made this process a pleasure and have always been on hand to remind me that there is more to life than vertical extensions.

Summary

"Vertical extension" refers to the addition of new storeys above existing buildings and is increasingly recognised as a means of generating new useable floorspace whilst reducing resource extraction, waste generation and associated carbon emissions. Despite this, understanding of the potential for vertical extensions remains limited, with existing work representing a series of fragmented perspectives from neighbouring contexts. The work contained within this thesis thus takes a more holistic and context-centric perspective to further understanding of the potential for future space provision through the vertical extension of existing buildings.

First, through a sequential explanatory mixed methods study, the relative importance of key drivers, barriers and enablers of vertical extension are assessed. Economic drivers are revealed to be most influential, with environmental considerations simply representing a secondary benefit. The most inhibitive barriers identified are typically technical, such as the identification of reserve capacity, but are not thought to indicate infeasibility. Recommendations to enable or promote extension include enhanced education of various stakeholders national and sub-national policy amendments.

Next, the influence of common design inefficiencies on utilisation and reserve capacity in steel framed buildings is considered. Column utilisation is found to vary greatly with design and appraisal approach, with an average reserve capacity of 10% being found even in least-weight Eurocode designs. This is found to facilitate extension without strengthening in 9%-36% of cases, depending upon structural form and use, with further reserve capacity and extension potential being found in buildings designed to superseded codes and using defensive or conservative approaches.

Finally, a bottom-up assessment framework is developed and applied to assess the potential for housing delivery through permitted development vertical extension across nine cities in England. Over 2 million properties are identified as eligible for extension, with this being capable of generating 176 km^2 of new useable floorspace and housing almost 3.8 million people. The spatial distribution of this within and between the considered cities is also assessed, revealing the majority of extension potential to be within suburban areas.

Together, this work offers the first holistic and context-centric perspective of the vertical extension of existing buildings. It illustrates a significant potential to meet housing needs through vertical extensions and that, although a number of barriers remain, reserve structural capacity is likely to be present within a large number of buildings. Remaining barriers are also shown not to be indicative of infeasibility, and instead may be mitigated through adjustment of national or regional policy.

Keywords: Vertical extension, adaptive reuse, circular economy, embodied carbon, decarbonisation, built environment, construction, utilisation, reserve capacity, housing, permitted development.

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Introduction

1.1 Background

1.1.1 Decarbonising the built environment

In 2015, “The Paris Agreement” was unanimously signed by members of the United Nations Framework Convention on Climate Change (UNFCCC) at the 21st Conference of Parties (COP21) (UNFCCC, 2015). This international treaty sets out a number of “aims to strengthen the global response to the threat of climate change”, perhaps most notably by “holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C” (UNFCCC, 2015). In 2019 the UK government responded by amending the 2008 Climate Change Act to dictate that “the net UK carbon account for the year 2050 is at least 100% lower than the 1990 baseline” (The Climate Change Act 2008 (2050 Target Amendment) Order, 2019), a requirement more commonly known as ‘net zero by 2050’. An additional legally binding commitment was subsequently set in the UK’s first Nationally Determined Contribution (NDC) to the UNFCCC in 2019, requiring a 68% reduction in greenhouse gas (GHG) emissions by 2030 (Department for Business Energy and Industrial Strategy, 2019).

Buildings and construction are responsible for 36% of global energy consumption and 37% of associated CO_2 emissions (United Nations Environment Programme, 2021). In the UK, 42% of economy wide greenhouse gas (GHG) emissions are attributed to the built environment, with 25% of the total figure resulting specifically from buildings and their supporting infrastructure (UK Green Building Council, 2021). As is also true globally (United Nations Environment Programme, 2021), the majority of emissions from UK buildings are in the form of *operational carbon* (UK Green Building Council, 2021), resulting from energy use, including for heating, cooling, lighting and ventilation. The remaining portion, termed *embodied carbon,* is attributed to the extraction, manufacture and transport of materials; construction, repair and deconstruction of buildings; and processing and disposal of waste (RICS, 2017).

Because of its majority contribution (Figure 1.1), emphasis has historically been placed on reducing operational emissions, including through improved building performance (HM Government, 2021) and decarbonised energy supply. Over time, however, this has resulted in an increase in the proportion of whole life emissions attributed to embodied sources, giving the current value of 18% (UK Green Building Council, 2021). As shown in Figure 1.1, this trend is expected to continue into the future, with embodied carbon predicted to represent 38% of whole life emissions by 2030, and a majority share before 2040 (UK Green

Building Council, 2021). Considering the immediacy with which decarbonisation is required, the pertinence of reducing embodied carbon is furthered by its ability to yield *upfront* emission savings, rather than these being accrued over a building's lifespan. In combination, these factors have led to a new impetus to reduce embodied carbon in the built environment, with this being driven both from within the construction sector (Part Z, 2022) and by local (The Greater London Authority, 2021) and national (HM Government, 2020) governance.

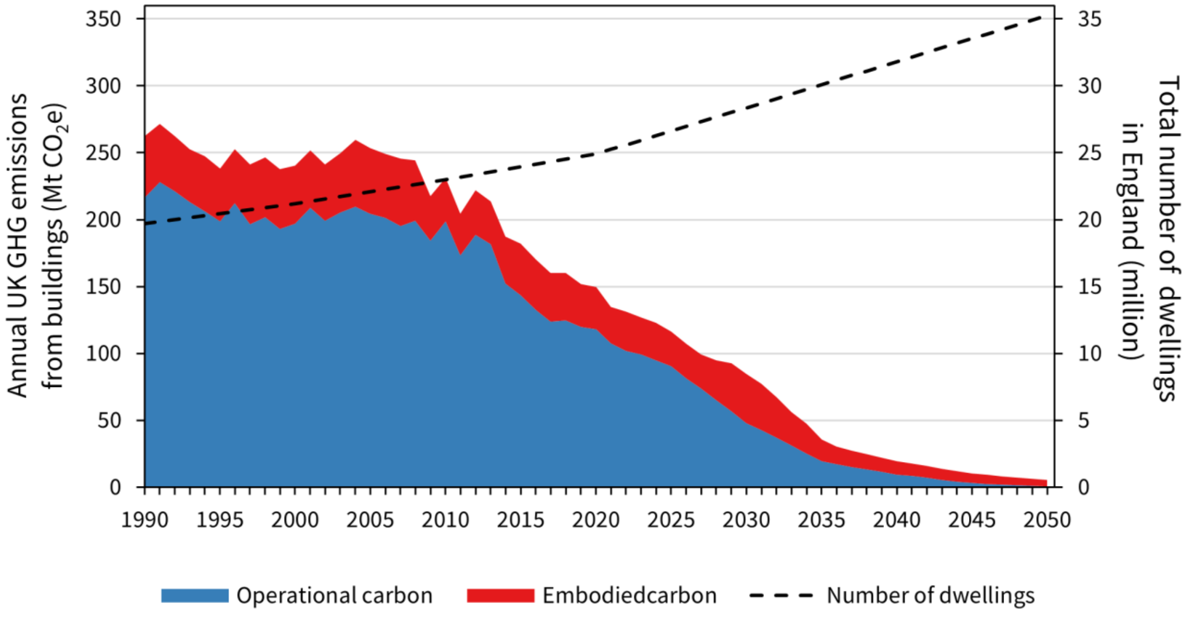

Figure 1.1 - Historic annual greenhouse gas (GHG) emissions from UK buildings (1990-2018) and projected decarbonisation scenario to 2050 (UK Green Building Council, 2021) (primary y-axis), with historic (1990-2020) (Taylor, 2022) *and required dwellings in England to 2050* (Bramley, 2018) *(secondary y-axis).*

1.1.2 Circular economy and building reuse

As embodied carbon is emitted through material consumption, waste generation and (de)construction processes, its reduction is inherently aligned with principles of the circular economy. In its most fundamental form, a circular economy aims to minimise the linear flow of resources through the anthroposphere by retaining these at the most useful level possible for as long as possible. This includes the slowing of resource flows through product life extension; narrowing of resource flows through efficient design; and closing of resource flows through reuse and recycling (Bocken et al., 2016). In the built environment these respectively translate to: the reuse of buildings and their design for longevity, adaptability and deconstructability; the optimization of structures and components; and the specification of reused/recycled and reusable/recyclable materials with maximum recoverability (Gillott et al., 2023). Motivations for a circular economy extend well beyond embodied carbon savings, with a reduction in raw material extraction and waste generation also being necessitated by increasing resource scarcity, biodiversity concerns, and depleting landfill availability. This is particularly relevant in the built environment, which consumes half of all extracted materials (European Commission, 2020) and generates 60% of the UKs waste (Department for Environment Food and Rural Affairs, 2021).

Building-level reuse is often viewed as the most favourable circular economy strategy as a result of it inherently retaining a maximum amount of material in its most useful form (Cheshire, 2016). This also averts carbon and financial costs associated with deconstruction and remanufacturing processes, which otherwise result from the reuse of components or materials ex-situ. “Adaptive reuse” involves repurposing an existing building to meet new or changing needs, including through environmental retrofit, change of use or building extension. The noted circular economy and embodied carbon benefits of this approach have led to an increased impetus for adaptive reuse within the construction industry, spearheaded by organisations including The United Kingdom Green Building Council (UKGBC), Low Energy Transformation Initiative (LETI) and the Institution of Structural Engineers (IStructE), as well as the Architects’ Journal's “RetroFirst” campaign.

1.1.3 The vertical extension of existing buildings

Vertical extension, also known as airspace or rooftop development, refers to the addition of new storeys above existing buildings. Unlike most adaptive reuse strategies, which simply repurpose or upgrade existing space, this provides new floorspace, as required by a growing population. There are numerous examples of vertical extensions to date, including those adding timber and steel storeys above existing steel, reinforced concrete and masonry structures (Gillott, Davison, & Densley Tingley, 2022a). Extensions have also been applied to buildings of various uses for both commercial and residential purposes, exemplifying their ability to deliver within- and across- use adaptations as well as mixed use spaces. The case by case variability of vertical extensions is further exemplified by their past completion typically as part of a wider refurbishment or with an intentionally minimal impact upon the existing building. Because of this high case specificity, and despite the potential benefits of vertical extensions, understanding of key factors surrounding their adoption is lacking. This includes those relating to financial costs, planning constraints, project programme and structural feasibility.

Although highly case specific, the potential for vertical extensions is increasingly recognised in the UK, including by both the Department for Levelling Up, Housing and Communities (DLUHC) and local planning authorities (LPAs) (DLUHC, 2017; Ministry of Housing Communities and Local Government, 2018). This has led to the adoption of various supplementary planning documents (e.g. from Haringey Council in 2013) as well as the 2020 introduction of six Permitted Development Rights (PDRs) for the delivery of housing through vertical extensions (Ministry of Housing Communities and Local Government, 2020a; The Town and Country Planning (General Permitted Development) (England) (Amendment) (No. 2) Order 2020; The Town and Country Planning (Permitted Development and Miscellaneous Amendments) (England) (Coronavirus) Regulations 2020). Despite these efforts, the success of PDR vertical extensions remains limited, with just 338 of 790 submitted applications being granted since June 2020 (Department for Levelling Up Housing and Communities, 2022a).

1.1.4 Housing demand and urban densification

The introduction of vertical extension PDRs form part of a wider governmental effort to increase housing supply in the UK (Department for Communities and Local Government, 2017). Amongst much discussion on the required affordability, tenure and location of future supply (Gibb, 2021; Preece, Hickman, & Pattison, 2020; Preece et al., 2020; James, Berry, & Marks, 2019), the overall housing deficit in Great Britain (GB) is estimated to be over 4.75 million units (4 million in England), including contributions to address overcrowding, affordability, homelessness, supressed households, and unsuitable accommodation (Bramley, 2018). As shown in Figure 1.1, by supplementing this estimate with adjusted household growth projections (Department for Communities and Local Government, 2016), housing requirement across GB is found to be 380,000 homes a year (340,000 in England) (Bramley, 2018). This value is significantly greater than the government's current target of 300,000 new homes per year (The Conservative Party, 2019)[1] and almost double the average annual supply since the year 2000 (Ministry of Housing Communities and Local Government, 2021).

Increasingly, the provision of housing in high-density, urban centres is being viewed as preferential to more traditional, low-density, suburban clusters. This is a result of their

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[1] At the time of writing the target to deliver 300,000 new homes a year remains mandatory. There was however indication in a press release on 05/12/2022 (Department for Levelling Up Housing and Communities, 2022b) that this may be made advisory in the forthcoming Levelling Up and Regeneration Bill.

ability to enhance economic productivity (Arbabi, Mayfield, & McCann, 2020) and access to services (Transport for New Homes, 2020; Royal Town Planning Institute, 2018), whilst also providing infrastructure more efficiently and reducing transport emissions (Resch et al., 2016; Arbabi & Mayfield, 2016; Nichols & Kockelman, 2015; Norman, MacLean, & Kennedy, 2006; Newman & Kenworthy, 1989). The vertical extension of existing buildings offers a means of generating floorspace within urban centres, thus increasing their density, without the requirement for demolition and new-build construction. This is particularly beneficial considering high land costs and limited availability of undeveloped sites within city centres (Lichfields, 2022), as well as increasing concerns regarding life-cycle emissions from the construction of new tall buildings (Pomponi et al., 2021).

1.2 Research aim, questions and objectives

A reduction in carbon emissions from the built environment is imperative to maintain the possibility of limiting global average temperature increase to 2°C. It is also clear that efforts should increasingly be placed in cutting *embodied* carbon, which may be achieved by reducing material extraction and waste generation as part of the transition to a circular economy. Adapting and reusing buildings, such as through their vertical extension, facilitates this transition whilst allowing the needs of a growing population to be met. One such need is the increasing demand for housing, to which vertical extensions are particularly suited as a result of their ability to increase residential density within urban centres.

Despite recognition of the suitability of vertical extensions, exemplified by a number of successful projects and the introduction of associated PDRs, the true potential for this construction technique remains unknown. This is primarily because of a limited understanding of the factors influencing uptake of vertical extensions, as well as their interaction and relative impact. One obvious influencing factor, and perhaps the most pertinent, relates to the ability of buildings to withstand the increased loads associated with extension, and whether this may be satisfied by reserve structural capacity or necessitates strengthening. Similarly, as exemplified by PDRs, planning constraints have further influence over the potential for a building's extension. As well as at the single-building level, there is also a lack of understanding regarding how influencing factors affect the potential of vertical extensions when considering this at a more widespread scale.

Against the backdrop of this context, the work contained within this thesis seeks to ***understand the potential for future space provision through the vertical extension of existing***

buildings. In meeting this aim three research questions (RQs), each with subsidiary objectives, are posed:

1.) What are the key factors influencing the uptake of vertical extensions, and how may this be enhanced in the future?
    a. Assess awareness and experience of vertical extensions amongst construction sector stakeholders.
    b. Identify context-specific factors influencing the uptake of vertical extensions and assess the relative importance of those from surrounding contexts.
    c. Understand the causes and interrelation of influencing factors and suggest recommendations to enhance uptake.

2.) How much reserve capacity do different underutilisation sources introduce in existing buildings, and how far does this facilitate their extension?
    a. Assess the influence of different sources of overdesign on the utilisation of columns in existing steel-framed buildings.
    b. Identify the reserve capacity associated with this in terms of a permissible load increase.
    c. Contextualise reserve capacities with respect to their potential to enable vertical extension.

3.) How much space could be provided by residential vertical extensions, and how is this distributed at the city and national level?
    a. Develop a bottom-up assessment framework to identify properties eligible for extension and the number of storeys that may be added.
    b. Apply the framework to estimate the amount of housing that may be generated by permitted development extensions at the property, neighbourhood, city and national level.
    c. Assess the distribution of extension potential between and within England's major cities.

1.3 Thesis outline and structure

As shown in Figure 1.2, Chapter 2 begins with an overview of existing work relating to the vertical extension of existing buildings. Studies conducted within this specific context are revealed to be limited in number and scope, representing a series of fragmented inward looking perspectives from various surrounding contexts. This is exacerbated by a noted focus on case-studies, further limiting the generalised applicability of existing work. As such, relevant studies addressing superordinate contexts such as adaptive reuse and circular economy in construction are also reviewed, as well as those considering adjacent decarbonisation strategies such as low-carbon materials. A review of existing work considering possible sources of underutilisation and reserve capacity is also conducted, as well as for studies considering the potential for vertical extension beyond the building level. This chapter closes by highlighting the position of the research aim and subsidiary questions within this wider body of work.

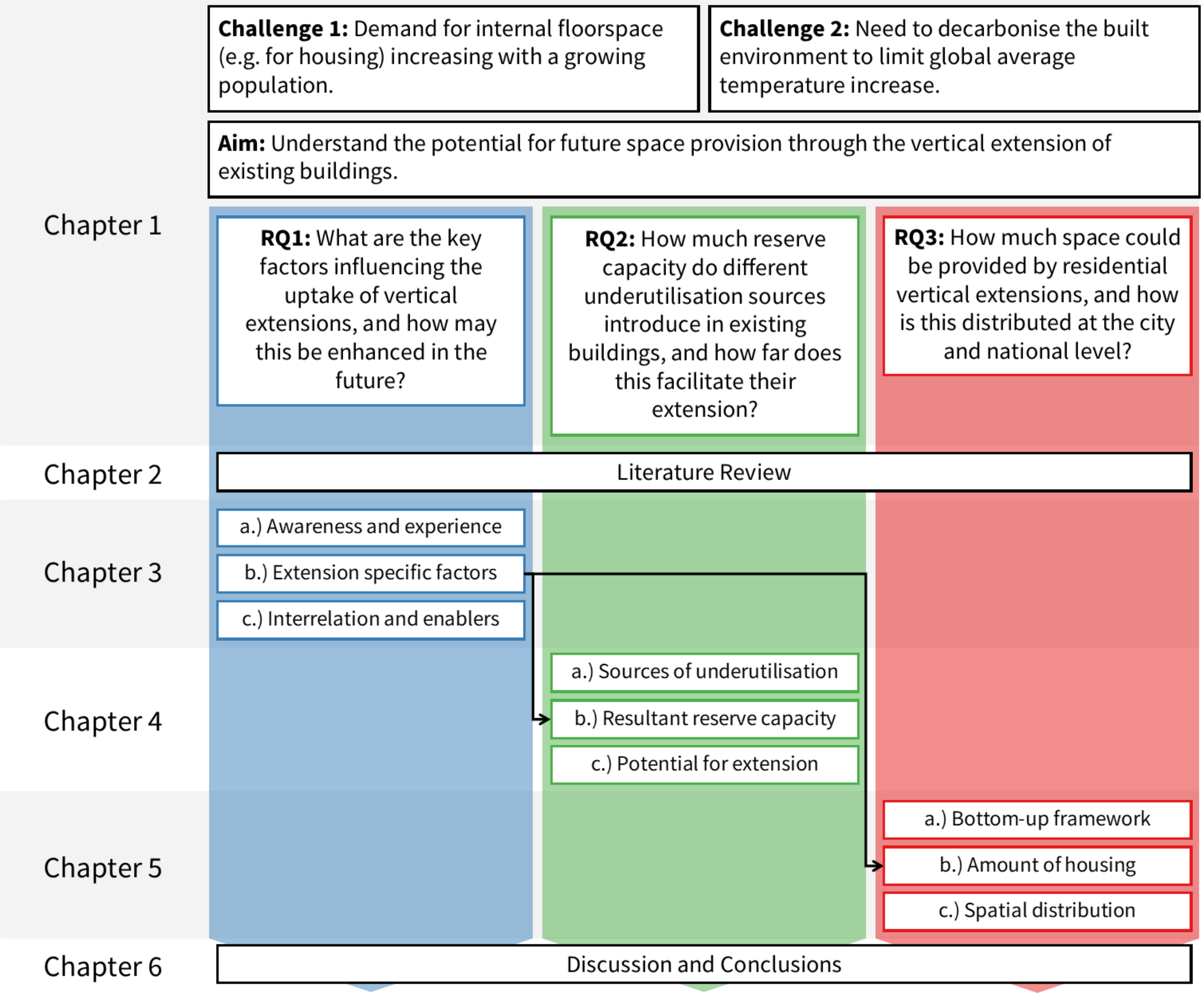

Figure 1.2 - Overview of the thesis showing its background motivation and overarching research aim, contributarty questions and contained objecitves, and the chapter in which these are addressed.

Although identifying a number of potentially relevant factors from wider contexts, the literature review in Chapter 2 is unable to uncover their significance with respect to vertical extensions and only captures a small number of extension-specific considerations. Chapter 3 therefore considers the views of construction sector stakeholders in order to identify the key drivers, barriers, and enablers of vertical extensions, as well as the causes, impacts and interrelation of these. A sequential explanatory mixed methods study is employed for this purpose, with stakeholder awareness, involvement and experience in vertical extension projects also being assessed. Based upon the identified influencing factors, this chapter closes by making recommendations to further enhance the uptake of vertical extensions.

Owing to identified variation in the requirement for structural strengthening (Chapter 2) and uncertainty regarding the presence of reserve capacity (Chapter 3), Chapter 4 considers the potential for vertical extension in terms of underutilisation and reserve capacity within existing buildings. Conceptual designs based upon hypothetical frame configurations are used for this purpose, rather than case-study buildings, in order to ensure generality of results and to allow the individual influence of different sources of underutilisation to be identified. Known underutilisation sources are taken from Chapter 2, and their effect on reserve capacity and extension potential in multi-storey steel-framed buildings assessed. As well as providing insight on typical permissible load increases associated with different design assumptions, as noted as beneficial in Chapter 3, this serves to contextualise reserve capacities in terms of numbers of storeys that may typically be added under different design scenarios.

Chapter 5 assesses the potential for vertical extension beyond the single-building level. In contrast with top-down and archetype based approaches in existing work (Chapter 2), a novel bottom-up methodology is developed for this purpose. As well as providing a more accurate estimation of extension potential, this enables the aggregation of individual-building extendibilities to the neighbourhood, city and national level, facilitating assessment of the spatial distribution of this across various scales. Although applicable more widely, this multi-scale assessment is based upon PDRs for housing delivery, providing more accurate insight on their potential and an increased understanding of disparity between this and current uptake. Through consideration of residential vertical extensions, this Chapter also enables investigation of their ability to increase residential densities within urban centres, as identified as beneficial in Chapter 2.

Chapter 6 discusses the individual knowledge contributions of each preceding chapter, their combined effect, and associated implications for policy and industrial practice. Findings are outlined with respect to the research questions and objectives they address and how this interlinks within the wider body of literature in Chapter 2. As part of this, the defined scope of this work is reiterated, with recommendations for the future advancement of this being made. Chapter 6 closes with concluding remarks summarising the work contained within this thesis.

2

Literature Review

2.1 Overview

The body of work addressing the vertical extension of existing buildings remains within its infancy. This is characterised by the existence of just over 30 extension-specific studies, of which around 25 are within in peer-reviewed academic journals. Aside from a small number (Clark et al., 2006; Li et al., 2004; Li, Yin, & Wang, 2003), these were all published from 2016 onwards and at a notedly increased rate since 2019.

As shown in Table 2.1, previous work concerning the vertical extension of existing buildings typically focusses on technical aspects, including those relating to a building's sub-structure, super-structure or seismic performance. Environmental implications of vertical extensions are also considered, including their whole life impacts, operational performance and microclimatic effects. Across these aspects, the majority of previous studies simply represent the development and/or verification of a, sometimes novel, system or solution to facilitate extension (Table 2.2). Albeit to a lesser degree, a number of studies also consider additional factors influencing the adoption of vertical extensions and their potential beyond the single-building scale (Table 2.1). As shown in Table 2.2, such studies typically take the form of a case-study analysis, completed either at the single- or multi-building level.

Topic	**Sub-topic**	**References**
Technical aspects	Substructure	(Jeong & Kim, 2020; Kim, Kim, & Jeong, 2019; Wang et al., 2018, 2019; Wang, Han, & Jang, 2019)
	Superstructure	(Amoruso & Schuetze, 2022; Bahrami, Deniz, & Moalin, 2022; Argenziano et al., 2021; Amer & Attia, 2018; Artés, Wadel, & Martí, 2017; Al-Nu'man, 2016; Nagy & Cristuţiu, 2013; Clark et al., 2006)
	Seismic performance	(Hur & Park, 2022; Marafini et al., 2022; Argenziano et al., 2021; Heo et al., 2021; Clark et al., 2006; Li et al., 2004; Li, Yin, & Wang, 2003)
Environmental implications	Whole-life impacts	(Amoruso & Schuetze, 2022; Wijnants, Allacker, & De Troyer, 2019; Hafner & Storck, 2019; Dind, Lufkin, & Rey, 2018; Wijnants, Allacker, & de Troyer, 2017)
	Operational performance	(Spirkova et al., 2021; Aparicio-Gonzalez, Domingo-Irigoyen, & Sánchez-Ostiz, 2020; Lešnik et al., 2020; Mendonça, Macieira, & Guedes, 2020; Dind, Lufkin, & Rey, 2018; Amer & Attia, 2018; Artés, Wadel, & Martí, 2017)
	Microclimatic effects	(Dinic Brankovic et al., 2022; Vuckovic et al., 2019)
Factors influencing adoption	-	(Pattison, 2021; Sundling, 2019; Sundling, Blomsterberg, & Landin, 2018)
Potential beyond the building level	-	(Spirkova et al., 2021; Aparicio-Gonzalez, Domingo-Irigoyen, & Sánchez-Ostiz, 2020; Ministry of Housing Communities and Local Government, 2020b; HTA Design, 2016)

Table 2.1 - Overview of the topics addressed by previous studies considering the vertical extension of existing buildings.

Methodological approach	**References**
Development and/or verification of a system or solution to facilitate extension	(Hur & Park, 2022; Amoruso & Schuetze, 2022; Heo et al., 2021; Spirkova et al., 2021; Argenziano et al., 2021; Lešnik et al., 2020; Mendonça, Macieira, & Guedes, 2020; Aparicio-Gonzalez, Domingo-Irigoyen, & Sánchez-Ostiz, 2020; Wijnants, Allacker, & De Troyer, 2019; Amer & Attia, 2018; Artés, Wadel, & Martí, 2017; Wijnants, Allacker, & de Troyer, 2017; Clark et al., 2006; Li et al., 2004; Li, Yin, & Wang, 2003)
Single building case study	(Bahrami, Deniz, & Moalin, 2022; Pattison, 2021; Dind, Lufkin, & Rey, 2018)
Multi-building case study	(Gillott, Davison, & Densley Tingley, 2022a; Marafini et al., 2022; Sundling, 2019; Sundling, Blomsterberg, & Landin, 2018)

Table 2.2 - Overview of the methodological approach applied in previous studies considering the vertical extension of existing buildings.

Table 2.3 reveals the majority of previous work addressing vertical extensions to originate from – and thus be conducted in – a Continental European context, including in Sweden, Belgium, Spain and Switzerland. A handful of studies have also been conducted in the UK, with those pertaining to geotechnical and seismic considerations being completed in South Korea and New Zealand (Table 2.3). Across these geographies, the motivation to investigate vertical extensions is consistently placed in its ability to provide new floorspace whilst reducing resource consumption, waste generation and associated carbon emissions. This is also often viewed from the specific perspective of housing provision, with facilitation of urban densification at a reduced environmental cost regularly being acknowledged.

Country	**References**
Sweden	(Bahrami, Deniz, & Moalin, 2022; Sundling, 2019; Sundling, Blomsterberg, & Landin, 2018)
Belgium	(Wijnants, Allacker, & De Troyer, 2019; Amer & Attia, 2018; Wijnants, Allacker, & de Troyer, 2017)
Spain	(Marafini et al., 2022; Aparicio-Gonzalez, Domingo-Irigoyen, & Sánchez-Ostiz, 2020; Artés, Wadel, & Martí, 2017)
Switzerland	(Marafini et al., 2022; Dind, Lufkin, & Rey, 2018)
United Kingdom	(Gillott, Davison, & Densley Tingley, 2022a; Pattison, 2021; Ministry of Housing Communities and Local Government, 2020b; HTA Design, 2016)
South Korea	(Amoruso & Schuetze, 2022; Hur & Park, 2022; Heo et al., 2021; Jeong & Kim, 2020; Kim, Kim, & Jeong, 2019; Wang et al., 2018, 2019; Wang, Han, & Jang, 2019)
New Zealand	(Clark et al., 2006)

Table 2.3 - Overview of geographic regions in which studies considering the vertical extension of existing buildings have been conducted.

The limited number and restricted topical and methodological scope of previous studies pertaining to vertical extensions indicates this to be an undeveloped research field. Instead, the vertical extension of existing buildings currently represents an external context to which researchers from numerous relevant specialisms (e.g. structural, geotechnical and seismic engineering) are beginning to apply their expertise.

Despite this infancy, and owing to its inherent practical focus, academic work considering vertical extensions is supplemented by additional literature from a number of industrial and governmental organisations (e.g. HM Government, 2020a, 2020b; HTA Design, 2016; Kay, 2020; Pattison, 2021). Both academic and non-academic outputs addressing a number of superordinate and adjacent contexts are also of relevance to vertical extensions, including low carbon design, circular economy in the built environment and structural optimisation. As such, an overview of the most pertinent of this surrounding work is integrated within proceeding subsections, alongside that from Table 2.1-Table 2.3 in specific consideration of vertical extensions through a purely academic lens.

2.2 Adoption of sustainable construction practices

Studies specifically addressing factors influencing the adoption of vertical extensions are limited in number and typically narrow in scope; comprising first-hand experiences (Pattison, 2021) and consideration of a small number of real-world (Gillott, Davison, & Densley Tingley, 2022a; Sundling, 2019; Sundling, Blomsterberg, & Landin, 2018; Artés, Wadel, & Martí, 2017) or hypothetical (Pattison, 2021) case studies. By neglecting to consider a range of contexts and viewpoints, these studies also have an inherent focus on technical factors and perhaps overlook legal, economic or cultural considerations.

There is a surrounding body of related work considering more general contexts, such as low-carbon design (Giesekam et al., 2014) and circular economy in construction (Kanters, 2020; Hart et al., 2019; Adams et al., 2017; Rizos et al., 2015), or adjacent decarbonisation strategies, such as adaptable buildings (Rockow, Ross, & Becker, 2021; Rockow, Ross, & Black, 2019; Manewa et al., 2016; Ross et al., 2016; Gosling et al., 2013) and low-carbon materials (Giesekam, Barrett, & Taylor, 2016). Methodological approaches employed in understanding such contexts are also typically more diverse, again including case-studies (Rockow, Ross, & Black, 2019; Manewa et al., 2016; Rizos et al., 2015) but also the systematic review of existing work (Rockow, Ross, & Black, 2019; Hart et al., 2019; de Jesus & Mendonça, 2018; Giesekam et al., 2014; Gosling et al., 2013) and stakeholder consultation (Giorgi et al., 2022; Kirchherr et al., 2018; Adams et al., 2017; Manewa et al., 2016; Giesekam, Barrett, & Taylor, 2016; Ross et al., 2016; Du et al., 2014; Kershaw & Simm, 2014; Osmani & O'Reilly, 2009). As the prevalence of influencing factors varies between contexts and stakeholder groups, the latter of these methodologies aims to minimise subjectivity by considering a greater range of viewpoints. This is typically achieved through the employment of a survey and/or interviews (Kirchherr et al., 2018; Adams et al., 2017; Giesekam, Barrett, & Taylor, 2016; Ross et al., 2016; Du et al., 2014; Kershaw & Simm, 2014), also capturing stakeholder perceptions which are thought to be equally as influential as evidence-based beliefs (Giesekam, Barrett, & Taylor, 2016).

2.2.1 Drivers

As introduced in Chapter 1, the main drivers of vertical extension as identified in existing work are its associated environmental and economic benefits. This includes those relating to reductions in embodied carbon (Wijnants, Allacker, & De Troyer, 2019; Hafner & Storck, 2019; Wijnants, Allacker, & de Troyer, 2017) and transition to a circular economy, as well as the ability to maximise refurbishment potential and thus asset value (Gillott, Davison, & Densley Tingley, 2022a; Pattison, 2021). Work considering real-world case studies also identifies the potential for reduced project cost and programme duration (Gillott, Davison, & Densley Tingley, 2022a), with that developing hypothetical case studies noting the relaxation of planning requirements as a further driver (Pattison, 2021).

2.2.2 Barriers

As well as through the aforementioned hypothetical extensions, Pattison (2021) considers barriers from a first-hand structural engineering perspective. Those identified are thus solely technical, including issues associated with increased design loads, the reuse of foundations, structural appraisal, intrusive investigation, structural robustness and fire (Pattison, 2021). Through consideration of real-world case studies, Sundling et al. (2018) identify a limited number of non-structural, yet-still-technical barriers to vertical extension, including site constraints (e.g. working at height and disruption to surrounding buildings) and the installation of building services. This work also outlines the need for further research on the barriers and enablers of vertical extensions and acknowledges the inefficacy of case-studies in identifying non-technical factors (Sundling, Blomsterberg, & Landin, 2018).

In the more general context of low carbon construction technologies, practices and materials, Giesekam et al. (2014) identify 30 common barriers through a systematic review of over 1000 publications. These are categorised as: economic, technical and performance-related; institutional and habitual; and knowledge and perception based. Through a sequential explanatory mixed methods approach (Creswell, 2009), a subsequent study (Giesekam, Barrett, & Taylor, 2016) aims to understand the relative significance of these factors in the context of low carbon building materials. This places perceived high costs, a shortage of knowledge and skills, inadequate design time, and an inability to establish responsibility among the most pertinent barriers.

Employing a similar mixed methods approach, Adams et al. (2017) identify 26 barriers to the implementation of circular economy in construction. In partial alignment with the work of Giesekam et al. (2014), these span three areas of technical concern ("manufacture of construction products", "designing and operating buildings", and "recovery of materials and products") as well as "awareness and understanding", "business and economics", and "legislation and policy". The most important challenges are identified as the complexity of buildings, insufficient consideration of their end of life, limited awareness and interest of stakeholders, an unclear financial case, and a lack of market mechanisms (Adams et al., 2017). These factors are also among the 18 cultural, regulatory, financial and sectoral barriers identified by Hart et al. (2019) in their review of 21 existing studies. This work concludes that, whilst there are a number of technical and regulatory challenges to circular economy in construction, the primary barriers are cultural (e.g. lacking collaboration across supply chains) and financial (e.g. difficulty demonstrating a business case) (Hart et al., 2019). Such findings are consistent with those of Kanters (2020), who, through a series of semi-structured interviews, identifies the inherent conservativeness of the construction sector to be one of the main barriers to the circular economy at present.

2.2.3 Enablers

As well as identifying barriers to vertical extensions, Sundling (2019) also suggests a number of high-level enablers. These too are derived from consideration of real-world case studies and include the presence of reserve structural capacity, stakeholder engagement and collaboration, and early-stage option evaluation. No specific approaches to achieving these enabling conditions are suggested however, as a result of the limited scope of this work (Sundling, 2019).

Using the same categorisations as for barriers, Adams et al. (2017) identify 15 enablers of circular economy in construction. These include best practice case studies to clarify the business case and end of life considerations such as material buy-back schemes (Adams et al., 2017). Similar recommendations are amongst the 20 cultural, regulatory, financial and sectoral enablers uncovered by Hart et al. (2019). In response to their identification of cultural and financial barriers, this work concludes that "technological and regulatory developments alone will not suffice, and a shift is required in business models and stakeholder behaviours and attitudes" (Hart et al., 2019). This further highlights the potential influence of non-technical factors, and thus the requirement for their consideration in the context of sustainable construction practice. Giesekam et al. (2016) reveal the need for best practice case studies identified by Adams et al. (2017) to also be relevant to the uptake of low-carbon materials. Additional identified enablers include early engagement of construction professionals; whole-life costing; changes to contract and tender documents; the provision of training and guidance; and (unspecified) regulatory drivers (Giesekam, Barrett, & Taylor, 2016).

Through a review of existing literature, Gosling, Sassi, Naim, & Lark (2013) identify key enablers of adaptable building design, categorising these as either design- (e.g. layering of building elements) or process- based (e.g. flexibility of planning practices). Subsequent work by Ross et al. (2016) considers the perceived effectiveness of 11 design-based enablers through a preliminary expert survey. This identifies the most important to be clear and accurate building records; the presence of reserve capacity; separation of buildings into layers; and open-plan layouts (Ross et al., 2016). Rockow et al. (2021) compare adaptability strategies from literature with empirical data from 89 case study projects, concluding that the most important enablers are quality design documentation and simple designs with open floor plans and large floor-to-floor heights.

2.3 Environmental impacts of vertical extensions

2.3.1 Whole-life environmental impacts

The detail of existing studies addressing the whole-life environmental impacts of vertical extensions is greatly varied and includes those providing little (Dind, Lufkin, & Rey, 2018) or no (Amoruso & Schuetze, 2022) quantification. A small number of studies do however conduct lifecycle analyses (LCAs) for this purpose (Wijnants, Allacker, & De Troyer, 2019; Hafner & Storck, 2019; Wijnants, Allacker, & de Troyer, 2017), with these experiencing varying levels of completeness and methodological rigour.

The first example of a comprehensive LCA for the vertical extension of an existing building is found in a 2017 conference paper from Wijnants et al. (2017). This sees the proposal of a prefabricated timber-framed ‘open renovation system’ for residential vertical extensions in Belgium, for which the whole-life impacts are then calculated. A total of seven variants of the proposed structural system, including those employing solid studs and I-joists, are assessed using an otherwise consistent wall composition. Impacts across all lifecycle stages are considered, with the exception of B1 (use), B3 (repair), B7 (operational water use) and C3 (waste processing) (Wijnants, Allacker, & de Troyer, 2017). This reveals that varying the sectional thickness of timber frame solutions has minimal impact upon embodied carbon emissions, but that, because of its allowance for a greater amount of insulation, I-joist systems typically have a lower operational carbon for the same frame thickness (Wijnants, Allacker, & de Troyer, 2017). A 2019 journal article from the same authors expands upon this work to consider a greater range of solid stud and I-joist frame arrangements, this time varying their spacing as well as sectional thickness (Wijnants, Allacker, & De Troyer, 2019). The effect of opting for different insulation materials was also investigated, as well as the influence of considering biogenic carbon on whole-life environmental impacts. Varying stud spacing was found to have minimal influence upon environmental impacts, whilst changing the insulation solution has the potential to achieve a whole-life saving of 17% (as a result of a 23% decrease and a 6% increase in embodied and operational carbon respectively) (Wijnants, Allacker, & De Troyer, 2019). Including biogenic carbon is revealed to change which solution is identified as environmentally preferable in some cases, with this effectively encouraging the use of more timber where this also yields the greatest reduction in operational carbon (e.g. colder climates and/or longer building lifespans) (Wijnants, Allacker, & De Troyer, 2019). Hafner and Storck (2019) also consider the whole-life environmental impacts of a timber vertical extension, including this as one of four construction materials to which a proposed LCA methodology is applied. Through this process, the timber extension system is, somewhat unsurprisingly, identified as having a lower environmental impact than those employing brick, concrete or steel, though no detailed design information is given in any case (Hafner & Storck, 2019).

Despite conducting LCAs for various prefabricated construction systems, the above studies do not specifically address how their employment in vertical extensions influences whole life environmental impacts. No consideration is made regarding potential requirements for strengthening of the existing building, or the reduced need for foundations and service-providing infrastructure. Assessing such relationships would require comparison of the conducted LCAs to equivalent space provision using the employed system for new build purposes. Similarly, as the whole life impacts of more traditional extension solutions are not assessed, the proposed systems' benefits relative to these are also unclear. Because of this, implications of previous studies considering the whole life impacts of vertical extensions are somewhat limited to the context in which they were derived, with their findings perhaps being more relevant to those with interest in timber use in construction, the balance between operational and embodied emissions, and the application of LCA methodologies.

2.3.2 Operational performance

Work considering potential operational energy benefits associated with vertical extensions includes studies assessing the performance of a single case-study building (Dind, Lufkin, & Rey, 2018; Artés, Wadel, & Martí, 2017) or extension solution (Aparicio-Gonzalez, Domingo-Irigoyen, & Sánchez-Ostiz, 2020; Mendonça, Macieira, & Guedes, 2020), as well as those attempting to optimise this for a given system (Spirkova et al., 2021; Lešnik et al., 2020; Amer & Attia, 2018).

Artés et al. (2017) estimate operational energy improvements for a single case-study building in Barcelona, Spain. This includes the heating, cooling and energy demand of both the extended and original portion of the building, with estimated annual CO_2 emissions being roughly 1/5 of that of a similarly sized reference building (Artés, Wadel, & Martí, 2017). It should be noted, however, that minimal methodological detail is provided for this process, with the estimation of operational energy being something of a secondary aspect of this work. A greater degree of detail and more robust methodology is seen in the work of Mendonça et al.(2020), who utilise a case study building in Porto, Portugal to the investigate the potential for using lightweight architectural membranes in vertical extensions. This is considered in terms of thermal insulation only, with architectural membranes combined with an insulating layer revealed to offer a similarly performing alternative to more traditional solutions. Despite its increased methodological rigour, similarly as for Artes et al. (2017), this study assesses only a single solution in order to verify its performance.

Aparicio-Gonzalez et al. (2020) go beyond this by conducting a series of EnergyPlus simulations to minimise the operational energy consumption of various modular CLT extension systems. This is completed with the aim of meeting Zero Energy Building (ZEB) and Nearly-Zero Energy Building (nZEB) standards as defined by the European Union (European Union, 2010). Achieving the required performance is revealed to be possible through the vertical extension and renovation of existing buildings, representing reductions in energy consumption of 74% and 62% for ZEB and nZEB respectively. It is worthy of note that, unlike most, this study is conducted at the multi-building level, with the optimised extension system being identified as applicable to 820 dwellings across a case study neighbourhood in Pamplona, Spain (Aparicio-Gonzalez, Domingo-Irigoyen, & Sánchez-Ostiz, 2020).

A number of additional studies have also attempted to optimise the operational performance of vertical extension systems, with this typically being considered alongside additional influencing factors. One such study is the previously discussed work of Amer et al. (2018), who carry out multi-objective optimisation to generate an external wall composition that minimises structural weight whilst maximising thermal performance. Similarly, Lešnik et al. (2020) attempt to define the optimum number and location of windows in extension storeys in order to ensure visual comfort and prevent overheating whilst also maximising operational efficiency. This study shows that considering solely operational efficiency can lead to glare and overheating issues in vertical extensions, in particular for south facing elevations, and that glazing ratios should typically be reduced in order to address this.

Although not engaging in optimisation, Spirkova et al. (2021) also consider financial implications of the operational performance of vertical extensions. By assessing three modular extension systems of varying performance it is revealed that energy cost savings of between 40% and 92% may be made when compared to the performance of a traditional brick extension. Similar to Aparicio-Gonzalez et al. (2020) this work is completed at the multi-building level, with a methodologically restricted top-down approach (Section 2.6) being employed to give an estimated potential for 900 extensions per year across Slovakia (Spirkova et al., 2021).

Although going some way in verifying the potential to deliver vertical extensions with high energy efficiency, the focus of existing studies on specific products and systems limits the generality of this. It is also the case that the majority of studies consider a single case study building, or a group of similar buildings, within a restricted geographical region, further limiting the applicability of their findings. By neglecting to compare the operational performance of these individual cases with that of a non-extension alternative (e.g. providing the same floor area through new-build or change of use), it is not explicitly the effect of vertical extension that is being assessed. As such, most existing studies are simply assessing the operational performance of a novel building system that is not specific to vertical extensions, despite being applied in this context.

2.3.3 Microclimatic influence

As a result of their increase in building height, the effect of vertical extensions on urban microclimates is the focus of two existing studies. The first of these compares pre- and post-extension scenarios using parametric modelling to investigate the influence of vertical extensions on the urban heat island in Vienna, Austria (Vuckovic et al., 2019). This revealed a significant daytime temperature decrease as a result of increased solar shading, coupled with a detrimental night-time warming effect due to higher thermal storage and a reduced sky view factor (Vuckovic et al., 2019). The work of Dinic Brankovic et al. (2022) expands upon this to consider the impact of residential vertical extensions on air temperature, mean radiant temperature, wind speed, relative humidity and solar radiation in three neighbourhoods in Niš, Serbia. Through computational modelling, this study reveals that changes in air-temperature, solar radiation and relative humidity are most significant when extending existing low-rise structures, with the extension of high-rise buildings having greatest influence on wind speeds. In general, it is found that vertical extensions result in decreased daytime air temperature and increases in mean radiant and night-time air temperatures, corroborating the results of previous work.

2.4 Structural aspects of vertical extensions

2.4.1 Superstructure

Previous work considering super-structural aspects of vertical extensions may be categorised into that considering solely the existing (Bahrami, Deniz, & Moalin, 2022; Al-Nu'man, 2016) or extended (Amoruso & Schuetze, 2022; Amer & Attia, 2018) portions of the building, or a combination of the two (Argenziano et al., 2021; Artés, Wadel, & Martí, 2017; Clark et al., 2006). Such studies are also typically based upon a single (Bahrami, Deniz, & Moalin, 2022) or small number (Amoruso & Schuetze, 2022; Argenziano et al., 2021; Artés, Wadel, & Martí, 2017) of case study buildings, and most often comprise simply of the development or verification of a structural system to facilitate extension (Amoruso & Schuetze, 2022; Argenziano et al., 2021; Amer & Attia, 2018; Artés, Wadel, & Martí, 2017; Clark et al., 2006).

Bahrami et al. (2022) use finite element methods (FEM) to assess the suitability for extension of a four-storey reinforced concrete building in Gävle, Sweden. The existing building is first modelled in its current form, before a single-storey extension of the same structural form is augmented and the FEM analysis repeated. Stress utilisation ratios (URs) reveal just seven elements to be overutilised, with a tertiary analysis verifying the suitability of the structure following the implementation of localised strengthening. Although revealing the presence of sufficient reserve capacity to allow for extension in most structural elements, these findings are specific to the single case study considered and thus not generalised. It is also the case that the study understates the ability of the structure's reserve capacity to facilitate extension because of the assumption that this would be carried out using a reinforced concrete system where a lightweight alternative is perhaps more likely.

Bahrami et al.'s FEM analysis of individual elements is the most advanced consideration of a building's extendibility seen in existing work. Most other studies instead employ a simplified mass-balance approach whereby loads from the extension are assumed to be offset by removed material and otherwise resisted by underutilisation in the existing structure. This is seen in the case Argenziano et al. (2021), who develop a number of concept-level extension designs for masonry structures in Italy, as well as Artés et al. (2017), who justify the lightweight extension of masonry structures in Spain, through the removal of water tanks, rooftop plant, and other roofing materials.

These studies' use of a concept-design-level mass balance approach is indicative of their consideration of a range of aspects (as discussed in Sections 2.4.2, 2.4.3 and 2.3.2) in both the existing and extended portions of a number of buildings. Despite this widened scope, each study considers only a single typology within a constrained geographic region (Argenziano et al., 2021; Artés, Wadel, & Martí, 2017), resulting in limited applicability beyond these contexts. Although only considering columns, a slightly more detailed appraisal process is undertaken by Al-Nu'man (2016) in their assessment of the requirement for strengthening of three conceptual reinforced concrete buildings subject to a two storey extension. This considers column section sizes, reinforcement percentages and respective material properties to reveal that, dependent upon the assumed concrete grade and extension solution, just 14-29% of columns within the considered buildings require strengthening. Interestingly, this small strengthening requirement is again identified when assuming a reinforced concrete- or steel-framed extension, where a lightweight solution would further reduce the need for strengthening.

Similarly as for the existing building, Artes et al. (2017) and Argenziano et al. (2021) give only concept-level consideration to structural aspects of the *extended* portion of their considered case study buildings. As such, although a steel-frame (Argenziano et al., 2021) and panelised/modular steel-timber system (Artés, Wadel, & Martí, 2017) are proposed respectively, no structural details (e.g. material grades or dimensions) are given. Despite inclusion of structural drawings, this is also the case in a subsequent study proposing three separate systems (cross-laminated timber, glue-laminated timber and steel frame) for the horizontal and vertical extension of different building typologies in South Korea (Amoruso &

Schuetze, 2022). In a slight improvement to this, Amer and Attia (2018) provide details of nominal structural thicknesses for their proposed CLT and timber frame systems, though no justification for assumed dimensions is given.

There is a clear lack of engineering rigour in existing studies considering superstructural aspects of vertical extensions, with only the work of Bahrami et al. (2022) and, to a lesser extent, Al-Nu'man (2016) utilising methodologies representative of detailed structural design or appraisal. Instead, most studies adopt concept-level design procedures (e.g. mass-balances and assumed structural dimensions), with this perhaps inaccurately representing the identified potential for extension and/or requirement for strengthening. Although some effort to consider a number of real-world case studies (Argenziano et al., 2021; Artés, Wadel, & Martí, 2017) or conceptual frame arrangements (Al-Nu'man, 2016) is seen, existing work is generally limited in scope due to its consideration of individual buildings. This means that, even if valid, the findings of existing studies are highly specific to the considered typology/ies (i.e. building age, use, structural form) and location(s), and are potentially invalid beyond this. The case specificity of existing work on structural aspects of vertical extensions is further contributed to by its focus solely on *identifying* reserve capacity or the requirement for strengthening, thus overlooking the underlying causes of this. For this reason, a supplementary review of work considering potential sources of underutilisation and reserve capacity in existing buildings is included in Section 2.5.

2.4.2 Substructure

Whilst the majority of the aforementioned case-studies do not consider substructural aspects of vertical extensions, a small number (Artés, Wadel, & Martí, 2017; Clark et al., 2006) do address this. There is also a growing body of literature pertaining specifically to geotechnical considerations of vertical extensions, with these typically proposing a novel solution (Wang et al., 2018, 2019; Wang, Han, & Jang, 2019) and/or verifying suitability of existing methods (Jeong & Kim, 2020; Kim, Kim, & Jeong, 2019) through numerical (Jeong & Kim, 2020; Kim, Kim, & Jeong, 2019; Wang et al., 2018, 2019) or experimental (Wang, Han, & Jang, 2019) means.

The first substructure strengthening solution, proposed by Wang et al. (2018), takes the form of a single pre-loaded reinforcement pile. Finite element methods (FEM) are used to show for a single case-study that, whilst a traditional reinforcement pile cannot provide sufficient resistance, pre-loading this to mobilise skin friction increases capacity such that this is the case. An alternative solution, this time considering jet-grouted piles, is proposed in a second conference paper from the same authors (Wang *et al.*, 2019). FEM is again used to compare the performance of parallel-sided reinforcing micropiles with a novel 'waveform' alternative, revealing this to carry 1.4 times the extended load for a given case (Wang et al., 2019). Through the application of an experimental modelling procedure for the same piling system, similar effects are shown in a follow up study by a number of the same authors (Wang *et al.*, 2019). Only a single ground condition and foundation configuration is considered by each of these studies, however, leading to limited transferability of these findings to other contexts.

More broad applicability is seen in the work of Kim et al. (2019), who use FEM to investigate the required axial stiffness of reinforcing piles considering various pile positions and end conditions, as well as different raft support conditions and pile stiffnesses. A similar follow up study has also been completed, including FEM analyses of both end-bearing *and* skin-friction piles of various lengths (Jeong & Kim, 2020). As well as considering a greater number of design scenarios, both these studies account for degradation of the existing piles and so more closely represent situations likely to be experienced in reality. Despite this widened scope and more applied approach, the findings of these works remain restricted in their generality as a result the consideration of a single, and somewhat favourable, ground condition.

In addition to limited applicability beyond the scenarios assessed, existing work considering substructural aspects of vertical extensions is contributed by a limited pool of authors. These also consistently view the problem from a geotechnical design perspective and, as such, place focus on the conceptual verification of foundation strengthening systems for a hypothetical design scenario. By looking inwards to the context of vertical extensions in this way, rather than holistically from within this context, more fundamental considerations are neglected. This includes the potential presence of reserve capacity within existing foundations, with this being overlooked by the assumption that the existing system is at, or near, the point of failure.

2.4.3 Seismic

Similarly as for substructural components, almost all works addressing seismic considerations of vertical extensions take the form of the proposal and/or verification of a novel strengthening solution. One study is however concerned with a more fundamental understanding of the seismic behaviour of vertical extensions, considering the historic extension of masonry structures in Barcelona, Spain (Marafini et al., 2022). Through the completion of numerical FEM analyses this shows extensions taking place at various points in time to be detrimental to the seismic performance of existing buildings, with this also having a potential influence on neighbouring structures (Marafini et al., 2022).

In terms of seismic strengthening, the first approach, proposed by Li et al. (2003), takes the form of a separate steel podium structure upon which the extended storeys are loaded. As well as transferring vertical loads directly to the foundation level, rather than these being incident upon the existing building, this serves to provide seismic resistance to both portions of the building. For this purpose, a series of energy dissipating dampers are used to tie the structures at each existing storey, and a friction layer introduced at the former roof level (Li, Yin, & Wang, 2003). Through a series of experimental tests, the suitability of this system for application to existing masonry structures is verified in the context of a case study in China. A subsequent study sharing a number of the same authors uses numerical methods to corroborate the validity for this specific case (Li et al., 2004), with a similar system also being proposed in work considering the extension of a reinforced concrete structure in New Zealand (Clark et al., 2006).

The use of podium strengthening structures is identified by Heo et al. (2021) as unsuitable for high-rise buildings or those in high density areas where perimeter land is not readily accessible. This leads to the proposal of an alternative solution of existing column strengthening and the use of rotary damper joints between and within the extended storeys (Heo et al., 2021). Numerical analysis is used to verify this system's performance in the context of an existing reinforced concrete and steel structure in Korea. A subsequent paper from a number of the same authors proposes a second strengthening solution to be implemented within the footprint of existing buildings. Again employing column strengthening techniques, this system attempts to provide seismic resistance through the introduction of an isolation storey between the existing and extended portions (Hur & Park, 2022). The use of an intermediate isolation system in this way is similar to proposals previously made for existing masonry (Argenziano et al., 2021) and reinforced concrete (Clark et al., 2006) buildings.

Because of its focus on the proposal and verification of novel strengthening solutions for individual cases, work addressing seismic considerations of vertical extensions is highly case specific. Perhaps unsurprisingly, it is also concentrated in more seismically active regions, again resulting in a limited pool of contributing authors. Despite this limited applicability, such studies serve to highlight key considerations relating to structural retrofit for adaptive reuse and go some way in providing insight regarding possible solutions where seismic performance is of concern.

2.5 Underutilisation and reserve capacity in existing buildings

Despite being conducted beyond the context of vertical extensions, work considering sources of underutilisation in engineering design remains relevant because of its potential to introduce reserve structural capacity within existing buildings. As such, an overview of work detailing both historic and prevailing causes of underutilisation is detailed below, alongside a review of studies considering the influence of this on material efficiency. This highlights the focus of existing work upon material savings through the optimisation of *new* buildings, and a neglect of how underutilisation causes reserve structural capacity in *existing* buildings that may be exploited through their adaptive reuse.

2.5.1 Historic design codes

The past employment of design codes that are more conservative than those in use today is perhaps the most obvious source of underutilisation in existing buildings. Although often introduced to account for reducing uncertainty in material properties and advancing manufacturing processes, Beal (2011) discusses how overall factors of safety in the design of steel structures have decreased over time. Early examples of reductions resulting from advancements in knowledge include the switch from Mitchell-Moncrieff to Perry-Robertson formula when calculating permissible stresses in BS 449 (British Standards Institution, 1969) (resulting in a nominal safety factor of 2.0), and the further revision of this this to 1.70 in 1964 (Beal, 2011). Similar amendments may also be seen with more recent limit-state design codes, including the reduction of partial safety factors for the combined effect of permanent and imposed loads (γ_G and γ_Q respectively) from 1.40 and 1.60 in BS 5950 (British Standards Institution, 2001) to 1.35 and 1.50 in Eurocodes (British Standards Institution, 2011). Eurocodes also introduce additional reduction factors for permanent loads (ξ) and combinations of variable actions (ψ), further reducing the overall factor of safety to between 1.30-1.45 (Beal, 2011). Reductions in factors of safety such as these suggest the presence of underutilisation in structures designed to historic codes, and thus the potential to identify reserve capacity should they be appraised using modern standards.

It is also the case that, as a result of some engineers' caution, inexperience and/or aversion to change, a number of historic practices prevail where modern design codes have otherwise been adopted. Examples of this include the neglect of Eurocode reduction factors for permanent loads (ξ) and combinations of variable actions (ψ), as well as variable actions acting over large areas or multiple storeys (α_A and α_n).

2.5.2 Partial factors for combinations of actions

Although initially intended to be calculated using a probabilistic approach, the partial safety factors for combinations of actions used in Eurocodes are derived using deterministic methods and 'calibration to a long experience of building tradition' (British Standards Institution, 2011). This means that designs generated in accordance with Eurocodes may have a probability of failure below the value of $7.2\text{x}10^{-5}$ required by the standard (British Standards Institution, 2011), and thus experience underutilisation.

The resultant scope for modification of the partial safety factors used in Eurocodes is investigated by Kala (2007) through the probabilistic study of a tensile member. It is revealed that, for commonly occurring structures (where the ratio of imposed to total loads is between 0.15 and 0.55), the partial safety factor for permanent loads may be reduced from 1.35 to 1.10 whilst retaining a probability of failure below $7.2\text{x}10^{-5}$. This indicates the potential to identify reserve structural capacity in existing structures designed in accordance with Eurocodes if they are appraised using modified partial safety factors or a fully probabilistic approach.

2.5.3 Imposed loads

Imposed loads are those acting on a structure as a result of its occupancy, including from inhabitants, furniture, storage and other moveable objects (e.g. partitions) (British Standards Institution, 2002). As determination of the exact imposed loads likely to be experienced by a structure is both time consuming and complex, *characteristic* values are specified in Eurocodes (British Standards Institution, 2002) and associated National Annexes (British Standards Institution, 2008). These represent imposed loads for which the probability of exceedance is perceived to be reasonably low (normally ≤0.05) (Orr, 2019) and are largely based upon historic practice and consensus amongst practitioners. For example, a report from the Minimising Energy in Construction (MEICON) project (Drewniok & Orr, 2018) reveals how characteristic office loads in Eurocodes have origins in the US as early as 1862 (Little, 1862) and the 1909 recommendation of 100 lb/ft^2 (4.8k N/m^2) for office buildings in London (Fletcher, 1909).

Since the introduction of BS6399 in 1984, imposed load recommendations for general office use have remained between 2.0-3.0 kN/m^2 (for storeys above ground level), with the additional allowance for moveable partitions of 1.0kN/m^2 in BS6399 (British Standards Institution, 1996) being replaced by 0.5, 0.8 or 1.2 kN/m^2 following the adoption of Eurocodes (British Standards Institution, 2002). Currently recommended imposed loads are therefore between 2.5 kN/m^2 and 4.2 kN/m^2. Despite the less intense occupation and increased digitisation of office environments with time, this is not significantly different to recommendations made at the start of the 18th century (Fletcher, 1909). As documented by Drewniok & Orr (2018), this contributes to a widely held view that characteristic imposed loads recommended by Eurocodes are greater than is required to ensure a reasonably low probability of exceedance. The same investigation, part of the MEICON project, collates results from 13 studies assessing the actual imposed loads experienced by office buildings, revealing the largest and average values to be 1.90 kN/m^2 and 0.63 kN/m^2 respectively (Drewniok & Orr, 2018).

Despite evidence that characteristic imposed loads recommended by Eurocodes are already greater than required to ensure a reasonably low probability of exceedance, additional work from MEICON shows that actual specified loads are often greater still (Orr & Drewniok, 2018). This study reveals the area-weighted average specified live load of 95 office buildings to be 3.57 kN/m^2, with an additional average allowance of 1.06 kN/m^2 for partitions. The over-specification of characteristic imposed loads and the common use of values exceeding these suggests a high likelihood of underutilisation in both historic and recently designed buildings. This results in an opportunity to identify reserve capacity in existing structures should they be appraised using reduced characteristic values, or actual experienced loads.

2.5.4 Rationalisation

In 1977 Needham highlighted that steel buildings designed to minimise weight (i.e. material) rarely have the lowest associated cost. This was attributed to the fact that detailing (e.g. design of connections) could be 20 times as costly as initial design (e.g. sizing of sections), should each member be designed for minimum weight. The 'grouping' of similar members was therefore recommended to enable their specification with consistent section size and minimised detailing requirements. Gibbons (1995) discusses how reductions in the cost of steel relative to labour costs has further promoted design simplicity, and thus ease of fabrication and construction, at the expense of minimised weight. This leads to explicit recommendation for 'rationalisation' of the number of different section sizes, member lengths and material grades, whilst ensuring no single element experiences more than a 20% increase in weight. More formal guidance on acceptable degrees of structural rationalisation and simplification has been provided since 1995, such as in The Steel Construction Institute's 'Design for Manufacture Guidelines' (SCI P150) (Gibson et al., 1995). Orr et al. (2019) reveal how such guidance has resulted in rationalisation and the grouping of members becoming standard practice in the design of steel buildings (Orr et al., 2019).

Through the analysis of 23 real-world case studies, Moynihan & Allwood (2014) find the average UR of beams and columns to be 0.40 and 0.49 respectively. Rationalisation is suggested as the primary cause of this underutilisation as a result of low variation in section sizes across a given storey, high and low URs for adjacent members of the same section, and low frequency of high URs. Based upon average URs and assuming proportionality of resistance and mass, it is concluded that rationalisation may be contributing up to 46% additional mass in steel framed buildings. This may be otherwise stated as 46% of the material in *existing* steel framed buildings currently being unutilised, representing a major source of reserve structural capacity to be exploited through increased loading (e.g. by vertical extension).

2.5.5 Defensive design

The validity of Moynihan and Allwood's assertion that rationalisation is the primary contributor of underutilisation in steel buildings is investigated in a later study by Dunant et al., (2018). This sees the computer-aided analysis of 27 real-world and three hypothetical case studies in order to assess the impact of frame regularity on the utilisation of steel beams. The average mass-weighted UR of all beams is found to be 0.65, in general agreement with the corresponding value of 0.54 for the earlier study (Moynihan & Allwood, 2014). Patterns of increasing utilisation with frame regularity or project cost are not seen, however, as otherwise expected if rationalisation was the primary cause of underutilisation (Dunant et al., 2018).

The distribution of beam URs identified by Dunant et al. (2018) exhibits a distinct peak at a value of 0.8, with a long tail for values below this, and a sudden drop off following the peak. From this profile it is suggested that, rather than rationalisation, the primary cause of underutilisation of steel structures is 'defensive' design practice. This represents the situation where engineers are reluctant to target UR values greater than 0.8 because of the ingrained desire to ensure safety, and to protect against potential alterations in later design stages

(Dunant et al., 2018). Such a process of engineers not seeking a fully utilised design (UR = 1 or $E_D = R_D$) is investigated further by a survey of structural engineering practice undertaken as part of the MEICON project. This sees the formulation of the notion of an ‘effect-resistance gap’, to which both defensive design and rationalisation contribute (Orr, 2018).

2.5.6 Section size limitations

Since the introduction of British Standard 4 (BS4) in 1903, steel members used in the construction of buildings have typically been selected from a catalogue of discrete standardised section sizes. Through evolution via BS4848 in 1972 and BS4-1 in 1980 (British Standards Institution, 2005), section sizes are now detailed by BS EN 10365 (British Standards Institution, 2017), and supplemented by additional sections in the more widely used Steel Building Design Data ‘Blue-book’ from SCI, Tata Steel and BCSA (The Steel Construction Institute, Tata Steel, & The British Constructional Steelwork Association, 2015). This contains 36 universal column (UC) and 96 universal beam (UB) sections alongside parallel flange channels and circular, rectangular and elliptical hollow sections.

Specification of members from this discrete catalogue of section sizes results in a non-continuous range of potential member resistances, and thus limited likelihood of full utilisation (UR=1). Moynihan and Allwood (2014) reveal that, on average, UB sections have 85% of the capacity of the next largest section size, with the corresponding value for UC sections being 81%. From this, they suggest an average UR of 0.9 to be possible for an optimised design using standard catalogue sections. This is corroborated by Dunant et al. (2018), who identify URs up to 0.95 in a large number of members employing standard catalogue sections. Although suggested to only reduce average member utilisation by approximately 10%, the use of standard catalogue sections in the design of historic and present-day buildings represents a potential source of reserve structural capacity.

2.5.7 Material properties

Because design takes place prior to the procurement of materials and components, engineers are required to assume characteristic material properties in the design of buildings. As with characteristic loads, these represent values with a reasonably low probability of exceedance (normally ≤0.05) and are multiplied by successive partial factors to give design values. Melcher et al. (2004) detail how commonly used characteristic yield strength values, perhaps the most important material property in the sizing of steel members, are based upon a distribution of experimentally derived values. This process dictates that the actual yield strength of structural steel currently specified for use in buildings is likely to be greater than the characteristic value with which the structure was designed. An example of this is given by Melcher et al. (2004), who find the average yield strength of S355 steel (which has a characteristic yield strength of 355 MPa) to be 402 MPa. The fact that structural material is already in place for adaptive reuse projects therefore offers an opportunity for the identification of reserve structural capacity should the reappraisal process utilise measured material strengths.

Further opportunities for identification of reserve capacity through the use of actual material strengths result from the reactive nature of historic design codes. As discussed in Section 2.5.1 and by Beal (2011), yield stresses recommended for use by various design codes have increased incrementally over time to match advancing manufacturing processes. Examples of these include that with the introduction of BS5950, as well as incrementally increasing permissible stress profiles prior to the introduction of limit state design. This means there is potential scope for the identification of reserve capacity where a structure was designed with components manufactured using a more advanced process than was acknowledged by the codes of that time.

2.5.8 Approaches to reducing underutilisation

Following recognition of underutilisation sources, there is a growing body of literature investigating approaches to reducing this through structural optimisation. As proposed by Baldock (2007), these may be categorised as topology-, shape- and size-optimisation strategies, which concern the configuration of members, structural shapes, and size/shape of cross-sections respectively. Owing to its relative simplicity, the latter of these strategies has received greatest focus, including in the aforementioned studies by Moynihan and Allwood (2014) and Dunant et al. (2018). Through consideration of real-world case studies, these identify average mass-weighted beam URs of 0.54 (Moynihan & Allwood, 2014) and 0.65 (Dunant et al., 2018), and, assuming proportionality of resistance and mass, suggest potential mass savings from increased optimisation of 46% and 35% respectively.

Validity of this assumption of mass-resistance proportionality of steel beams, and the influence of catalogue section sizes on the potential for optimisation, are considered in a subsequent study by Drewniok et al. (2020). This proposes a ‘lightest beam method’ (LBM) for the selection of the optimum (minimum weight) UB catalogue section for a given design scenario, considering both ultimate (bending, shear and buckling) and serviceability (deflection and vibration) limit states in accordance with Eurocodes (Drewniok, Campbell, & Orr, 2020). By applying the LBM to the 30 case studies considered by Dunant et al. (2018) and comparing the optimised and original floor plates, a reduced average material saving of 27% was identified (Drewniok, Campbell, & Orr, 2020). The study goes on to consider the potential for further material savings through structural optimisation using adjusted Eurocode scenarios. These are inspired by findings from previous research, including the use of reduced partial safety factors, relaxed serviceability criteria, average yield strengths, and increase potential mass savings to 35% (Drewniok, Campbell, & Orr, 2020).

The potential mass saving of 27% identified by Drewniok et al. (2020) is in general agreement with the findings of a previous study by D'Amico and Pomponi (2018). In this, an assessment framework is developed to sequentially optimise secondary beams, primary beams, columns and bracing members for a specified steel frame configuration. A non-optimised version of the same configuration is then generated, with vertically aligned columns adopting the largest section size across all storeys, and horizontally aligned beams adopting the largest section size within their respective storey (D'Amico & Pomponi, 2018). By comparing the relative mass of these design scenarios for a hypothetical frame configuration, potential material savings, and resultant embodied carbon reductions, of up to 23% are identified.

Although existing work suggests potential sources of underutilisation (Dunant et al., 2018; Drewniok & Orr, 2018; Orr & Drewniok, 2018; Moynihan & Allwood, 2014; Beal, 2011; Kala, 2007; Melcher et al., 2004) and identifies this in real-world (Drewniok, Campbell, & Orr, 2020; Dunant et al., 2018; Moynihan & Allwood, 2014) and hypothetical (D'Amico & Pomponi, 2018) buildings, approaches to reducing this are typically placed on material savings through the optimisation of new structures (Drewniok, Campbell, & Orr, 2020; Dunant et al., 2018) considering current (Drewniok, Campbell, & Orr, 2020; Dunant et al., 2018; D'Amico & Pomponi, 2018; Moynihan & Allwood, 2014) or modified (Drewniok, Campbell, & Orr, 2020) design codes. Such studies therefore overlook how underutilisation may have resulted in reserve structural capacity in *existing* buildings, and how this may be exploited through their future adaptive reuse.

2.6 Potential for vertical extension beyond the building level

Across academic, industrial and governmental literature there are a small number of studies assessing the potential for vertical extensions to deliver housing beyond the building-scale, conducted both in the UK (Ministry of Housing Communities and Local Government, 2020b;

HTA Design, 2016) and overseas (Spirkova et al., 2021; Aparicio-Gonzalez, Domingo-Irigoyen, & Sánchez-Ostiz, 2020). Various methodological approaches are seen across such studies, including those aggregating building-level extendibilities (Aparicio-Gonzalez, Domingo-Irigoyen, & Sánchez-Ostiz, 2020; HTA Design, 2016) or based upon inter- or national statistics (Spirkova et al., 2021; Ministry of Housing Communities and Local Government, 2020b). In consistency with nomenclature used in research on built environment material stocks (Lanau et al., 2019), such approaches are herein referred to as ‘bottom-up’ and ‘top-down’ respectively.

As in Section 2.3.2, Aparicio-Gonzalez et al. (2020) extrapolate their consideration of building extendibility across an entire neighbourhood in Pamplona, Spain. A typology-based, bottom-up approach is used for this purpose, whereby the extendibility of a single representative case-study is assessed and assumed applicable to all buildings belonging to that typology. An existing geospatial dataset categorising buildings within the Chantrea neighbourhood is used for this purpose, with only a single typology being considered out of the four that are identified. In addition to this typology-level assessment, consideration regarding the proximity of individual properties to adjacent buildings is also made. This sees all properties closer than the building’s total height being deemed in violation of local planning regulations and thus non-extendible. Through this process, 278 out of 410 buildings belonging to the considered typology are identified as extendible, representing potential to deliver 820 new dwellings across the considered neighbourhood. Despite going beyond most existing studies to consider extension potential beyond the single-building level, there are a number of methodological deficiencies which limit the accuracy of this work. The first of these relates to the consideration of only a single building typology, which represents just 15% of the building stock in the considered region (Aparicio-Gonzalez, Domingo-Irigoyen, & Sánchez-Ostiz, 2020), and the determination of its extendibility based upon assessment of a single case study building. Effects of this are worsened by the limited scope of this case-study extendibility assessment itself, which focusses solely on operational energy aspects and arbitrarily assumes a consistent potential for extension by one story. In addition to these typology-based limitations, this study considers only a small number of buildings within a geographically restricted area, with a number of key methodological details (e.g. conversion from extendible buildings to numbers of dwellings) also being omitted (Aparicio-Gonzalez, Domingo-Irigoyen, & Sánchez-Ostiz, 2020).

A similar typology-based, bottom-up approach is adopted by HTA Design (2016) in their consideration of the potential for residential vertical extensions in Camden, London. This process utilises aerial imagery to identify 475 suitable extension sites across the considered area and is largely based upon the presence of existing flat roofs. Following this, identified properties are categorised into one of eight building typologies, taking consideration of building age, use and form, each with a similar potential for extension and ability to be extended using a typical solution. Such typical solutions are generated for each typology, detailing the number of storeys that may be added and the employed structural form (e.g. modular or on-site construction). By combining the proposed extendibility of each typology with the number of associated properties and their respective footprints, an estimation of the floor area generated by each typology may be ascertained. Across Camden, this process identified potential to deliver 198,660 m^2 of new useable floorspace, equating to 2,485 new homes (assuming 60m^2 per home and 75% floorspace utilisation). This represents 1.14 new homes per hectare in Camden, leading to the estimation of 179,126 homes across the entirety of London when assuming a consistent density of housing potential. Although more refined than the work of Aparicio-Gonzalez et al. (2020) as a result of its consideration of eight building typologies, this study experiences many of the same shortfalls associated with its typology-based, bottom-up assessment. This includes assumed homogeneity within typologies likely to experience variation in reality, as well as the neglect of planning and technical aspects (e.g. reserve structural capacity) in determining the extendibility of each typology. Owing to a lack of methodological detail, it is also unclear how the number of sites belonging to each typology, and their associated footprint, is determined from aerial imagery, with this seemingly being based largely upon the presence of existing flat roofs. Evidently, this is only one of a multitude of factors influencing the ability of a building to be extended, both overlooking potentially suitable properties and neglecting to include those with non-flat roofs that are otherwise suitable for extension. Although scaled beyond this by assuming uniform potential across the entire city, this work again considers a geographically restricted region. As such, and owing to the discussed methodological deficiencies, the accuracy and validity of the extension potential estimated in this work is largely unknown.

As discussed in Section 2.3.2, Spirkova et al. (2021) apply a top-down approach to extrapolate building-level extendibilities across the entirety of Slovakia. This adjusts national-level statistics on historic housing delivery to identify the number of houses generated through vertical extensions per year. A value of 900 new dwellings per annum is derived from this process and, perhaps erroneously, assumed indicative of the scale of potential for residential vertical extensions within the country. As is common with top-down approaches, the spatial resolution of this study is limited (i.e. to the national level), with the accuracy and validity of findings being further mitigated by the application of numerous unjustified assumptions.

A similar top-down approach is employed by the Ministry of Housing, Communities and Local Government (MHCLG), now the Department for Levelling Up, Housing and Communities (DLUHC), in their 2020 impact assessment (Ministry of Housing Communities and Local Government, 2020b) of vertical extension Permitted Development Rights (PDRs)[2]. Total numbers of residential and commercial properties from the English Housing Survey (EHS) (Ministry of Housing Communities and Local Government, 2017) and rateable property statistics (Valuation Office Agency, 2020) are first used in order to estimate the number of eligible properties at the national level. This value is then refined into potential, feasible, and likely numbers of deliverable dwellings by applying assumptions based upon building typology, location, height and age, as well regional economic activity and extension size. A total of 53,000 properties are identified as eligible, giving lower and upper bounds of 15,000 and 190,000 deliverable dwellings (Ministry of Housing Communities and Local Government, 2020b). Such a large range of potential dwellings is indicative of a number of methodological inaccuracies inherent within the followed top-down approach. These include, but are not limited to, the neglect of a number of location-based eligibility criteria (e.g. removal of buildings within national parks, world heritage sites, areas of outstanding natural beauty and sites of special scientific interest) and listed or scheduled monument status, as well as extendibility restrictions on individual storey and total building height (The Town and Country Planning (General Permitted Development) (England) (Amendment) (No. 2) Order 2020; The Town and Country Planning (Permitted Development and Miscellaneous Amendments) (England) (Coronavirus) Regulations 2020). As a result of its basis on national-level summary statistics, this work also fails to correctly categorise properties as they appear in PDRs (The Town and Country Planning (General Permitted Development) (England) (Amendment) (No. 2) Order 2020; The Town and Country Planning (Permitted Development and Miscellaneous Amendments) (England) (Coronavirus) Regulations 2020) and spatially disaggregates simply to properties within- or beyond-London. In addition to inaccuracies in total numbers of deliverable dwellings, this inhibits consideration of the spread of extension

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[2] An overview of vertical extension PDRs is given in Chapter 5, alongside a more comprehensive review of the methodology discussed here.

potential between different building typologies and in geographic regions, further limiting this study.

2.7 Conclusions

The limited number and scope of studies addressing vertical extensions indicates this to be an undeveloped field, instead representing an external context to which relevant specialisms are beginning to apply their expertise. Because of this, although growing, understanding of vertical extensions is currently limited to a series of fragmented perspectives from isolated disciplines. A more holistic and context-centric outlook is thus required to ascertain the potential of this construction technique, including identification of areas in which advancement of knowledge is most required and the development and application of methodologies to facilitate this. Within this broader need for more holistic consideration of the potential for vertical extension, the most relevant knowledge gaps identified by this literature review are thus:

1. Existing studies considering factors influencing the uptake of vertical extensions are limited in number and typically narrow in scope. By neglecting to consider a range of contexts and viewpoints in this way, these studies have an inherent focus on technical factors and overlook those relating to financial aspects, legal considerations, or cultural beliefs. This means that there are perhaps a number of context-specific factors with influence over the potential for vertical extension that as yet remain unknown. Although more broad consideration of non-technical factors is made in work conducted in surrounding contexts, the applicability of their identified factors to the specific context of vertical extensions has not been considered, and is thus unclear.

2. Whether relating to superstructure, substructure or seismic resistance, work considering technical aspects of vertical extensions typically focusses on the assessment or verification of a single or small number of case study buildings. Although successful in exemplifying the technical possibility or suitability of vertical extensions in certain cases, such studies are highly specific to the building, extension or strengthening process under consideration and thus lack widespread applicability. This is again a symptom of the fragmented perspectives from which the potential for vertical extensions is currently viewed, with no consideration of the underlying causes of reserve capacity and/or strengthening requirements being made in these studies. Although known sources of

underutilisation in existing buildings are documented in adjacent contexts, existing studies view this solely as an opportunity to reduce material consumption in new buildings. Resultant reserve capacity in existing buildings is thus yet to be considered, and the influence of this on the potential for vertical extensions unknown.

3. Existing work considering the potential for vertical extensions beyond the single building level is consistently hindered by a number of methodological deficiencies. This is true both for top-down and bottom-up approaches, with the former typically being restricted in terms of its spatial resolution and being based upon a large number of potentially invalid assumptions. Use of top-down approaches also limits ability to consider the spatial distribution of extension potential within considered areas, limiting the usefulness of generated results. On the other hand, although of higher spatial resolution and potentially greater accuracy, as a result of their consideration of building characteristics, bottom-up studies are limited by their consistent application of a typology-based approach. Similar to in top-down approaches, this introduces a number of underlying assumptions (e.g. regarding homogeneity of extendibility within each typology) and thus, albeit to a lesser degree, presents potential for invalidity and inaccuracy in identified extension potentials. Owing to their more refined spatial resolution, and thus more data-intense analysis, existing bottom-up studies are also applied over a more restricted geographic extent. In combination, these factors dictate that an accurate and spatially refined estimation of the potential for vertical extensions has not yet been generated in a UK context or overseas. As a result of this, the spatial distribution of extension potential is also yet to be considered.

In meeting its overarching aim to ***understand the potential for future space provision through the vertical extension of existing buildings***, this thesis provides a more holistic and context-centric outlook identified as required within this chapter. The constituent research questions (RQ1-3) introduced in Chapter 1 and answered in Chapters 3-5 are also effective in addressing the specific knowledge gaps detailed above. More explicitly, Chapter 3 addresses the first knowledge gap by answering RQ1 ("What are the key factors influencing the uptake of vertical extensions, and how may this be enhanced in the future?"), Chapter 4 addresses the second knowledge gap by answering RQ2 ("How much reserve capacity do different underutilisation sources introduce in existing buildings, and how far does this facilitate their extension?") and Chapter 5 addresses the third knowledge gap by answering RQ3 ("How much space could be provided by residential vertical extensions, and how is this distributed at the city and national level?”).

3

Construction Sector Views – Drivers, Barriers and Enablers

This chapter contains work previously prepared for the following publication:

Gillott, C., Davison, B. and Densley Tingley, D. (2022). Drivers, barriers and enablers: construction sector views on vertical extensions. *Building Research & Information*, 50(8), 909-923.

3.1 Introduction and research aims

As discussed in Chapter 1, consideration of the potential for vertical extensions is inhibited by a limited understanding of key factors influencing its adoption. Although some studies do assess this specifically, these are revealed by Chapter 2 to be limited in number and typically narrow in scope. For example, such works generally consider first-hand experiences or a small number of real-world or hypothetical case studies (Table 2.2). By neglecting to consider a range of contexts and viewpoints in this way, the findings of these studies are highly case specific and often have an inherent focus on technical factors, while overlooking those relating to financial aspects, legal considerations, or cultural beliefs. This means that there are perhaps a number of extension-specific factors with significant influence on the potential of this construction that to date remain unknown.

More broad consideration of non-technical factors is made in the surrounding body of work which addresses superordinate contexts such as low-carbon design and the circular economy, and adjacent decarbonisation strategies such as adaptable buildings and low-carbon materials (Table 2.1). Methodological approaches employed in understanding these are also more diverse, including stakeholder consultation and the systematic review of existing work (Table 2.2). Despite the enhanced scope of such works, the applicability of their identified factors to the specific context of vertical extensions has not been considered and thus remains unclear.

To address these knowledge gaps this chapter aims to understand ***the key factors influencing the uptake of vertical extensions, and how may this be enhanced in the future***. In achieving this, three objectives are defined.

a.) Assess awareness and experience of vertical extensions amongst construction sector stakeholders.
b.) Identify context-specific factors influencing the uptake of vertical extensions and assess the relative importance of those from surrounding contexts.
c.) Understand the causes and interrelation of influencing factors and suggest recommendations to enhance uptake.

3.2 Methodology

To ensure the capture of perceptions and non-technical factors, a sequential, explanatory mixed methods approach (Creswell, 2009) is adopted. Similar to previous work discussed in

Chapter 2 (Kirchherr et al., 2018; Giesekam, Barrett, & Taylor, 2016; Du et al., 2014), this comprises a survey and semi-structured interviews to consider a wide range of views whilst obtaining sufficient detail for the formation of justified conclusions (Saunders, Lewis, & Thornhill, 2016; Knight & Ruddock, 2008). To further promote the consideration of non-technical factors and minimise the influence of subjectivity, the construction sector in its entirety is taken as the target population. The study does not seek to recruit a statistically representative sample however, and acknowledges the potential influence of purposive sampling and self-selection bias (Bryman, 2016). The vertical extension of all building typologies, by any height, is considered in this work.

Both elements of the study assess current awareness, uptake, and experience of vertical extensions, as well as the drivers, barriers and enablers influencing adoption. The primary purpose of the survey is to provide a quantitative measure of this, with semi-structured interviews capturing any previously unidentified factors and generating a qualitative understanding of the themes identified within the survey.

3.2.1 Survey

The survey was hosted online using Qualtrics (Qualtrics, 2020) for a six month period between 2020 and 2021. As suitable participants were defined as anyone working within the construction sector, this was openly accessible and a self-selective, non-probabilistic sampling process was adopted (Saunders, Lewis, & Thornhill, 2016). Invitation to participate was issued in The Structural Engineer (The Institution of Structural Engineers, 2020) and on The Urban Flows Observatory's news feed (Urban Flows Observatory, 2020), as well as at events held by the Association of Consulting Engineers (ACE) and Resource Efficiency in Construction and the Built Environment (RECBE) groups. Further requests for participation were made through social media and to established industry contracts via email. Upon recruitment, and following completion of the survey, a request for dissemination to potential respondents was made to increase the range and number of responses through snowball sampling (Saunders, Lewis, & Thornhill, 2016).

In addition to the collection of demographic information, the survey included sections collecting quantitative and qualitative data on respondents' awareness, involvement and experience of vertical extension projects, as well as their views on potential barriers and enablers (see Appendix 1). The barriers and enablers presented to respondents were derived from a formal review of existing studies considering the implementation of sustainable construction practices. This collated over 300 factors in total and resulted in the 19 influencing factors shown in Figure 3.3 through a process of duplicate deletion, merging, and re-specialisation. Similarly to previous studies (Hart et al., 2019; Adams et al., 2017; Giesekam, Barrett, & Taylor, 2016; Giesekam et al., 2014), these are disaggregated as technical, cultural, economic and legal.

A range of multiple-choice categorical, rating scale, and free text entry questions were utilised in the survey. Branch- and show/hide- logic was implemented to tailor the experience to each participant based upon previous inputs. This increased the ease-of-completion of the survey, ensured sufficient quantitative data was collected from each respondent, and provided opportunity for qualitative explanation where desired. Following completion of the survey, respondents were invited to provide contact details for further research. A copy of the survey is included as supplementary information.

Owing to the descriptive labelling of rating scale points (e.g. “extremely negative”) resulting data is treated as ordinal. Mode and median are therefore used as measures of central tendency, rather than the mean as in some existing studies (Adams et al., 2017). This is also the case for responses to categorical multiple-choice questions. Qualitative free-text responses were thematically analysed in NVivo (QSR International, 2020) using an inductive process (Braun & Clarke, 2006) to allow the emergence of themes to be dictated by the data.

3.2.2 Interviews

Based upon their ability to provide further insight and to maximise the spread and even representation of demographics, a number of respondents indicating willingness were invited to a follow up interview. These were conducted via video call over a two-month period in 2021, lasted between 30 and 60 minutes, and were recorded to enable transcription.

A semi-structured format was adopted, employing a consistent question guide across interviews (see Appendix 2 for details). This ensured all key themes were discussed by each interviewee, whilst encouraging the exploration of additional topics arising naturally in conversation. Occasionally guiding interviewees towards topics beyond their area of expertise (e.g. inviting engineers to discuss tax regimes) assisted in capturing stakeholder perceptions in addition to more justified beliefs. Prescribed discussion points were influenced by the findings of the survey, and included specific drivers, benefits and personal experiences, as well as barriers and enablers to uptake. Before closure of each interview, opportunity was given for interviewees to raise any additional points not yet considered. As such, and because of the diverse expertise of the interviewees and the discursive nature of the semi-structured approach, the themes explored in each interview vary in both range and depth.

Following semi-automated transcription, an inductive thematic analysis (Braun & Clarke, 2006) was again conducted in NVivo (QSR International, 2020). Data extracts assigned to each resulting theme were then reviewed in turn to build an explanatory discourse surrounding each.

3.3 Results

3.3.1 Demographics

The survey received 87 responses in total, 60 of which had a completion rate >90% and were carried forward for analysis. Respondent numbers for individual questions are typically lower than this, however, as a result of alternative routes through the survey (Appendix 1) and the optional nature of certain questions[3]. To ensure transparency considering this, the number of respondents selecting a response is reported as a fraction of the sample size for the associated question, rather than as a percentage.

Out of the 24 respondents indicating willingness to be contacted for further research, 17 were invited to interview, of which 11 were held. A breakdown of respondent and interviewee demographics is given in Figure 3.1, detailing participants' stakeholder group, the number of years they have worked in the construction sector, and the size of their current company.

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[3] Alternative routes through the survey and optional questions were included to prevent respondent fatigue and avoid false positives associated with forced responses.

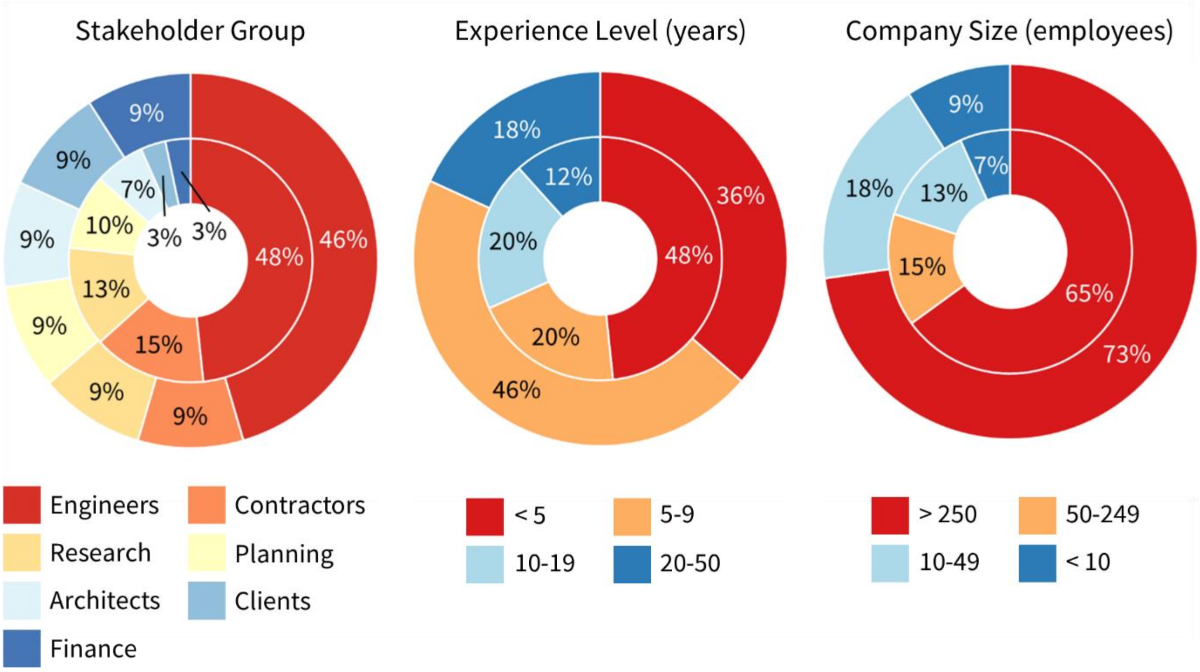

Figure 3.1 - Proportion of total survey respondents (n=60) (inner ring) and interviewees (outer ring) of different stakeholder groups, experience levels and company sizes.

3.3.2 Awareness, uptake and experience

Prior awareness of vertical extension was shown by 54/59 (n=59) of respondents, suggesting knowledge of this construction technique to be widespread across the sector. This is reinforced by general agreement that vertical extension refers to the addition of "new storeys" to "existing buildings", with these phrases gaining 37 and 33 explicit mentions in definitions provided across survey and interview responses.

This widespread awareness is not matched by current uptake however, with 19/42 of respondents having never been involved in a project where vertical extension was considered at preliminary design stages (Figure 3.2). Similarly, 26/42 respondents have never been involved in a project in which vertical extension was selected as the preferred solution. Where respondents indicated that vertical extension has been considered as a preliminary design option but not selected as the preferred solution, project uncertainty and resulting commercial risk were the most commonly reported causes. This is consistent with interview findings, as discussed later.

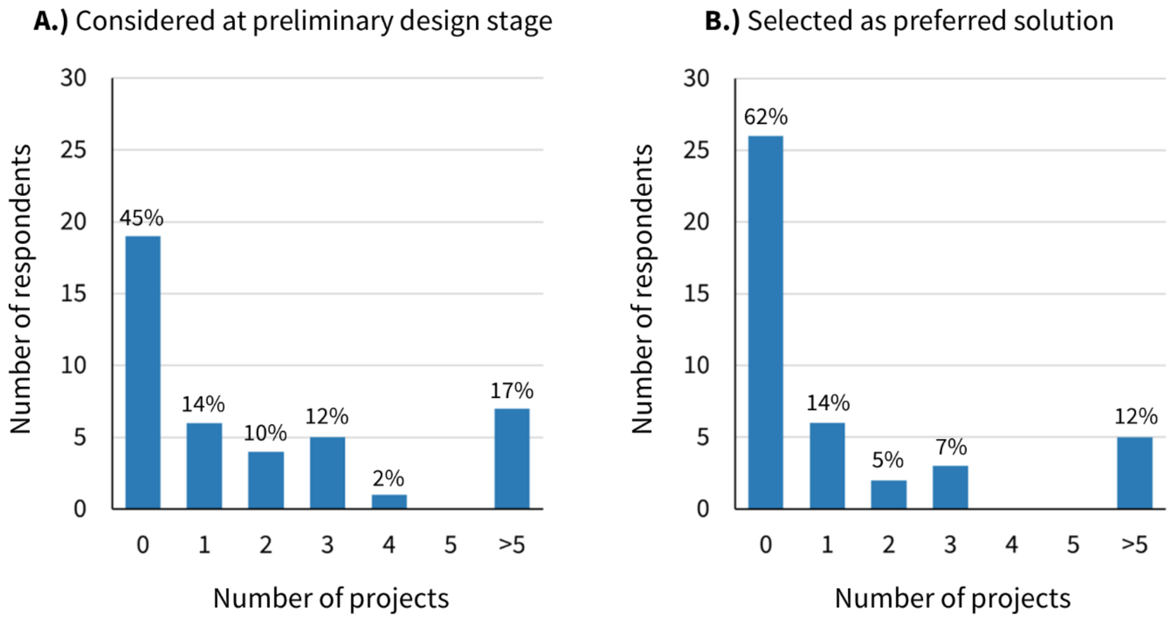

Figure 3.2 - Survey respondent involvement in projects in which vertical extension was considered at preliminary design stages (A) and selected as the preferred solution (B).

Of the 23 respondents involved in project(s) where vertical extension has been considered, the largest number (7) have done so more than five times. Fewer respondents (6, 4 and 5 respectively) report being involved in one, two and three projects, with involvement four or five times being noted only once. A similar pattern is observed for projects where vertical extension was selected as the preferred solution. This suggests that some stakeholders have a greater-than-average appetite for vertical extensions and potentially indicates the emergence of specialists.

Of the 21 of survey respondents who rated their experience being involved in vertical extension projects, 16 indicated this to be either somewhat (13) or extremely (3) positive, whilst three respondents stated this to be neither positive nor negative. Only two respondents indicated somewhat negative experiences and no extreme negative views were expressed. This suggests that negative perceptions held by stakeholders perhaps represent a greater barrier to vertical extensions than negative views from first-hand experience. Disparity in respondents' desire to be involved in future extension projects corroborates this, with 20/22 and 3/6 of those with and without prior experience stating this to be the case.

3.3.3 Drivers

Interviewees reveal the primary drivers of vertical extensions to be economic. This is generally rooted in a desire to increase asset value and the potential to do so at a reduced cost. Possible savings are identified in the avoidance of land costs, a typically reduced material requirement, and potential for a reduced programme in comparison with (demolition and) new build projects. Although the majority of survey respondents (32/50) believe that material costs will be lower for vertical extension schemes, there is disagreement regarding the influence of *total* project costs, with 22/50 and 20/50 believing this to be an enabler and barrier respectively. Despite being recognised by the majority of interviewees, embodied carbon savings are consistently viewed as a secondary benefit.

3.3.4 Barriers

Technical

Reserve structural capacity

All but two interviewees recognise existing structures' ability to resist increased loads as a key technical consideration for vertical extensions. Seven of these suggest a high likelihood of reserve structural capacity within existing buildings, with engineers claiming that "you can find a [...] lot of additional capacity in *any* structure" and that identifying 20-30% capacity "isn't unusual". In contrast, two further engineers argue that buildings are unlikely to be suitable for extension without strengthening works because the "existing building stock has been efficiently designed with limited spare capacity".

Structural appraisal and the ability of engineers

Interviewees reveal that "the assessment of existing buildings is [...] seen as [...] a specialist discipline within structural engineering" and that this has resulted in "a distinct split of experience" between "those who understand how to assess existing structures [...] and those who rely on outdated rules of thumb". This is consistent with the split in opinion of survey respondents, with 26/41 believing engineers are equipped to design for extension projects whilst 15/41 believe this is not the case. Examples of such rules of thumb are discussed by four engineers, all of whom report assuming a permissible vertical load increase of up to 10%.

Availability of design information and structural surveys

Limited availability of original design information is noted by nine interviewees, with one stating that this is "always the problem" on vertical extension projects. In combination with buildings' deviation from their original form, this typically necessitates a degree of structural investigation, at a time and cost expense to the project. Despite the general negative perception, two interviewees report being able to obtain sufficient information from as-built drawings and operation and maintenance manuals by working closely with asset and estate managers.

Design challenges and constraints

A number of spatial constraints associated with reusing existing buildings are identified by interviewees. These include restrictive structural grids and floor-to-ceiling heights, as well as insufficient core and riser space for the flow of people and provision of services. Spatial constraints are revealed to represent a barrier because clients are effectively “committing to the existing part of the building and making sure that fits [their] needs for the next 50 years”, meaning they are often unwilling to compromise on perceived spatial requirements. Site constraints regarding access within and surrounding the existing building are also reported by interviewees as a barrier to vertical extension. These pose an issue during both investigation and construction stages and are most prevalent where a building is to remain operational throughout. Consistent with interviewees, six survey respondents report the unsuitability of existing buildings and inability to meet client requirements as reasons for non-involvement in vertical extension projects to date.

Cultural

Nature of the construction sector

The majority (28/42) of survey respondents believe the nature of the construction industry acts as a barrier to vertical extensions. This is discussed by five interviewees, who suggest that corporate inertia and individuals’ aversion to change result in resistance to innovative techniques within the sector. A consequent difficulty in getting people “on board” with extension schemes is reported by one interviewee, who adds that initial programme delays and investment in overcoming resistance is typically recouped in later project stages.

Economic

Uncertain business case and commercial risk

Despite the *potential* to increase asset value at a reduced project cost, interviewees reveal case-by-case variability to result in an uncertain business case for vertical extensions. This is because of variation in the form and condition of existing buildings, their ability to be extended, and the need for structural alteration. The resultant requirement for upfront investment (e.g. in site investigations and structural appraisal) with no guarantee that extension will be possible poses a commercial risk to clients. Two interviewees report instances of clients' aversion to this risk resulting in them opting for (demolition and) new build without considering reuse.

Legal

Tax regimes

One interviewee discusses how current tax regimes "fight against doing refurb[ishments]" and act as a barrier to vertical extension. This is because value-added tax (VAT) is currently zero-rated for the construction of new dwellings in the UK, whilst a rate of 5-20% is applied to the structural alteration of residential premises (HM Revenue and Customs, 2014). It is argued that this can result in (demolition and) new build being financially favourable over building reuse, leading to a general preference for this amongst clients.

Planning permission

Difficulty obtaining planning permission for vertical extensions is reported by five interviewees, whilst 25/45 survey respondents believe that planning policy acts as a barrier to adoption. Although "rights to light", "visual pollution", "materiality" and "the nature of the design of the addition" are reported as potential reasons for non-approval, one interviewee states that they have "hardly seen any [...] that have been refused". They do however report the planning process to be lengthier and more onerous for vertical extensions, representing a barrier through a prolonged project programme, and increased cost and uncertainty.

3.3.5 Enablers

As shown in Figure 3.3, all potential enablers are viewed as important to increasing the uptake of vertical extension. This also reveals technical enablers to be of greatest importance, with each of the eight considered factors being in the top nine most important. In contrast, all of the three least important enablers are cultural, with employers' corporate social responsibility and employees' personal moral obligation being viewed as least effective. Contradicting this trend of cultural unimportance is the formation of long-term partnerships, which is viewed as the seventh most important enabler overall.

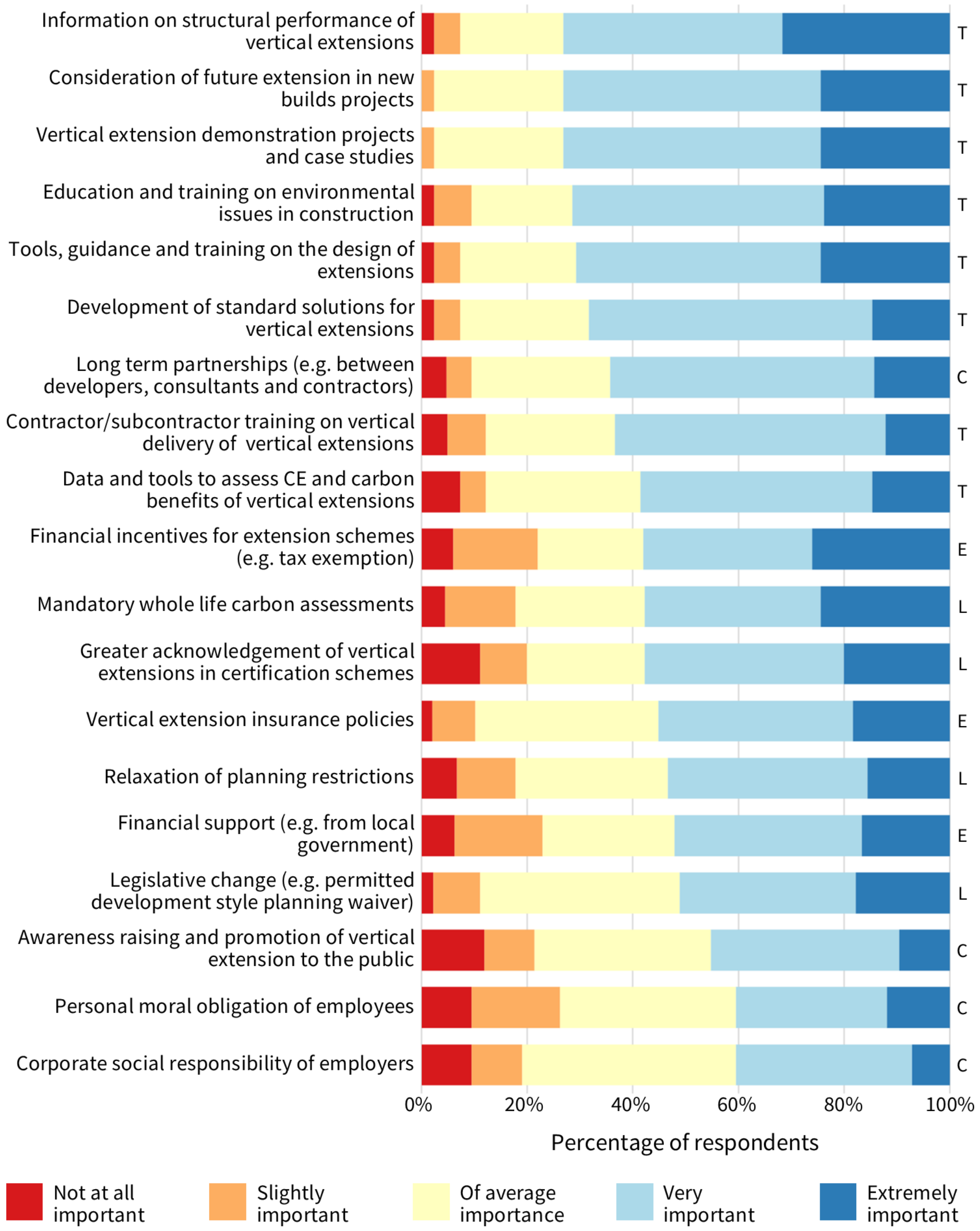

Figure 3.3 - Rated importance of potential enablers (response to survey question "Please rate the following in terms of their importance in increasing uptake of vertical extension”), in order of most to least important. Lettering to the right of the figure indicates whether enablers are categorised as technical (T), cultural (C), economic (E) or legal (L).

Technical

Education of structural engineers

To overcome the aforementioned disparity in engineers' ability to appraise existing structures, five interviewees discuss the benefits of enhanced education of engineers on structural appraisal and adaptive reuse. This is rooted in an observed neglect of this at university, with the engineers interviewed suggesting they “didn't really cover anything in relation to assessment [of existing buildings]”, “how buildings were built 100 years ago”, or “what you can think about doing to change those buildings”. Four interviewees also suggest educating engineers on “the bigger picture” of adaptive reuse and the circular economy in the context of climate change, in agreement with the 30/42 survey respondents who rate “education and training on environmental issues in construction” as of above average importance.

Design tools and guidance

Increased provision of tools, guidance and training for the design of vertical extensions was rated as the fifth most important enabler (Figure 3.3), with 29/41 of survey respondents stating this to be of above average importance. Four interviewees state that there “isn't much guidance available” at present and that this typically focusses on “workflows and diagrams” rather than decision making, as is suggested to be required for building reuse.

Demonstration projects and case studies

The provision of demonstration projects and case studies is noted by 30/41 of survey respondents to be of above average importance in enabling vertical extensions. Interviewees suggest that these would be particularly beneficial in providing initial design guidance and an indication of viability at early project stages, where insufficient funds currently preclude the detailed exploration of innovative design options.

Consideration of future extension

Increased consideration of future extension in new-build projects is revealed by survey respondents to be the second most important factor in enabling uptake, with 30/41 stating this to be of above average importance. This theme is discussed further by interviewees in terms of improved recording, storage and transfer of design and construction information, with one interviewee arguing that this would help to “preserve the value of our assets [...] rather than ending up in the same situation in 30 to 50 years”. As well as more general improvements, it is suggested that BIM models could be used for this purpose and extended to include as-built construction information (e.g. material test results) as well as pre-construction design details.

Greater integration of adaptability strategies in new build design is also suggested by interviewees as a means of enabling future extension. Rather than "designing for all eventualities" and increasing the structural capacity of new buildings, which would increase upfront embodied carbon, recommendations typically relate to the generation of intervention plans for potential future adaptations. Interviewees perceive this to be "a very small amount of work relative to the reward", giving examples such as column strengthening for vertical extensions.

Cultural

Questioning the brief

Despite personal moral obligation and corporate social responsibly being rated as comparatively unimportant in increasing uptake (Figure 3.3), the importance of challenging the brief is discussed by eight interviewees. These generally recognise their responsibility to do so, and note a recent increase of this in industry. In contrast however, one junior structural engineer suggests that it is simply their task to fulfil the client's brief as received, and that only more senior engineers "would have a little bit more power" to ask questions. The likelihood of success when challenging a brief is also noted to be greatest at earlier project stages and where clients aren't "looking for standard answers".

Adaptive reuse specialists

Three interviewees discuss the need for vertical extension specialists to aid ease and speed of completion and reduce commercial risks. As well as the formation of specialists within existing roles (e.g. architects, engineers, and contractors), the generation of new specialist services is suggested. An example of this is given by one interviewee who describes an urban development company who "help you figure out [...] whether it [an extension] is viable or not" before "connecting the whole process [...] from design to supply chain".

Economic

Costing of uncertainties

Two interviewees suggest that the assumption of a worst-case scenario when costing vertical extensions results in them erroneously being presented as economically unviable. They therefore propose a "structured risk and uncertainty management approach" whereby multiple stakeholders work collaboratively in "understanding all the uncertainties, listing them out, and pricing them". This allows different scenarios (e.g. degrees of structural intervention) to be considered, offering a more accurate approach than "using a percentage contingency" as is often seen at present.

Remuneration of additional works

Although design costs for vertical extensions are perceived to be higher than new build projects by 26/50 of survey respondents, interviewees reveal that consultants rarely receive increased fees to reflect this. Correct remuneration of stakeholders for additional works is therefore suggested as an enabler of vertical extension by three interviewees, with recommendations including additional fees for generating design options and quantifying their carbon impacts; appraising existing structures; and considering future extendibility in new build design.

Legal

Tax regimes

As present tax regimes "fight against doing refurb[ishments]", interviewees suggest that adjusting these is key to incentivising reuse. This is reinforced by survey respondents, 29/50 of which state financial incentives to be very or extremely important to increasing uptake of vertical extension. For housing, such an incentive may be achieved by increasing VAT for new build dwellings (such that they are treated equally to refurbishments), or by reversing the current imbalance to actively encourage reuse. Similar VAT incentivisation is suggested by interviewees to be extended to all building use types.

Whole life carbon assessment, benchmarking and regulation

Promoting vertical extension through the consideration of whole-life carbon is discussed by five interviewees, with one suggesting that the key to encouraging reuse is "how we [...] drive the industry forward on valuing embodied carbon, and the decisions people make around that". Considering the whole life carbon of different options at early project stages is suggested as one way of achieving this, with another interviewee calling for a "cost-carbon exercise" considering the economic and environmental merits of building retention and replacement.

Interviewees generally suggest that, although "some people will get on board with it [whole life carbon assessments]", most see time and cost constraints "as a reason not to do it". Four interviewees therefore argue for compulsory whole life carbon assessments, in agreement with the 26/45 survey respondents who suggest this to be of above average importance in increasing uptake of vertical extension (Figure 3.3). As well as requiring the measurement of whole-life carbon, one interviewee believes that future regulation “should dictate targets for embodied carbon”, which all developments would be required to meet.

Permitted development rights

Although specifically questioned on the matter, only one interviewee was aware of existing permitted development (PD) rights (PDRs) allowing for vertical extensions without planning permission. They believe that “planning is probably the main barrier” at present and state that “PD rights [...] could play a massive role in opening up housing”. The limitations of PDRs are acknowledged however, including their restriction to adding “up to two floors on a post-war building” and the fact that formal planning is required where other alterations are to be to be made. Increased design guidance on “what is and isn't acceptable” in PD-delivered extensions is suggested to increase uptake further, preventing “bad examples” that could harm the perceptions of the construction sector and general public.

Local authority plans

Three interviewees suggest that the uptake of vertical extension could be increased by introducing circular economy considerations in local authority plans, similar to as seen in Greater London (The Greater London Authority, 2021). This is noted to be “explicit about the consideration of the future of [...] building[s]”, enhancing both the reuse of current building stock and the future reusability of new builds. As a result of these requirements “forcing clients to go outside the comfort zone”, consideration of the circular economy in local authority plans is seen as a potential mechanism to overcome the cultural barriers discussed previously.

3.4 Discussion

3.4.1 Technical

The importance of technical factors identified in Section 3.3 is in general agreement with existing extension-focussed work (Pattison, 2021; Sundling, 2019; Appendix 4). This is shown by both the identification of similar specific barriers, including the justification of increased loads and requirement for intrusive investigation, and the important rating (Figure 3.3) and regular discussion (Section 3.3.5) of multiple technical enablers. When compared with work from neighbouring contexts the importance of technical factors is generally lower than identified for vertical extensions, with cultural and legal factors instead being reported to be of greater relevance (Hart et al., 2019; Giesekam, Barrett, & Taylor, 2016). Although likely to result from vertical extensions being an inherently technical technique, this may be contributed to by the over-representation of engineers across both the survey and interview elements (Figure 3.1).

As result of the likely presence of reserve capacity in existing buildings, it is thought to be engineers' inexperience or inability in appraising structures that represents a barrier to adoption at present, rather than technical infeasibility. This leads to the recommendation for demonstration projects and case studies to enable vertical extensions, as similarly identified for low-carbon materials (Giesekam, Barrett, & Taylor, 2016) and the circular economy more widely (Adams et al., 2017). In addition to providing early-stage design guidance, itself identified as an enabler, such exemplar projects would serve to convey the benefits of vertical extensions in terms of a potential time, financial and carbon saving. To further overcome the barrier posed by present inexperience and inability, enhanced education of engineers on structural appraisal techniques and the adaptive reuse of existing buildings is also suggested.

Recommendations for increased education extend beyond this to capture not only the extension of existing buildings, but also the design of new buildings with their future extendibily in mind. As this is effectively a form of building adaptability, which itself is a circular economy design strategy, many identified enablers are consistent with literature from these contexts (Rockow, Ross, & Becker, 2021; Adams et al., 2017; Ross et al., 2016). This includes the proficient collection, storage and maintenance of design and construction data, as well integration of key circular economy and adaptability concepts (e.g. reserve structural capacity and spatial flexibility).

Similar to previous work (Rockow, Ross, & Becker, 2021; Adams et al., 2017; Ross et al., 2016), considering these aspects is thought to be one approach to overcoming poor data availability and the resultant requirement for intrusive investigation, as well as the barrier posed by the complexity and unsuitability of certain buildings. In terms of building unsuitability, specific technical challenges identified in this work include the provision of sufficient building services and safe ingress/egress routes, as well as the requirement to work within pre-determined spatial constraints (e.g. column spacings and floor-ceiling heights).

3.4.2 Cultural

Consideration of cultural factors relating to vertical extension is limited in existing work, with those previously identified in neighbouring contexts being revealed to be only somewhat applicable here. Notwithstanding the influence of acquiescence and self-selection bias, this is exemplified vertical extensions being more widely known and understood than other sustainable practices (Adams et al., 2017; Giesekam, Barrett, & Taylor, 2016). A similar result is also seen for supply chain issues and responsibility for implementation, which appear to be less of an issue for vertical extensions than in the case of the circular economy (Adams et al., 2017) and low-carbon materials (Giesekam, Barrett, & Taylor, 2016).

The view of cultural enablers as least important to the uptake of vertical extensions (Figure 3.3) also contrasts previous work in more general contexts (Hart et al., 2019; Giesekam, Barrett, & Taylor, 2016), which typically take the view that technological and legal enablers are insufficient in isolation, and that shifts in stakeholder behaviour and attitude are also required. This disparity may be because of the specificity of vertical extensions (in comparison with the circular economy and low-carbon design), resulting in a diminished recognition of the importance of more abstract enablers. Alternatively, differences in the perceived importance of cultural factors may result from the momentum gained by low-carbon design and the circular economy between previous work and this study

In contrast with the relative unimportance of cultural factors identified in this work, the conservativeness of the construction sector is shown to be similarly restrictive of vertical extension as it is the circular economy more widely (Kanters, 2020; Hart et al., 2019). Interviewees also offer greater recognition of the importance of cultural barriers, with questioning the brief being identified as a specific behaviour change to increase uptake. The suggestion of vertical extension specialists is also consistent with previous calls for early engagement of construction professionals (Giesekam, Barrett, & Taylor, 2016) and stakeholder collaboration (Sundling, Blomsterberg, & Landin, 2018).

3.4.3 Economic

Consistent with existing work (Pattison, 2021; Sundling, 2019; Sundling, Blomsterberg, & Landin, 2018), the primary driver of vertical extensions is found to be their ability maximise refurbishment potential and asset value at a minimal financial cost. This means that, although acknowledged as in previous studies and Appendix 4, the embodied carbon and circular economy benefits of vertical extension are viewed simply as a subsidiary advantage at present.

Despite being identified as a primary driver, high case-by-case variability can result in economic barriers in some instances. As previously reported for the circular economy more widely (Hart et al., 2019; Adams et al., 2017), this limited generality across different projects is suggested to result in an unclear financial case for vertical extensions. Combined with stakeholders' *perception* of high costs, as also seen in the context of low-carbon materials (Giesekam, Barrett, & Taylor, 2016), this is suggested to often result in the erroneous presumption of economic unfavorability.

Suggested enablers to overcome these barriers are consistent with those from surrounding contexts, which typically view economic factors to be more inhibitive than is the case for vertical extensions. For example, the identified need for adjustments to uncertainty costing in extension projects is consistent with previous calls for whole-life financial costing (Hart et al., 2019; Giesekam, Barrett, & Taylor, 2016) and business model adjustment (Hart et al., 2019). Beyond this, interviewees also call for correct remuneration of additional design work associated with vertical extension, something which would also help to combat the barriers of lower design fees and inadequate design time associated with low carbon materials (Giesekam, Barrett, & Taylor, 2016).

3.4.4 Legal

Despite the introduction of permitted development rights (PDRs) being cited as a driver of vertical extensions in previous studies (Gillott, Davison, & Densley Tingley, 2022a; Pattison, 2021), widespread unawareness of these is reported here, with difficulty obtaining planning permission in fact being one of two legal barriers identified. This representation of planning as a barrier to vertical extension also contrasts with work in surrounding contexts, for which this is not identified to be the case (Rockow, Ross, & Becker, 2021; Hart et al., 2019; de Jesus & Mendonça, 2018; Artés, Wadel, & Martí, 2017; Adams et al., 2017; Giesekam, Barrett, & Taylor, 2016; Ross et al., 2016; Kershaw & Simm, 2014). Considering the proximity of the introduction of PDRs and the completion of this study, these disparities in their perceived influence may be contributed to simply by respondents' unawareness at the time of survey and interview. In view of this, the presently limited uptake of PDRs (Department for Levelling Up Housing and Communities, 2022a), and inherent differences between these and extensions delivered through the traditional system, further research on planning considerations of vertical extensions (including PDRs) is recommended here.

Similarly as for planning, and although only identified by a single interviewee in this study, VAT tariffs are not recognised as a barrier in existing work. This is likely to be because of its focus on technical aspects (Pattison, 2021) and non-UK cases (Sundling, 2019; Sundling, Blomsterberg, & Landin, 2018), as well as contexts to which building-level reuse does not directly apply (Rockow, Ross, & Becker, 2021; Hart et al., 2019; Giesekam, Barrett, & Taylor, 2016). The identified barrier posed by present VAT tariffs leads to suggestion of the adjustment of these as a potential enabler of vertical extensions, expanding previous and upon more general suggestions for tax incentives to promote circular economy in construction (Hart et al., 2019) and low carbon material use (Giesekam, Barrett, & Taylor, 2016). It is recommended that such an amendment sees VAT for new build dwellings raised, such that they are treated equally to refurbishments, or the current imbalance reversed to actively encourage reuse whilst disincentivising new developments.

The identification of a number of specific legal reforms in Section 3.3.5 is consistent with more general calls for this in previous work (Hart et al., 2019; Adams et al., 2017; Giesekam, Barrett, & Taylor, 2016). Interviewees' suggestion of mandatory whole life carbon assessment, benchmarking and regulation, for example, echoes similar recommendations made in the context of low-carbon material use (Giesekam, Barrett, & Taylor, 2016). This is also consistent with increasing advocacy for measurement and regulation of embodied carbon within industry (Part Z, 2022), and the requirement of this by some local planning authorities (The Greater London Authority, 2021). Similarly, the suggestion to integrate circular economy considerations in local development plans (Section 3.3.5) is aligned with the ongoing adoption of these by a number of combined authorities (e.g. The Greater London Authority, 2021)

3.4.5 Limitations and future work

Over-representation of engineers

Although not intended to be statistically representative, and despite efforts to ensure even consideration in the interviewee selection process, both elements of this study experience over-representation of engineers (Figure 3.1). This may result from self-selection bias (Bryman, 2016) and the survey's advertisement in The Structural Engineer (The Institution of Structural Engineers, 2020), with the effects of this also being exacerbated by snowball sampling (Saunders, Lewis, & Thornhill, 2016). Owing to their inherent technical focus, the over-representation of engineers may reasonably be expected to have contributed to the high importance of technical considerations identified, with similar, yet less extreme, results potentially present for imbalances in respondents' experience level and company size.

As a result of the *inductive* approach applied in the thematic analysis of qualitative survey and interview responses (Section 3.2), sensitivity of these elements to the over-representation of certain stakeholder groups may not be readily assessed. In the case of quantitative response data, its treatment as ordinal, and resultant consideration of mode and median values (Section 3.2.1), precludes the simplistic reweighting of mean responses as would otherwise be suitable here. For these reasons, the influence of engineer over-representation is instead considered through the random subsampling of five engineers as a means of adjusting their representation to the mean size of other stakeholder groups. The effect of this resampling process on the rating of potential enablers in shown in Figure 3.4.

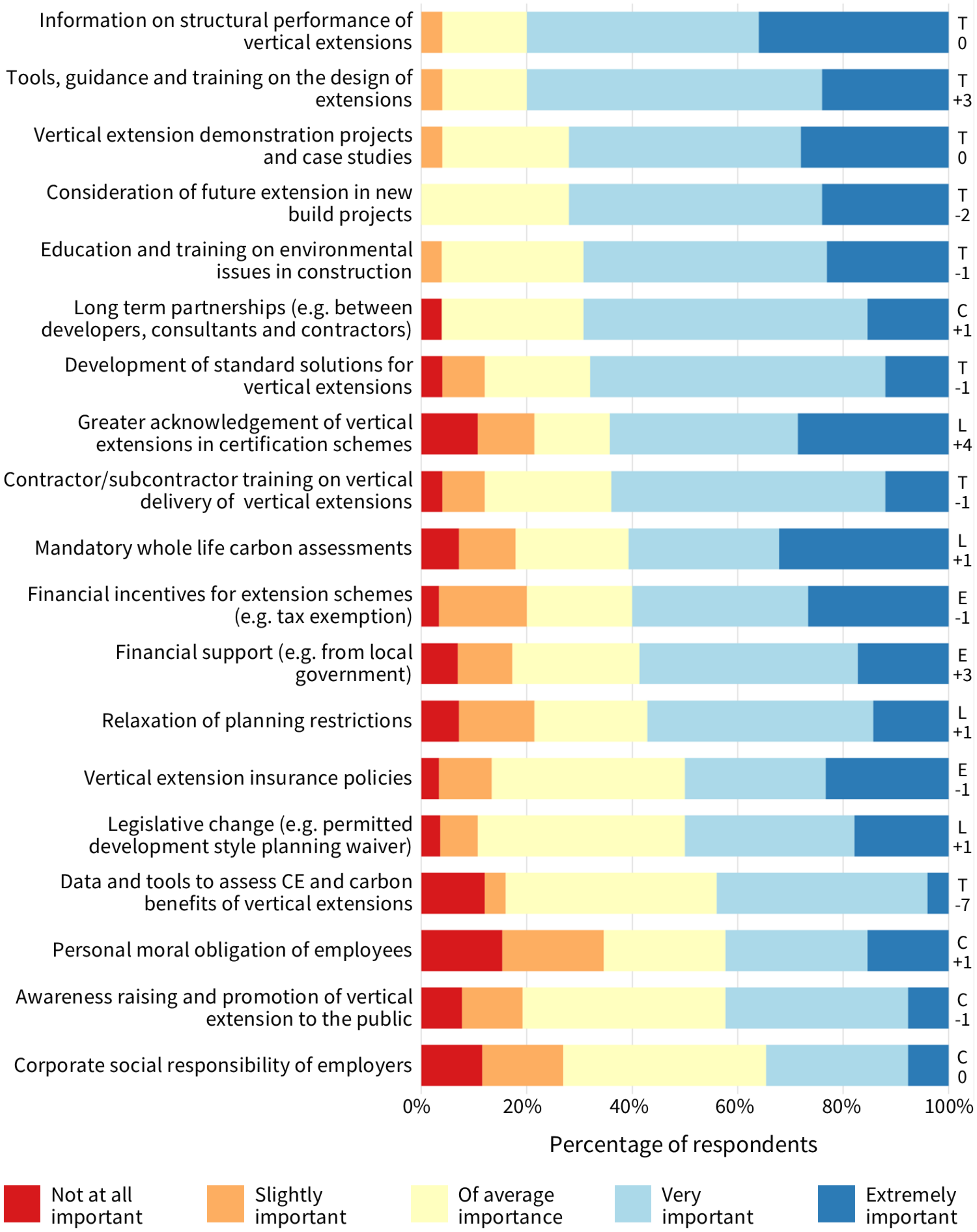

Figure 3.4 - Rated importance of potential enablers, in order of most to least important, following random subsampling of five engineers. Values and lettering to the right of the figure indicate change in rank order compared with the full sample, and whether enablers are categorised as technical (T), cultural (C), economic (E) or legal (L).

Figure 3.4 reveals subsampling of engineers to have a generally minimal effect on the rating of enablers, with each of these still being rated as of average or greater importance by the majority of respondents. Similarly, although to a lesser degree than in Figure 3.3, technical enablers continue to be most consistently rated as of greatest importance, as shown by seven of eight technical factors remaining within the nine highest ranked. Falling by seven positions (Figure 3.4), ‘data and tools to assess CE and carbon benefits of vertical extensions’ is the only technical enabler experiencing a significant decrease in ranked importance as a result of engineer subsampling. Being one of the least engineering-centric technical factors, this result is surprising and perhaps indicates non-engineering stakeholder groups to have limited recognition of responsibility for carbon accounting and CE assessments when compared with engineers.

The three factors rated as least important in Figure 3.3, all of which are cultural, remain as such following engineer subsampling (Figure 3.4). Although changing in rank order, this shows the initial over-representation of engineers in this study to have had minimal effect of the view of ‘corporate social responsibility [...]’, ‘personal moral obligation [...]’ and ‘awareness raising [...]’ as the least important enablers. Similarly, the original cultural outlier of ‘long term partnerships’ (Figure 3.3) experiences only a minimal increase in rated importance in Figure 3.4, displacing ‘development of standard solutions for vertical extensions’ to move up one position and be ranked sixth most important overall.

Although typically only marginal, all legal enablers experience an increase in rated importance as a result of engineer subsampling (Figure 3.4). This sees ‘legislative change’, ‘relaxation of planning restrictions’ and ‘mandatory whole life carbon assessments’ each increase in rank order by a single position, with ‘greater acknowledgement of vertical extensions in certification schemes’ moving up by four positions overall. This small yet consistent increase in rated importance from Figure 3.3 indicates that legal factors are generally viewed as marginally less important by engineers than other stakeholder groups.

In contrast with legal considerations, although also minimally affected, both ‘financial incentives for extension schemes’ and ‘vertical extension insurance policies’, experience a *decrease* in rated importance, falling by a single ranked position each (Figure 3.4). More general ‘financial support’ increases by three positions, however, revealing no consistent pattern in the rating of economic factors between engineers and other stakeholder groups.

Overall, the random subsampling of engineers for more equal representation is shown to have minimal effect on the importance-rating of enablers and typically only slightly adjusts their rank order (Figure 3.4). This reveals that, although present, the influence of the overrepresentation of engineers on quantitative survey responses is limited and rarely follows a clear pattern capable of strongly distinguishing the views of engineers from other stakeholder groups. Perhaps most importantly, representative consideration of engineers' views is shown in Figure 3.4 not to dramatically decrease the relative importance with which *technical* enablers are rated, which would otherwise be expected to result from their over-representation. Considering this, and the fact that the quantitative rating of potential factors represents only a small part of the wider sequential, explanatory mixed-method study, initial over-representation of engineers is unlikely to have significantly impacted the findings of this Chapter. Notwithstanding this, subsequent work specifically targeting under- or un-represented stakeholder groups would be of value. Owing to the nature of a number of specific barriers and enablers identified in Section 3.3, it is suggested that this includes building surveyors and architectural technologists as well as experts in real estate, construction finance and tax.

Perceptions and realities

The study's intentional capture of perceptions means it is unclear whether the factors identified are real or simply common misconceptions. This does not diminish their value, however, with perceived factors being similarly capable of influencing adoption as those founded in reality. Notwithstanding this, further research on some themes is recommended, such as where conflicting project cost views are reported. Greater understanding could be achieved here by analysing real-world cost data for vertical extension projects in the UK, similarly to that already completed for a small sample in Sweden (Sundling, 2019; Sundling, Blomsterberg, & Landin, 2018).

Reserve structural capacity

Additional work is also recommended to better understand the presence of reserve structural capacity within existing buildings. As discussed in Chapters 1 and 2, this should build upon previous studies' identification of overdesign and reserve capacity (e.g. by Moynihan and Allwood, 2014) to quantify this in terms of a potential load increase. The validity of commonly used rules of thumb, such as the aforementioned 10% permissible load increase, should also be considered here.

Permitted development rights

Combined with the limited uptake identified in Chapter 2, respondents' unawareness of permitted development rights (PDRs) reveals poor understanding of their influence upon the adoption of vertical extensions. This too may be addressed by future work, for example by assessing the potential for PDR vertical extension if engaged with at-scale.

3.4.6 Recommendations for policy and practice

Considering the drivers, barriers and enablers identified in Section 3.3, four overarching recommendations are made below to enhance the future uptake of vertical extensions through changes to construction sector policy and practice.

1. To combat neglect reported by interviewees and resultant disparity in engineers' ability, the content of undergraduate civil and structural engineering courses should be reviewed to ensure the appraisal of existing structures and design for reuse are adequately addressed. Such a review of course content is consistent with the Joint Board of Moderators' recognition of the need to increase focus on the climate crisis in civil and structural engineering degrees (Joint Board of Moderators, 2021).

2. To counter the effects of project uncertainty and allay concerns regarding commercial risk, VAT rates for refurbishments should be aligned with those for new build projects across all use types. Improving the business case in this way would serve to mitigate the economic barriers present in some extension projects, and also enhance the uptake of adaptive reuse more generally.

3. To elucidate the embodied carbon benefits of building reuse and act as driver of vertical extensions, whole life carbon assessments should be made mandatory for all construction projects. Building upon this with sequential benchmark targets and regulatory limits would further promote vertical extension, forcing clients to consider building reuse and encouraging associated design compromise. This is consistent with wider advocacy for measurement and regulation of embodied carbon within the construction industry (Part Z, 2022).

4. To counter the presently limited consideration of future reuse in the design and construction of new buildings, as well as the barriers of poor design data availability, greater consideration of the circular economy should be integrated in local authority

planning requirements. As well as promoting key circular economy strategies such as design for adaptability and longevity, and the proficient storage, management and transfer of design data, this would also instil the benefits of a circular economy across all stakeholder groups.

3.5 Conclusions

Through a sequential explanatory mixed methods study, this investigation yields new insights on drivers, barriers, and enablers of vertical extension. The conducted survey and interviews also, for the first time, assess stakeholders' awareness, uptake and experiences of this construction technique. This study addresses a previously limited understanding by considering a wide range of viewpoints to identify new influencing factors and assess the applicability of those from surrounding contexts. A further contribution to knowledge is made by this work's consideration of the causes, impact and interrelation of influencing factors, as well as their potential to enable uptake.

The ability of vertical extension to increase the value of buildings is revealed to be its primary driver at present. Despite this, high case-by-case variability and deficiencies in the costing of uncertainties result in an uncertain and unfavourable business case in some instances. This can create a barrier in the form of commercial risk, which is worsened by current tax regimes and conservativity of the construction sector. Although widely acknowledged, environmental benefits are viewed as a secondary benefit of vertical extension at present.

Technical considerations such as the justification of reserve capacity, working within spatial constraints, and unavailability of design information are identified amongst the most inhibitive barriers to vertical extensions. This is not perceived to be an indication of technical infeasibility however, with these barriers suggested to result from the inexperience of engineers, clients' unwillingness to compromise, and limited consideration of future reuse in new build design.

4

Underutilisation and Reserve Capacity in Existing Buildings

4.1 Introduction and research aims

Examples of completed vertical extensions exhibit great variation in their requirement for strengthening (Gillott, Davison, & Densley Tingley, 2022a). This is further exemplified by work assessing reserve capacity and extension potential in existing buildings (Amoruso & Schuetze, 2022; Bahrami, Deniz, & Moalin, 2022; Argenziano et al., 2021; Amer & Attia, 2018; Artés, Wadel, & Martí, 2017; Al-Nu'man, 2016; Clark et al., 2006). Such studies typically focus on the transfer of vertical loads and attempt to identify reserve capacity and/or strengthening requirements within a single or small number of case study buildings. Most often, a simplified mass-balance approach is used for this purpose, with the extension loads offset through the removal of weight within the existing building (e.g. structural screeds and existing plant). A similar mass-balance approach is reported by practicing structural engineers in Chapter 3, with a 10% permissible increase in total mass at foundation level often being used. Chapter 3 also identifies structural considerations to be amongst the key barriers to vertical extensions and reveals disagreement amongst engineers regarding the ability of existing buildings to withstand increased loads. Technical enablers are consistently identified as most important, including improved information on the structural performance of vertical extensions, the development of standard solutions and provision of tools, guidance and training on designing for vertical extensions (Chapter 3).

Despite the apparent prevalence of reserve capacity in existing buildings, previous work has focus on a limited number of specific cases and is thus poorly generalised. This is worsened by the high case-by-case variability identified across these studies, completed extension projects (Gillott, Davison, & Densley Tingley, 2022a), and further existing works (Chapter 2). Such high variability in reserve capacity is contributed to by the employment of a large number of different materials and structural forms in existing buildings, the complexity of structural design, and the variation of both of these aspects over time. Generating a more generalised understanding of reserve capacity and extension potential within existing buildings therefore requires consideration of the underlying causes of this, rather than simply its prevalence within case study buildings.

Existing work suggests potential sources of underutilisation (Dunant et al., 2018; Drewniok & Orr, 2018; Orr & Drewniok, 2018; Moynihan & Allwood, 2014; Beal, 2011; Kala, 2007; Melcher et al., 2004) and identify this for real-world (Drewniok, Campbell, & Orr, 2020; Dunant et al., 2018; Moynihan & Allwood, 2014) and hypothetical (D'Amico & Pomponi, 2018) buildings.

Despite this, such studies typically view this from the perspective of increasing utilisation in future new builds through optimisation (Drewniok, Campbell, & Orr, 2020; Dunant et al., 2018) considering current (Drewniok, Campbell, & Orr, 2020; Dunant et al., 2018; D'Amico & Pomponi, 2018; Moynihan & Allwood, 2014) or modified (Drewniok, Campbell, & Orr, 2020) design codes. Although essential in reducing carbon emissions in *new* buildings, this neglects to consider how underutilisation results in reserve capacity in *existing* buildings, as well as how this may be exploited through their adaptive reuse.

To address these knowledge gaps, this chapter considers ***how much reserve capacity different underutilisation sources introduce in existing buildings, and how far this facilitates their extension.*** In achieving this, three objectives are defined.

a.) Assess the influence of different sources of overdesign on the utilisation of columns in existing steel-framed buildings.
b.) Identify the reserve capacity associated with this in terms of a permissible load increase.
c.) Contextualise reserve capacities with respect to their potential to enable vertical extension.

4.2 Methodology

Despite recognition of increased wind loading associated with vertical extensions, and the potential requirement for increased bracing and localised strengthening, the ability of existing buildings to withstand increased vertical loads is the primary focus of this work. This is because of the pertinence of vertical load transfer in the context of vertical extensions and other adaptive reuse strategies such as change of use. Because of this, and a presently limited understanding of their utilisation in comparison with that for beams (Drewniok, Campbell, & Orr, 2020; Dunant et al., 2018; Moynihan & Allwood, 2014), this chapter addresses underutilisation and resulting reserve capacity solely in column elements. Owing to their inherent durability and reusability, historic and continued dominance of the non-residential market (British Constructional Steelwork Association, 2021) and experience of a greater range of potential sources of underutilisation, steel-framed buildings are selected as structural form for which the effect of these are investigated. Focus is also placed upon office buildings, which are the second largest consumer of structural steel in the UK (British Constructional Steelwork Association, 2021) and experiencing increasing long-term vacancy rates (Knight Frank, 2022; Lawson et al., 2022). It should be noted here that, despite the effect of underutilisation on reserve capacity being studied solely for steel-framed office buildings within this chapter, its findings remain relevant to other structural materials and uses as a result of the cross-context applicability of the considered underutilisation sources.

An overview of the methodology employed in this chapter is given in Figure 4.1, with details of each step being provided in the following subsections. All stages were implemented computationally in MATLAB. Initially, a set of hypothetical steel framed office configurations are generated (Section 4.2.1). For each frame configuration, the optimal (least-mass) column section is selected for a range of different design approaches (Section 4.2.2). The current frame configuration and column section combination is then re-assessed using a range of reappraisal approaches (Section 4.2.2) in order to calculate adjusted design effects and/or resistances. Original and adjusted design effects/resistances are then compared to give a measure of column utilisation and reserve capacity resulting from each underutilisation source (Section 4.2.3). Corresponding potential for building reuse is next assessed in terms of a permissible percentage load increase. Finally, reserve capacity is contextualised as a potential for vertical extension using a range of typical 'all up', per-storey extension loads (Section 4.2.4).

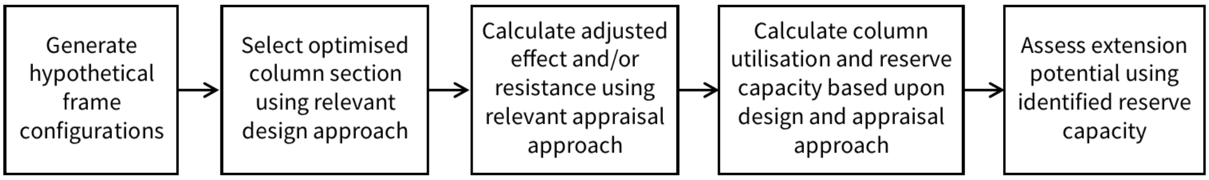

Figure 4.1 - Overview of the developed assessment framework, subsequently applied in calculating underutilisation, reserve structural capacity and resultant extension potential in steel-framed buildings.

4.2.1 Hypothetical frame configurations

In order to consider the influence of different sources of underutilisation on a wide range of buildings, a set of hypothetical frame configurations are adopted. Analysis of hypothetical building designs instead of real-world structures also facilitates the consideration of each underutilisation source in isolation, and averts data availability issues associated with assessing a large number of real-world case studies.

The adopted configurations are based upon a generalised braced steel frame, whereby a range of simplified, nominally pinned arrangements are described by their storey height (h), bay width (b) and storey number (n). This regularised and simplified arrangement dictates that all internal columns are identical, allowing underutilisation and reserve capacity to be investigated through the consideration of a single column, as shown in Figure 4.2. The bisymmetry of the generalised arrangement also results in a one-dimensional problem, eliminating the need to consider real and nominal end moments and dictating that minor axis capacity is critical in all instances.

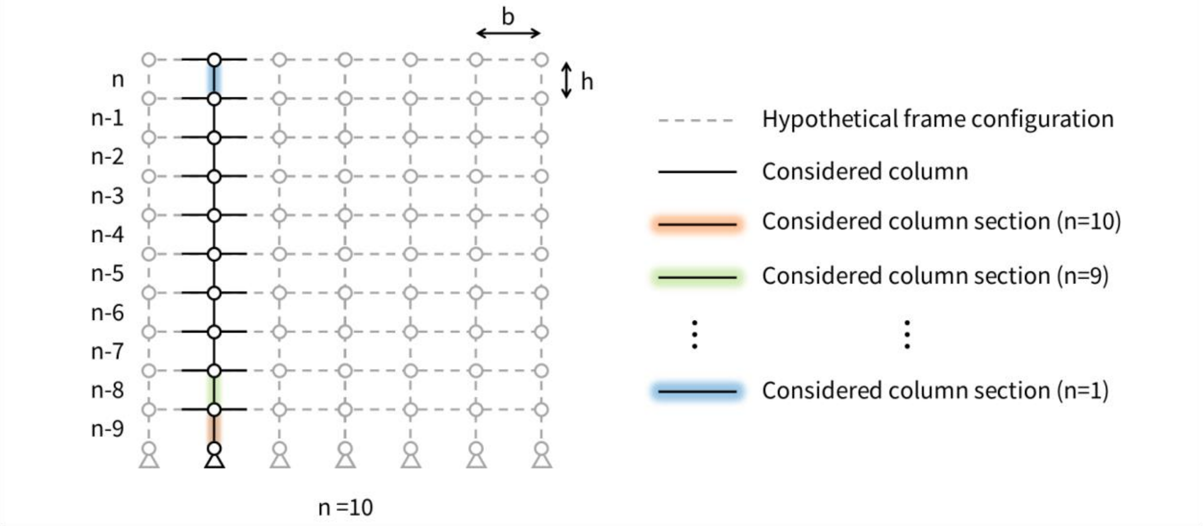

Figure 4.2 - Conceptual frame configuration representing a generalised braced steel frame described by storey height (h), bay size (b) and storey number (n).

In order to ensure representation of a pragmatic range of likely real-world structures, storey height (h), bay width (b) and storey number (n) are varied between upper and lower limits reasonably expected to be found in reality. This sees storey height varied between 2m and 8m in steps of 0.25m, bay width varied between 4m and 15m in steps of 0.25m and storey number varied between 1 and 10, resulting in a total of 11,250 unique frame configurations overall. For computational efficiency, only the ground floor column in each frame configuration is explicitly analysed. This does not neglect consideration of potentially critical columns in higher storeys, however, with these being modelled when assessing frames configurations of fewer storeys, as shown in Figure 4.2.

4.2.2 Modelled scenarios

To assess the impact of previously identified sources of underutilisation (Orr, 2019; Dunant et al., 2018; Drewniok & Orr, 2018; Orr & Drewniok, 2018; Moynihan & Allwood, 2014; Beal, 2011; Kala, 2007; Melcher et al., 2004; Needham, 1977) on reserve capacity in multi-storey steel framed building, a set of 12 scenarios have been developed. As detailed in Table 4.1, these each comprise a *design* and *reappraisal approach*, representing the methods applied in the buildings' original design and subsequent reappraisal. In all scenarios, either the design or reappraisal approach follows standard Eurocode compliance, ensuring the influence of a single utilisation source is considered in isolation. Details of the parameters used in consideration of each design and appraisal are included in Appendix 3.

Scenario No.	**Design Approach**	**Reappraisal Approach**	**Modelled Underutilisation Source**
1	BS449 (least weight)	Eurocode compliant	Original design to BS449
2	BS5950 (least weight)		Original design to BS5950
3	Eurocode (least weight)		Use of standard catalogue sections in original design
4	Eurocode (no reduction factors (ξ, ψ))		Omission of permanent load reduction (ξ) and imposed load combination factors (ψ) (use of BSEN1990 eqn. 6.10) in original design
5	Eurocode (no reduction factors (α_a, α_n))		Omission of reduction factor for imposed loads acting over large areas (α_a) or multiple storeys (α_n) in original design
6	Eurocode (defensive)		Defensive original design (i.e. targeting UR≤ 0.8)
7	Eurocode (rationalised)		Rationalisation of original design (i.e. resulting in average UR=0.49)
8	Eurocode (overspecified imposed loads)		Use of typically assumed imposed loads in original design
9	Eurocode compliant (least weight)	Eurocode (experienced imposed loads)	Reappraisal using average-experienced imposed loads
10		Eurocode (residential imposed loads)	Reappraisal assuming changing use from office to residential
11		Eurocode (average material strength)	Reappraisal using average yield strength in place of characteristic values
12		Eurocode (reduced partial factors (γ))	Reappraisal using reduced load combination factors

Table 4.1 - Overview of considered scenarios detailing associated design and appraisal approaches, and the corresponding source of underutilisation modelled modelled by each.

4.2.3 Identification of underutilisation and reserve capacity

Because of their comparison to Eurocode-compliant reappraisal and design processes respectively, consideration of design- (1-8) and reappraisal-based (10-12) scenarios is inherently different. As such, although both following the general approach shown in Figure 4.1 and discussed below, these are considered in separate analysis workflows. Across all scenarios, a per storey steel self-weight of 0.5kN/m^2 is assumed for frame configurations less than 7 storeys and 0.7kN/m^2 per storey for those of 7 or above (The Steel Construction

Institute, 2008). A lightweight composite slab at 2.5kN/m^2 is assumed at all floors and an allowance on 0.7kN/m^2 made for services, floor coverings and suspended ceilings (The Steel Construction Institute, 2008) to give a range of 3.7-3.9kN/m^2 per storey. Imposed loads at occupied floors are taken as 3.3kN/m^2 for Eurocode compliant approaches as standard, comprised of the recommended 2.5kN/m^2, plus 0.8kN/m^2 for moveable partitions (British Standards Institution, 2002). Corresponding values of 2.5kN/m^2 and 1.0kN/m^2 are adopted for design approaches following British Standards (British Standards Institution, 1996), giving a value of 3.5kN/m^2. For all scenarios, an additional imposed roof load of 0.6kN/m^2 is assumed, in accordance with the UK National Annex to Eurocode 1 (British Standards Institution, 2008).

Unless otherwise stated, per-storey design effects in accordance with British Standards (design approaches 1 and 2) are calculated using Equation 1 (British Standards Institution, 2001), with those for Eurocodes being taken as the largest of Equations 2 and 3 (British Standards Institution, 2011). For each scenario, values for imposed loads γ_G, γ_Q, ψ_0 and ξ are taken as detailed in Appendix 3.

$$\sum_{j\geq 1}\gamma_{G,j}G_{k,j}+\sum_{i\geq 1}\gamma_{Q,i}Q_{k,i} \qquad 1$$

$$\sum_{j\geq 1}\gamma_{G,j}G_{k,j}+\gamma_{Q,1}\psi_{0,1}Q_{k,1}+\sum_{i>1}\gamma_{Q,i}\psi_{0,i}Q_{k,i} \qquad 2$$

$$\sum_{j\geq 1}\xi_j\gamma_{G,j}G_{k,j}+\gamma_{Q,1}Q_{k,1}+\sum_{i>1}\gamma_{Q,i}\psi_{0,i}Q_{k,i} \qquad 3$$

Where γ_G = partial factor for permanent loads, G_k = permanent loads, γ_Q = partial factor for imposed loads, Q_k = imposed loads, ψ_0 = load reduction factor for combinations of variable actions, and ξ = reduction factor for permanent loads.

Design-led scenarios

For each frame configuration and design approach, the axial load incident upon the assumed critical column is first calculated in accordance with the conditions stipulated in Section 4.2.2. Initially, as indicated in Figure 4.3, the lightest UC section specified by the Steel Building Design Data 'Blue-book' (The Steel Construction Institute, Tata Steel, & The British Constructional Steelwork Association, 2015) is selected, and its design resistance calculated. A check for design compliance is then performed, following the principle of utilisation ratios (URs) in all cases except scenario 1, for which the permissible stress approach is used. If the presently selected section size does not satisfy the resistance requirements of the current design approach and frame configuration, the next lightest section is selected, the resistance recalculated, and the compliance check repeated. Once identified, details of the lightest compliant section size are outputted.

The selected section is then used in conjunction with the present frame configuration to calculate the design effect and resistance in accordance with Eurocodes. This facilitates the calculation of reserve capacity and a second UR, indicating the utilisation of the considered column if appraised to current design codes. The UR then is outputted alongside reserve capacity in absolute and per m^2 functional units, as well as a percentage of the column's Eurocode compliant design effect. Per m^2 reserve capacities for each frame configuration are also outputted, calculated by dividing absolute values for each column by the floor area they support.

Reappraisal-led scenarios

As shown in Figure 4.3, for each frame configuration the design effect is first calculated in accordance with Eurocodes. The lightest UC section is initially selected, and its Eurocode compliant design resistance calculated. A UR may then be calculated and used to assess the suitability of the current section. If this does not satisfy the resistance requirements of the present frame configuration, the next lightest section is selected, the design resistance recalculated, and the compliance check repeated. Once identified, details of the lightest suitable section are outputted alongside its associated resistance and the previously calculated design resistance.

For each reappraisal approach, an adjusted design effect and resistance are calculated in accordance with the conditions stipulated in Section 4.2.2. The adjusted UR for this scenario is then calculated alongside reserve capacity, which is reported in absolute and per m^2 functional units, as well as a percentage of the column's Eurocode compliant design effect.

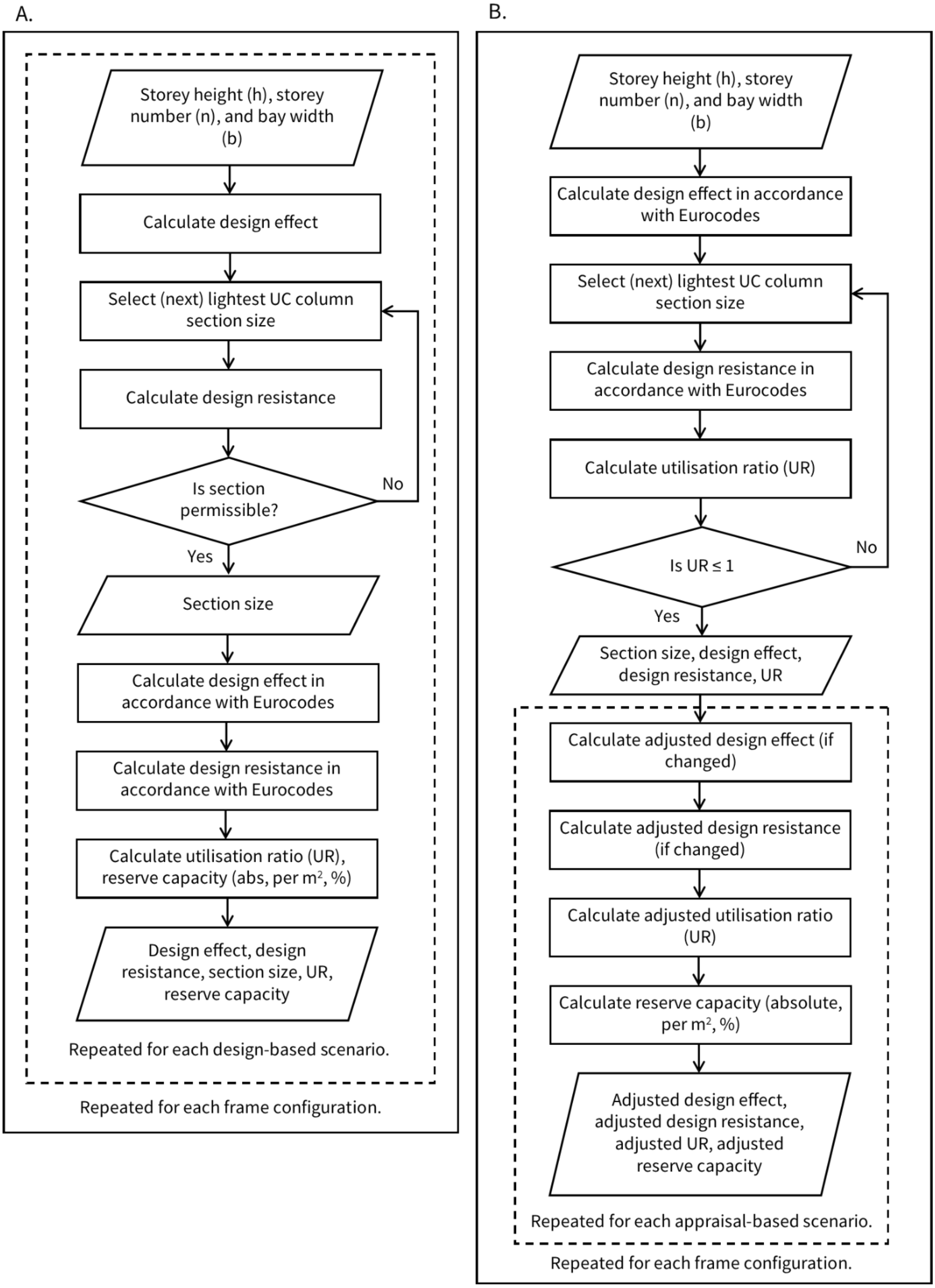

Figure 4.3 - Detailed assessment workflow for design-based (1-8) (A) and appraisal-based (9-12) (B) scenarios as per Table 4.1.

4.2.4 Calculation of extension potential

Extension scenarios

To contextualise the reserve capacities identified in Section 4.2.3 in terms of their resultant potential for vertical extension, a set of four extension scenarios have been developed. These comprise hypothetical extensions employing the same steel frame solution as the existing building, and a lightweight alternative using cold-formed steel. Each of these are modelled for both office and residential use.

Permanent loads for the existing frame solution are taken as in Section 4.2.3, whilst values of 1kN/m^2 and 0.25kN/m^2 are used for cold formed steel framing (including flooring) (Lawson, Ogden, & Rackham, 2004) and accompanying services (The Steel Construction Institute, 2008) in the lightweight alternative. Similarly, whereas imposed loads due to moveable partitions remain at 0.8kN/m^2 per storey for the standard framing case, these are taken as the reduced value of 0.5kN/m^2 (British Standards Institution, 2002) for the lightweight solution. Additional imposed loads are assigned according to the hypothetical extension's assumed use, with values of 2.5kN/m^2 and 1.5kN/m^2 being adopted for office and residential use respectively (British Standards Institution, 2002).

In each of the four design scenarios, load reduction factors for permanent loads (ξ), combinations of variable actions (ψ) and variable actions acting over large areas or multiple storeys (α_A and α_n) are omitted. Although this neglects potential for identification of further reserve capacity (e.g. where the load reduction factor applied at all storeys increases as a result of the extension), it is a conservative approach and ensures comparability of results across extension use cases. Omitting reduction factors in this manner also allows a single per-storey load to be calculated for each extension type. This in turn enables the extension potential of considered frame configurations and scenario combinations to be found simply by dividing identified reserve capacities by this value. Finally, resulting extension potentials are rounded down to the nearest whole number to give the number of storeys that may permissibly be added in each case.

4.3 Results and discussion

4.3.1 Utilisation

Utilisation ratios for each scenario vary greatly across considered frame configurations, resulting in minimum URs of between 0.11 and 0.12 for all scenarios, and maximum URs of between 0.94 and 1.00 for all scenarios except 6 and 7 (representing defensive and rationalised design). Such low minimum URs result from the consideration of a small number of particularly non-onerous frame configurations (i.e. combinations of low bay width, storey height and storey number) that are unlikely to be observed in reality. For this reason, the distribution of URs for each scenario is represented by a box plot in Figure 4.4, with whiskers showing upper and lower bounds at 1.5 times the interquartile range from the median.

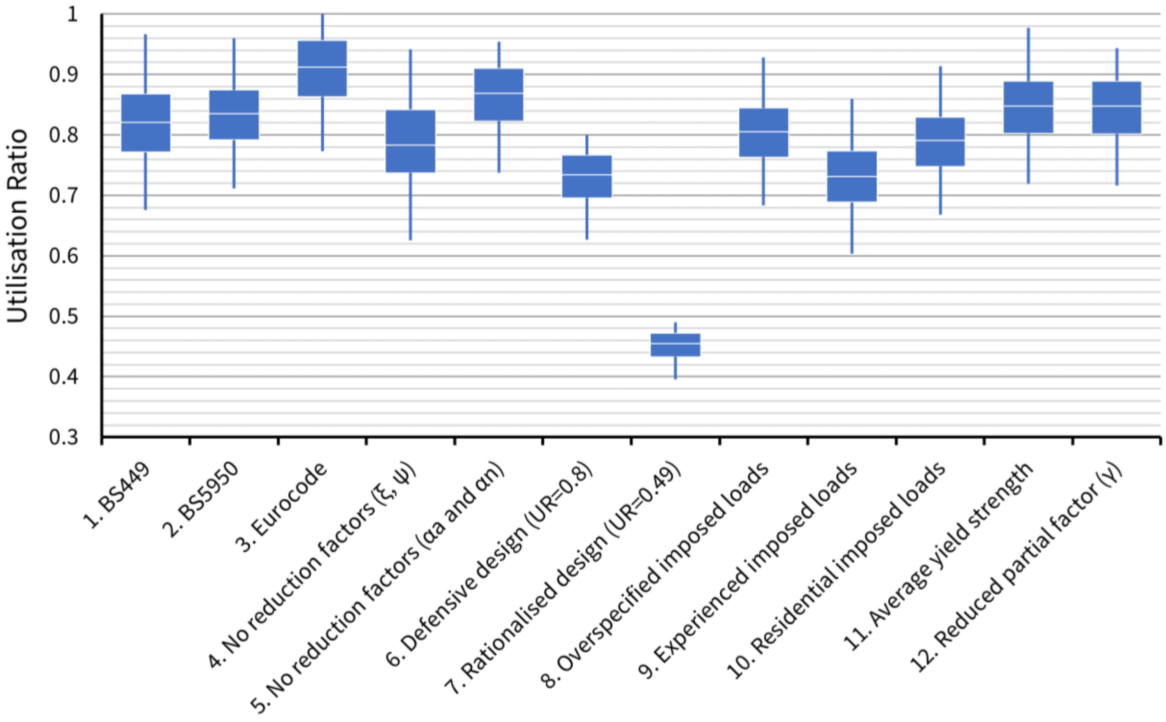

Figure 4.4 - Distribution of utilisation ratios for the 11,252 frame configurations considered under each scenario (Table 4.1, 1-12), representing 135,000 combinations overall.

Significantly less variation is seen across all scenarios when considering the inter-quartile range, as in Figure 4.4. Alongside median values, this may be reviewed in order to uncover patterns in column utilisation across the 12 scenarios. Median UR values of 0.82 and 0.84 are seen for BS449 (Scenario 1) and BS5950 (Scenario 2) designs when reappraised to Eurocode compliance. This represents the sequential increase in material efficiency between these standards, with the reduced interquartile range for BS5950 designs suggesting it generate designs that are more consistently utilised than BS449.

When reappraised to Eurocode compliance, the median UR for a least-weight Eurocode design (Scenario 3) is revealed to be 0.91. This is in general agreement with the value of 0.90 reported by Moynihan and Allwood (2014), and suggests the use of standard catalogue sections to result in an underutilisation of 9% in existing structures that are perceived to be structurally efficient. As expected, the increase in median UR between British Standards and Eurocodes exemplifies an increase in material efficiency between these codes of practice and results in a typically greater degree of underutilisation in historic buildings.

For more conservative Eurocode compliant designs omitting permanent load reduction (ξ) *and* imposed load combination factors (ψ) (Scenario 4), i.e. where design effects are determined using equation 6.10 in BS EN 1990 (British Standards Institution, 2011), the median UR value falls to 0.87. A more dramatic effect is seen if reduction factors for imposed loads acting over large areas (α_a) and multiple storeys (α_n) are omitted instead (Scenario 5), resulting in a median UR of 0.78. In both instances, this represents a reduction in member utilisation of more than 10% when compared to least-weight Eurocode design.

Defensive (Scenario 6) and rationalised (Scenario 7) Eurocode designs, aiming for maximum UR values of 0.8 (Dunant et al., 2018) and 0.49 (Moynihan & Allwood, 2014) respectively, result in median URs of 0.73 and 0.46. This suggests both the risk averse nature of structural engineers and the prioritisation of cost over material efficiency to contribute significantly to underutilisation in new and existing buildings. As both these scenarios essentially represent scaled versions of Scenario 3, their interquartile ranges are also more restricted (0.07 and 0.04 respectively, compared with 0.09 for standard Eurocode compliance).

Further conservativity and resulting underutilisation is contributed by the common overspecification of imposed office loads (Scenario 8). When designs generated using average specified values (Orr & Drewniok, 2018) are reappraised using Eurocode recommended values (British Standards Institution, 2002), a median UR of 0.81 is achieved. Similarly, reappraising designs generated using Eurocode recommended values (British Standards Institution, 2002) with average experienced values (Drewniok & Orr, 2018) (Scenario 9) gives a UR of 0.73. A slightly larger median UR of 0.79 is obtained by reappraising designs originally generated using Eurocode recommended office loads when assuming residential values (British Standards Institution, 2002) (Scenario 10). It should also be noted here that these three scenarios are not mutually exclusive, i.e. a building originally designed with over specified office loads may be reappraised assuming residential loads, creating the potential for further underutilisation in real world structures.

Reappraisal of least-weight Eurocode designs using average yield strength (Melcher et al., 2004) (Scenario 11) or a modified permanent load factor (Kala, 2007) (Scenario 12) both result in a median UR of 0.85.

4.3.2 Reserve capacity

In order to allow for comparison between scenarios, Figure 4.5 reports reserve capacity for each frame configuration and scenario combination as a percentage of its associated Eurocode design effect. In simplified mass-balance terms, as employed by Argenziano et al. (2021) and Artés et al.(2017) (Chapter 2), these reserve capacities may be thought of as permissible percentage load increases. Upper and lower bounds are again indicated by whiskers at 1.5 times the interquartile range to avoid representation of particularly (non-) onerous and unlikely frame configurations (Section 4.3.1). Figure 4.5 therefore enables the validity of existing rules of thumb for reserve capacity to be assessed, including the notion of a consistent 10% permissible load increase identified in Chapter 3. Upon intial inspection, Figure 4.5 reveals median reserve capacities to vary between 10% and 120% across all 12 scenarios, confirming the high degree of case-by-case variability suggested in previous work (Bahrami, Deniz, & Moalin, 2022; Gillott, Davison, & Densley Tingley, 2022a, 2022b; Argenziano et al., 2021; Artés, Wadel, & Martí, 2017; Al-Nu'man, 2016; Clark et al., 2006). Despite the broad range of values seen in different cases, following the removal of outliers corresponding to unlikely and inefficient frame configurations (as discussed in Section 4.3.1), clear patterns in reserve capacity may be established for each scenario.

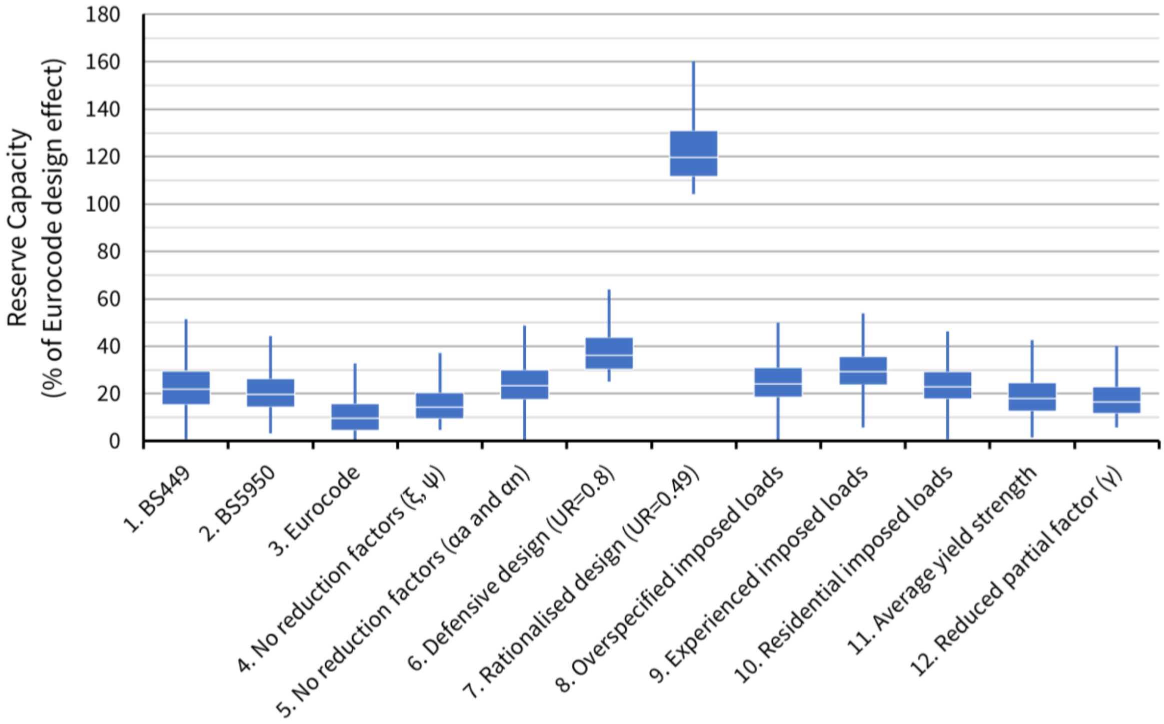

Figure 4.5 - Distribution of reserve capacities as a percentage of Eurocode design effect for each of the 11,252 frame configurations considered under each scenario (Table 4.1, 1-12), representing 135,000 combinations overall.

Figure 4.5 shows Eurocode compliant designs (Scenario 3), to yield reserve capacities of between 0% and 33%, with the corresponding median value being 10%. This suggests potential validity of the 10% permissible load increase value reported in Chapter 3, but that this is also potentially conservative (indicated by an upper quartile value of 16%) or unsafe (indicated by a lower quartile value of 5%) in some cases. Median reserve capacities for BS449 (Scenario 1) and BS559 (Scenario 2) designs are 22% and 20% respectively, indicating the presence of significant reserve capacity in structures designed to superseded codes of practice. Despite respective lower bounds of 0.7% and 3.2%, these median values and lower quartiles of 15% and 14% suggest the possibility to adopt a higher benchmark value for permissible load increases in structures designed in accordance with British Standards.

Reappraisal of Eurocode designs omitting reduction or combination factors when correctly considering these results in median permissible load increases of between 14% (Scenario 4) and 23% (Scenario 5). This reveals the omission of reduction factors for imposed loads acting over large areas (α_a) or numbers of storeys (α_n) to contribute greater amounts of reserve capacity than permanent load reduction (ξ) and imposed load combination factors (ψ). Together these values exemplify the possible presence of greater amounts of reserve capacity than is currently expected in existing structures, as a result of the conservative misapplication of design codes. The commonality with which different load reduction and combination factors were neglected at different points in time is unclear, however, meaning that the likelihood of this heightened capacity is unknown.

Perhaps more likely considering the findings of previous work (Orr et al., 2019; Dunant et al., 2018; Orr, 2018) is engineers' engagement in defensive design practices such as targeting maximum UR values of just 0.8 (Scenario 6). Figure 4.5 reveals the effects of this to compound with the 10% median reserve capacity from section size limitations (Scenario 3), to give an overall median percentage reserve capacity of 36%. This indicates that design efficiencies resulting from risk aversion and over conservativity can result in potential permissible load increases of over 1/3 in existing buildings.

Rationalisation (Scenario 7) results in a significantly larger median reserve capacity of 120%, representing this scenario's limitation of design URs to just 0.49. Despite this value representing the mean value identified in previous work considering real-world case studies (Moynihan & Allwood, 2014), this indication of the ability to more than double the loads experienced by rationalised buildings is unlikely to be valid in reality. This is because the spatial distribution of rationalisation-induced underutilisation is unlikely to be consistent over a building's plan area (Moynihan & Allwood, 2014), as is otherwise assumed by the adopted conceptual frame configuration. Notwithstanding this, Scenario 7 demonstrates the average level of rationalisation-induced underutilisation experienced in real-world structures to result in reserve capacities of between 104% and 160% in some elements (Figure 4.5).

Scenario 8 reveals that, should they be reappraised using Eurocode recommended values (British Standards Institution, 2002), an average reserve capacity of 24% may be identified in existing office buildings designed using commonly assumed values (Orr & Drewniok, 2018) (Figure 4.5). Even if designed using Eurocode recommended office loads, there remains scope for identification of average reserve capacity of 29%, through a building's reappraisal using typically experienced values (Drewniok & Orr, 2018) (Scenario 9). Furthermore, Scenario 10 shows a median reserve capacity of 23% to be identified in situations where a building originally designed for office use is converted to residential purposes. As Scenario 8 may occur concurrently with either Scenario 9 or 10 (i.e. an office building designed to over-specified loads reappraised using experienced values *or* those for residential use), it is possible that these sources of underutilisation may be compounded in real world structures, furthering the potential for load-based reserve capacity identification.

Reappraisal of Eurocode compliant designs using average yield strengths (Melcher et al., 2004) (Scenario 11) and a reduced partial factor for permanent loads (Kala, 2007) (Scenario 12) result in median percentage reserve capacities of 18 and 17% respectively. On top of the 10% resulting from section size limitations, this indicates potential for a further 7-8% reserve capacity to be identified, in designs otherwise perceived to be efficient, should they be reappraised using tested material strength values or a fully probabilistic approach. It should be noted however that the former of these situations is perhaps more likely in reality, as a result of the ability to test materials that are already in-site, and the unwillingness of engineers to design beyond the scope of codes of practice.

4.3.3 Extension potential

Figure 4.6 shows the proportion of the 11,252 considered frame configurations to which different numbers of storeys may be added in each of the 12 scenarios considered. These are indicated for extensions for both office and residential use, as well as those employing a hot-rolled steel frame similar to the existing building and a lightweight cold-formed steel alternative. Variation of between 9% and 100% of buildings extendible by at least one storey is shown in Figure 4.6, representing a Eurocode-designed building (Scenario 3) extended in hot rolled steel-framing for office use and a rationalised building (Scenario 7) extended using lightweight steel framing for residential use. This illustrates and corroborates the high case-by case variability in reserve structural capacity identified in previous work (Chapter 2) and Chapter 3. In general Figure 4.6 shows extensions for residential use and/or using a lightweight steel frame to exhibit the greatest potential for extension, as a result of the lower load increases associated with this.

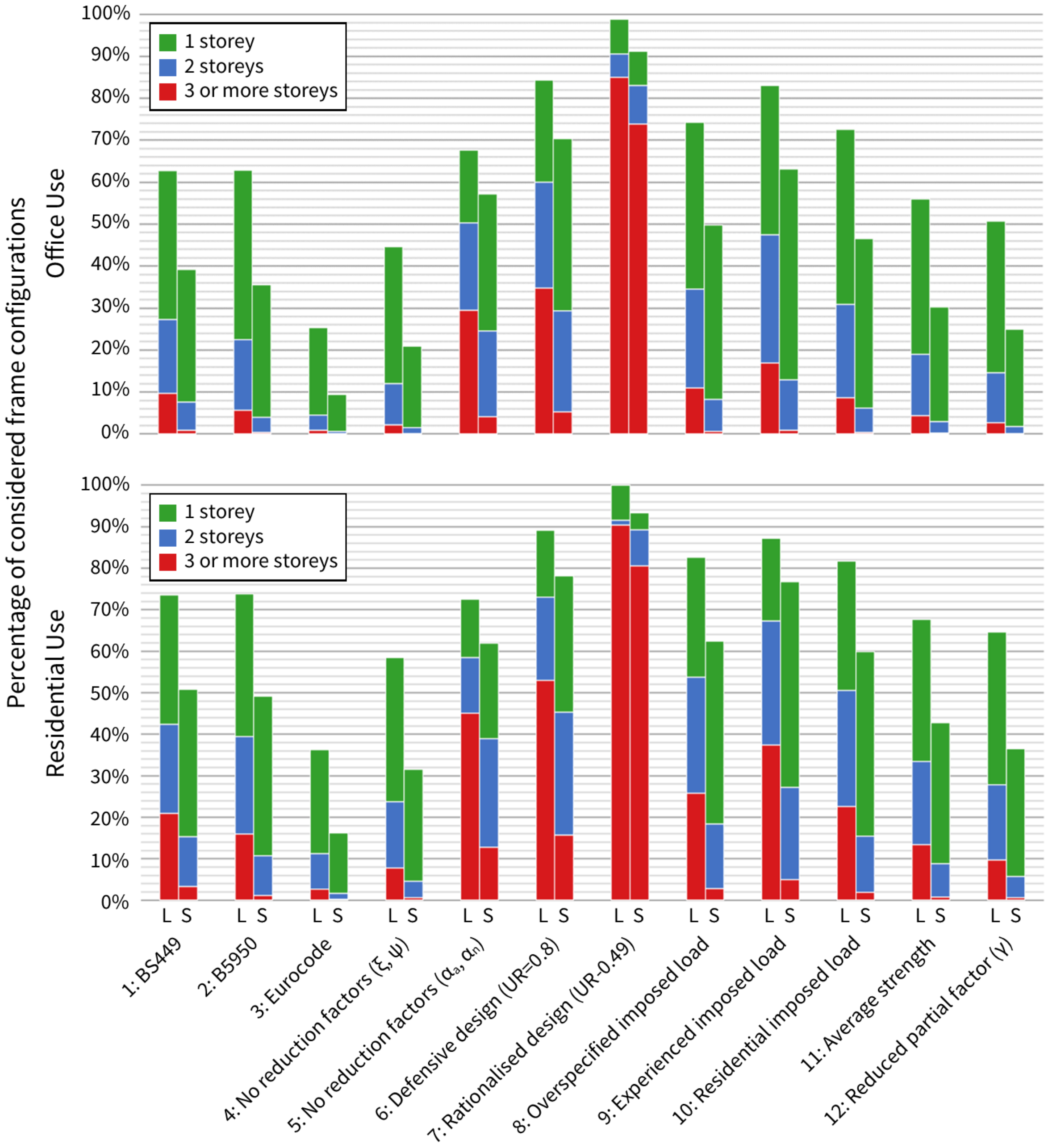

Figure 4.6 - Stacked 100% bar chart showing the percentage of considered frame configurations extendible by different amounts under each scenario (Table 4.1, 1-12) using lightweight (L) or steel (S) framing for office or residential use[4].

When considering least-weight Eurocode designs, reappraised to standard Eurocode compliance (Scenario 3), between 9% and 36% of considered frame configurations are

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[4] In Figure 4.6, each series represents only the number of storeys to which it explicitly refers (i.e. that associated with '1 storey' is not also inclusive of '2 storeys' and '3 or more storeys'), with the reading of cumulative effects instead being enabled by the stacking of individual bars. Extendibilities of '3 or more storeys' are grouped here simply for clarity, with all values being weighted equally within this series.

deemed extendible by at least one storey. These values correspond to an extension in traditional steel framing for office use, and that using a lightweight solution for residential purposes. In the former of these cases just one storey may be added to almost all extendible configurations, with lightweight residential extensions of two or three or more storeys being possible for 9% and 3% of Scenario 3 configurations respectively (Figure 4.6). This represents occasional potential for extension (≈1 in 10), even when an onerous extension form is applied to a building otherwise viewed as optimally designed (Scenario 3). Beyond this, a significantly greater potential for extension (>3 in 10), and by a greater number or storeys, is seen should a more suitable structural form be used to provide extension for residential means. Scenario 10 assumes residential loads throughout the original building as well as the extended portion, increasing the potential for extension to 82% of considered configurations (Figure 4.6). This represents the situation where an existing office building is converted to residential use and extended, for which 28% and 23% of configurations are extendible by two or three or more storeys respectively. There is thus significant potential for the vertical extension of existing buildings as part of their conversion to residential use, as is increasingly being seen (Gillott, Davison, & Densley Tingley, 2022a).

In buildings designed to superseded codes of practice, there is potential for extension in up to 74% of considered configurations should they be reappraised to Eurocode compliance (Figure 4.6). This is the case for both BS449 and BS5950 designs extended for lightweight residential use, with those designed to BS449 typically being extendible by a greater degree (e.g. 21% vs. 16% extendible by three or more stories) as a result of greater conservativity. When considering office use, the potential for extension drops to 63% of configurations for a lightweight extension solution, and 39% and 36% for standard steel extensions above BS449- and BS5950-designed buildings respectively. Notwithstanding potential issues regarding the consideration of British Standard designs employing modern UC sections (as discussed in Section 0), this shows a significant potential for the vertical extension of steel framed buildings designed prior to the adoption of Eurocodes.

Similar levels of extension potential may be identified in buildings designed using Eurocodes in a conservative manner, such as through the omission of reduction factors for imposed loads acting over large areas (α_a) or numbers of storeys (α_n) (Scenario 5). Reappraisal of such structures to standard Eurocode compliance results in 73% of buildings being extendible in the lightweight residential case, with 45% being extendible by three or more storeys.

Comparable worst-case values for the standard office extension are 57% and 4% respectively (Figure 4.6), suggesting this particular source of underutilisation to contribute significantly to reserve capacity within existing buildings. Although not modelled in this work, reduction factors for imposed loads acting over multiple storeys (α_n) may also offer further scope for the identification of reserve capacity in existing buildings should a vertical extension push a building beyond the threshold at which a greater reduction factor may be applied (British Standards Institution, 2002). Extension potential associated with the omission of permanent load reduction (ξ) and imposed load combination (ψ) factors (Scenario 4) are lower than this, with 58% and 21% of considered configurations being extendible in the lightweight residential and steel-framed office scenarios respectively (Figure 4.6). It is also the case that frame configurations extendible under Scenario 4 experience typically lesser extendibilities than for Scenario 5, with the majority of those that are extendible being so by just one storey.

Rationalised (Scenario 7) Eurocode designs result in the greatest extension potential when reappraised to standard Eurocode compliance, exemplified by 100% of configurations being identified as extendible when considering the lightweight residential case (Figure 4.6). Despite this, as discussed in Section 4.3.2, the validity of identified extendibilities for Scenario 7 remain uncertain as a result of underutilisation from rationalisation being non-uniformly distributed over a buildings plan area (Moynihan & Allwood, 2014). Notwithstanding this, such high extendibilities do highlight the potential for extension of rationalised building designs should a small number of critical columns be strengthened. Extendibilities identified for buildings designed employing a defensive approach (Scenario 6) are much more likely to be experienced in reality (Orr et al., 2019; Dunant et al., 2018; Orr, 2018), with 89% and 70% of configurations being identified as extendible in the lightweight residential and steel-framed office cases respectively (Figure 4.6).

Similar potential for extension is identified across each of the three load-based scenarios (Scenario 8-10). For an office building originally designed using over specified loads (Orr & Drewniok, 2018) (Scenario 8), between 83% and 50% of considered configurations are found to be extendible by at least one storey considering a lightweight residential and steel-framed office extension respectively (Figure 4.6). In the case of a lightweight residential extension, the number of configurations extendible by one, two or three or more storeys are relatively evenly split, with these being represented by 29%, 28% and 26% of configurations respectively. For office buildings originally designed using imposed load values from

Eurocodes, up to 87% of considered configurations may be extended should they be reappraised using imposed loads likely to be experienced in reality (Drewniok & Orr, 2018) (Scenario 9) (Figure 4.6). Despite this, considering variation in loading with time and the need to design for the most likely worst loading case, the potential for office building to be safely reappraised with such low imposed loads is uncertain and requires further investigation. Significantly more likely to be observed in reality is a buildings extension as part of a wider change of use (Gillott, Davison, & Densley Tingley, 2022a). In this case (Scenario 10), 82% of Eurocode-compliant office configurations are identified as extendible for lightweight residential use should they be reappraised assuming residential loads throughout (Figure 4.6). This represents significant potential for this increasingly common strategy.

As structural members are already in place when reappraising a building, there is potential to use actual material strength values, derived from testing, in place of the characteristic values used in design. This situation is represented by Scenario 11, which reappraises configurations originally designed using Eurocode-recommended yield strength with an average value taken from literature (Melcher et al., 2004). Between 68% and 30% of considered configurations are identified as extendible through this approach, representing values for lightweight residential and steel-framed office extensions. Considering such extension potential is likely to be compounded with that from other sources (e.g. overspecification of loads or conservative/defensive application of design codes), this represents a significant opportunity for the vertical extension of steel framed buildings. Existing work also shows potential to reappraise structures using reduced partial safety factors, whilst ensuring their probability of failure is less than that required by design codes (Kala, 2007). Applying such a process in Scenario 12 identifies between 65% and 25% of considered configurations as extendible by at least one storey (Figure 4.6).

4.3.4 Applicability to the UK building stock

Due to consideration only of *known* sources of overdesign (Section 2.5) and *likely* frame configurations (Section 4.2.1), the utilisations, reserve capacities and extendibilities identified in Sections 4.3.1-4.3.3 broadly represent those expected to be found within the UK's building stock. Despite this, the range of values identified suggests that the commonality of different extendibilities depends upon the relative prevalence of the considered design approaches and different frame configurations. As such, to better understand applicability of the above findings to real world structures in the UK, this subsection considers the sensitivity of results to assumed frame configurations and the proportion of the existing building stock to which different scenarios pertain.

Prevalence of different design scenarios

Owing to a lack of suitable design data, the commonality with which scenarios 4, 5 and 8 have been implemented in the design of UK buildings is unknown, meaning that these are not considered here. This is similarly true of scenarios 6 and 7, despite theoretically applying to all structures due to representation of *average* UR values from the survey of engineers (Orr, 2018) and analysis of real world structures (Moynihan & Allwood, 2014). For the same reason again, all appraisal-based scenarios (i.e. 9-12), which are consistently applicable in theory, are also omitted here.

This means that the prevalence of different design scenarios within the UK building stock is assessed solely through consideration of the proportion of this likely to have been designed using different codes of practice (i.e. Scenarios 1-3). To this end, the percentage of residential and non-residential buildings constructed in different time periods in the UK (extracted from "UKBuildings" from Verisk 3D Visual Intelligence (licence no. 5560) (Geomni, 2020)) is compared with the periods for which BS449 (Scenario 1) , BS5950 (Scenario 2) and Eurocodes (Scenario 3) were the most widely used code of practice for the design of steel framed structures. Assuming supersedence of the previous code upon first introduction of the next, these are defined in Figure 4.7 as 1932-1985 for BS449, 1985-2002 for BS5950 and 2002-present for Eurocodes. In Figure 4.7, the proportion of steel-framed buildings designed under each code of practice is calculated using the total numbers of residential and non-residential buildings constructed within corresponding age bands[5], with weightings applied to account for partial overlap where present.

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[5] Data for the total number of buildings constructed within each age band is used here due to unavailability of that relating specifically to steel framed structures. This process thus assumes proportionality of steel-framed and total building constructions from 1932 onwards.

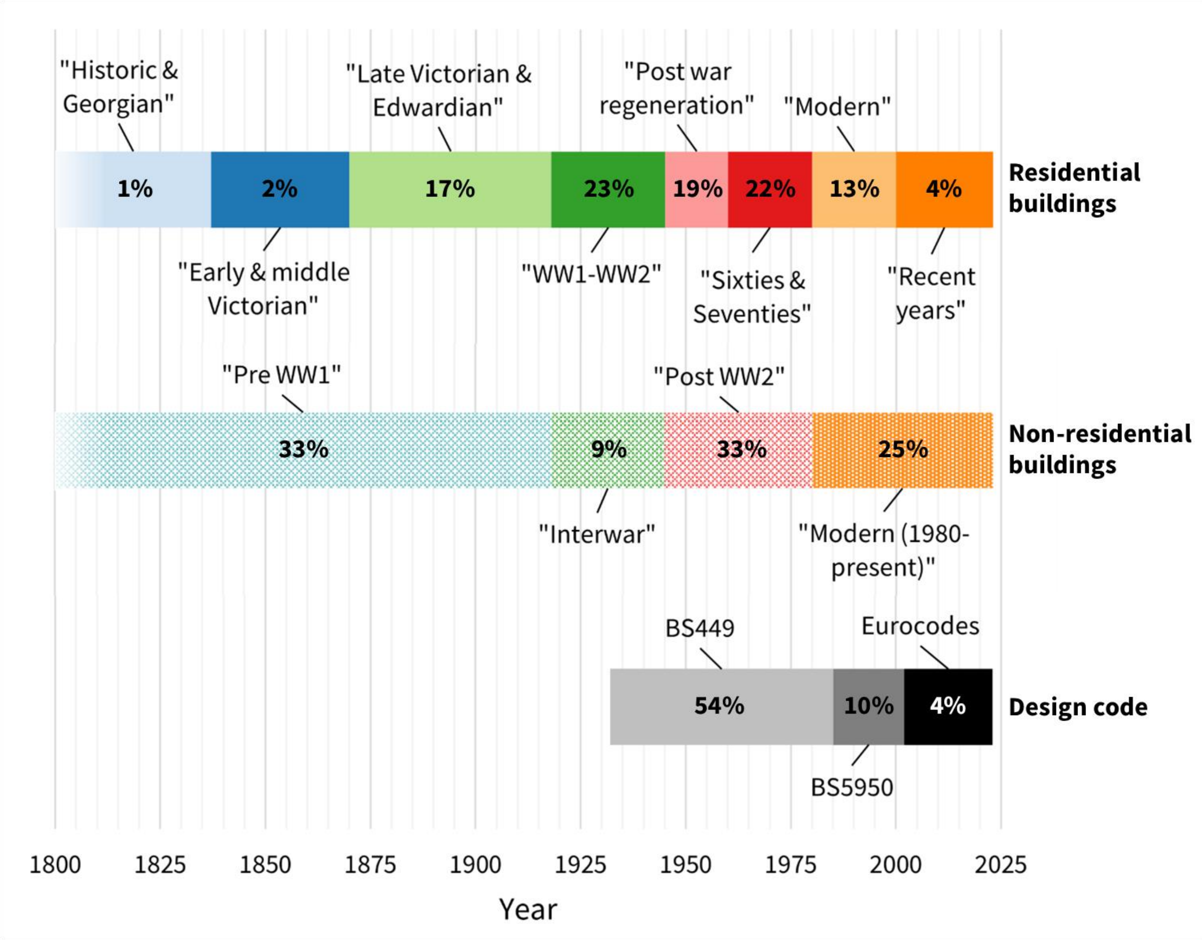

Figure 4.7 - The proportion of residential and non-residential buildings constructed in the UK during different time periods (Geomni, 2020)*, and resulting percentages of existing steel-framed buildings likely to have been designed using different codes of practice.*

Figure 4.7 reveals 68% of the UK's building to stock to have been constructed since the introduction of BS449 in 1932, suggesting the majority of steel-framed buildings in the UK to experience column utilisations, reserve capacities and extendibilities similar to those identified under Scenarios 1-3 (Sections 4.3.1-4.3.3). More specifically, the proportion of buildings constructed in the periods for which BS449 (Scenario 1), BS5950 (Scenario 2) and Eurocodes (Scenario 3) were most widely used are found to be 54%, 10% and 4% respectively. Assuming proportionality of the rate of steel-framed building construction and that of other structural forms, the majority of these are likely to experience URs and reserve capacities similar to the median values of 0.82 and 22% observed for Scenario 1 (BS449). A further 10% of steel framed buildings are expected to have URs and reserve capacities of around 0.84 and 20%, with just 4% of the existing building stock exhibiting reserve capacities around 10% as a result of being designed in accordance with Eurocodes (Scenario 3).

Overall, despite revealing around 1/3 of the UK building stock to have unknown reserve capacity due to its construction before 1932 (i.e. prior to the introduction of BS449), Figure 4.7 suggests the majority existing steel framed office buildings (64%) to have been designed using British Standards and thus have reserve capacities around the median values of 20-22%. Combined with its representation of just 4% of the building stock, this suggests that the commonly assumed value of 10% reserve capacity associated with Eurocode design (Scenario 3), may be conservative in a large number of real world cases. This is increasingly the case when considering that it is this 4% of the existing stock that may contain structures designed with one or more of the inefficiencies modelled in Scenarios 4-8.

Most common frame configurations

Although representing those that are *likely* to be observed in reality, the frame configurations considered in Section 4.2.1 do not necessarily represent those that are *most common* within the UK building stock. As such, in order to identify the range of underutilisation values most likely to be observed in reality, and to assess the sensitivity of findings to assumed design inputs, UR values for a subset of the initial frame configurations are considered below. Based upon design guidance for office buildings in the UK (Government Property Agency, 2022; British Constructional Steelwork Association, Steel Construction Institute, & Steel for Life, 2021; SteelConstruction.info, 2019), this sees storey number (n) reduced to between 4 and 10, and bay width (b) to between 6m and 9m (again in steps of 0.25m). Throughout this process, storey height (h) is taken as either 3.75m or 4.00m, representing floor-ceiling heights of 2.75-3.00m with a 1m allowance for raised floors, suspended ceilings and/or other service voids. Reducing hypothetical frame parameters to between these values results in consideration of just 182 of the initial 11,250 configurations, to give the associated UR distributions in Figure 4.8. The reduced range of URs associated with this results that there are no outliers, with whiskers in Figure 4.8 thus representing minimum and maximum values rather than upper and lower bounds (as was otherwise the case in Figure 4.4).

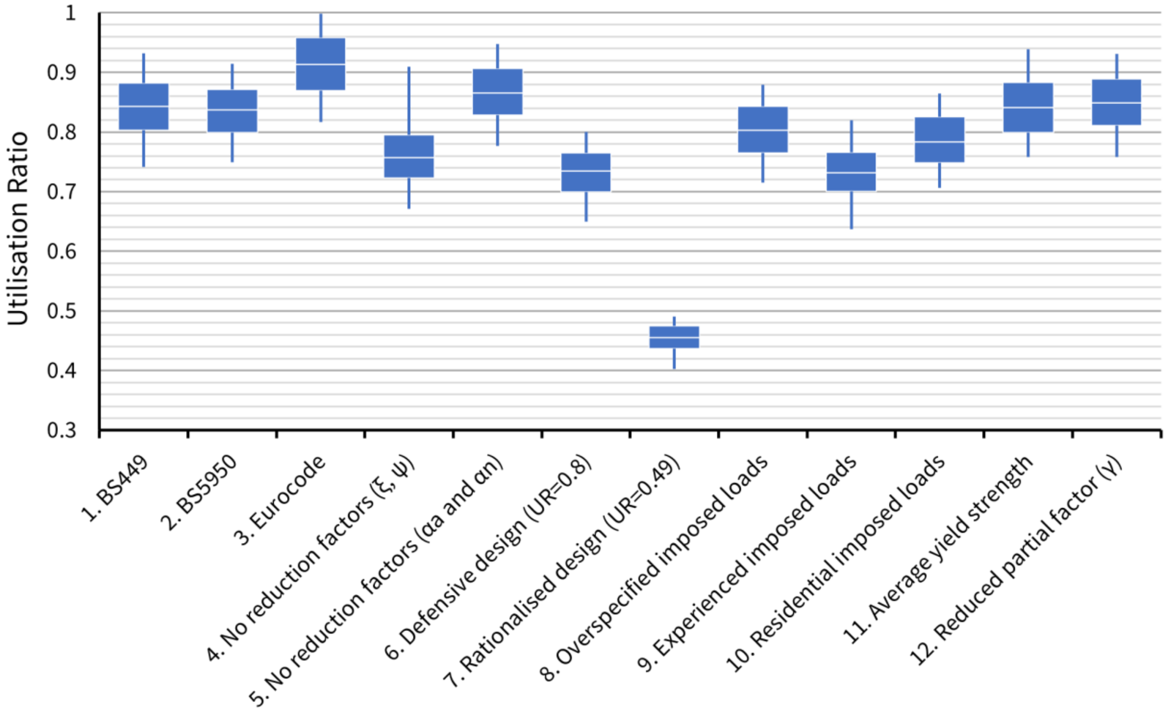

Figure 4.8 - Distribution of utilisation ratios for the 182 reduced frame configurations considered under each scenario (Table 4.1, 1-12), representing 2,184 combinations overall. In the absence of outliers, whiskers indicate minimum and maximum values rather than lower and upper bounds as in Figure 4.4.

Comparison of Figure 4.4 and Figure 4.8 reveals consideration of only the most common frame configurations to have a minimal impact upon the median UR value obtained for each scenario. This is exemplified by a largest increase of 0.02 and decrease of 0.03, obtained for designs employing BS449 (Scenario 1) and omitting load reduction factors (Scenario 4) respectively. Aside from this, all other scenarios experience a change in median UR of less than ±0.01 (i.e. 1%). As to be expected when restricting input frame parameters, the interquartile range for all scenarios is reduced Figure 4.8 compared with Figure 4.4. Such a change is typically minimal, however, and only exceeds 1% (i.e. a value of -0.01) in the case of Scenarios 4, 9 and 1, which experience reductions of 0.03, 0.02 and 0.02 respectively.

Somewhat predictably, the greatest variation between UR distributions for *likely* (Figure 4.4) and *most common* (Figure 4.8) frame configurations is observed in the overall range of values obtained in each. This is exemplified by whiskers being larger in Figure 4.4 than in Figure 4.8, despite representing lower and upper bounds (at 1.5 times the interquartile range from the median) in the former and minimum and maximum values in the latter. Comparing minimum UR values for all frame configurations (Section 4.3.1) with those in Figure 4.8, shows initially consistent URs of between 0.11 and 0.12 to increase significantly, but by a varying degree, to between 0.40 and 0.82 (obtained for Scenarios 7 and 3 respectively). This is a result of particularly inefficient configurations not being included in Figure 4.8, as are otherwise considered in Section 4.3.1 and omitted in Figure 4.4 through the use of upper and lower bounds. These lower bound values (which range from 0.40-0.77) in Figure 4.4 are similar to minimum values in Figure 4.8 (0.40-0.82), confirming validity of the initial removal of inefficient (i.e. non-onerous) frame configurations in this way. In contrast with minimum values, because of the occurrence of structurally efficient configurations in both likely (Section 4.3.1) and most commonly structures (Figure 4.8), maximum URs for all scenarios in Figure 4.8 remain between 0.49 and 1.00 as in Section 4.3.1. Because of the limited presence of top-end outliers in Section 4.3.1, this range is also the same as that for upper bounds in Figure 4.4, further confirming the validity of omitting unlikely frame configurations in this manner.

Overall, consideration of only the most commonly occurring steel framed structures reveals the initial inclusion of a large range of frame configurations to have had minimal influence upon results. This is revealed by limited sensitivity of output URs to input design parameters, with typically negligible changes in median and interquartile range values being observed across all scenarios. As a result of this, the URs, reserve capacities and extendibilities identified in Sections 4.3.1-4.3.3 are thought to be representative both of the steel framed office configurations that occur most commonly within the UKs building stock, and the broader range of configurations that are likely to be observed. The validity of accounting for structural inefficient and unlikely configurations through the removal of outliers in Sections 4.3.1-4.3.3 has also been confirmed by the similarity of initial lower and upper bounds and associated minimum and maximum UR values for most common frame configurations.

4.3.5 Limitations and future work

Although successfully providing an indicative measure of the effect of different sources of underutilisation on reserve capacity and extension potential in existing buildings, the above work possesses a number of limitations which may be addressed in future work. Perhaps the most apparent of these is its consideration solely of column sections, with the capacity of other building elements (e.g. foundations, baseplates and splices/connections) evidently requiring assessment in the case of a vertical extension. Although potentially remedied by localised strengthening, greater consideration of load transfer between the existing and extended portion of the building is also required, as well as for the building's lateral stability and robustness. This limitation is linked to the fact that only column failure through member buckling is considered, with future work perhaps being expanded to consider additional failure modes as well as both braced and moment frames. Even within member buckling of braced frames there is scope to consider a greater range of potential scenarios, owing to this work's sole consideration of columns with effective length equal to storey height. This represents potential to both reduce the identified extendibilities (i.e. if a building was originally designed using effective length factors less than 1) or act as a source of additional reserve capacity (i.e. where a building originally designed with effective length factors of 1 may reasonably be reappraised using a value less than this). Additional scope for future identification of reserve capacity lies in reduction factors for imposed loads acting over multiple storeys (α_n) and the potential for an extension to push a building beyond the threshold at which a greater reduction factor may be applied (British Standards Institution, 2002).

Further opportunity to enhance applicability of this work to a greater range of real-world structures lies within the future consideration of non-square structural grids and asymmetric bay sizes. This would however negate one-dimensionality of the considered case and require consideration of nominal moments, necessitating more complex and less generalised analysis. It is also evident that other structural forms (e.g. reinforced concrete frames) and building uses could be assessed in the future, though the majority of considered scenarios are at least somewhat applicable across all uses and structural forms. Considering the combined effect of multiple underutilisation sources would also better represent real-world constructions, representing scenarios such as those where both conservative (Scenarios 4 and 5) and defensive (Scenario 6) design approaches have been applied. As well as the reserve capacity resulting from combined scenarios, further analysis of the consequent potential for change of use is also recommended. This would serve to assess the ability of underutilisation in enabling the adaptive reuse of existing buildings in a more general sense, rather than in the specific context of vertical extensions.

4.4 Conclusions

Despite its focus upon the buckling capacity of column elements in steel framed buildings, the findings of this work offer an indicative measure of the reserve capacity contributed by different sources of underutilisation, and the potential for extension resulting from this.

Although somewhat generalisable, different sources of underutilisation are shown to contribute to reserve capacity and extension potential in existing buildings to a varying degree, with median reserve capacities of 10% and 120% being identified for least-weight and rationalised Eurocode designs. The frame configuration to which underutilisation sources are applied is also shown to contribute variation to resultant reserve capacity, with upper and lower quartiles values for least-weight Eurocode designs of 5% and 16% respectively. Increased reserve capacity may be identified in buildings designed to superseded codes of practice, employing conservative, defensive or rationalisation processes, and assuming different loading scenarios or material strengths. Whilst partially validating the reliability of the 10% permissible load increase cited in Chapter 2, this does suggest potential for future development of greater benchmark values for a number of buildings. Owing to their representation of a majority of the UK's existing stock (Section 4.3.4), perhaps the most pertinent of these is buildings designed using British Standards, for which a value closer to 20% may be more appropriate.

Even in buildings designed as efficiently as allowed by current codes of practice, the identified reserve capacity is often sufficient to facilitate extension without structural strengthening. For least-weight Eurocode designs, this results in potential for extension in between 9% and 36% of considered configurations depending upon the extension's structural form and use. Significantly greater extension potential of up to 75% of configurations may be identified in buildings designed using superseded codes of practice, with those conservatively omitting certain reduction factors enabling extension in up to 58% of cases. Similarly, a defensive design processes enables extension in between 70% and 89% of considered frame configurations, with this likely to be the case for a large number of real world structures (Orr et al., 2019; Dunant et al., 2018; Orr, 2018). Adjustment of imposed loads assumed in appraisal from those used in design also represents the potential for vertical extension. As well as using Eurocode recommended or average experienced office loads, reappraising an office building using those for residential use reveals potential for extension in up to 82% of cases. This is particularly relevant considering the increased commonality with which office-residential conversions are being observed (Gillott, Davison, & Densley Tingley, 2022a) and the large number of buildings to which such a case may be applicable. Further reserve capacity may be identified through the use of tested material strengths in place of characteristic values and the modification of design codes whilst ensuring safety.

Although completed in the context of steel framed office buildings, as the majority of considered underutilisation sources are applicable across use types and structural forms their identified effect remains relevant beyond this. The adopted methodology may however be readily adapted to represent a greater variety of real-world structures more closely, through the consideration of additional structural elements, failure modes, underutilisation sources as well as structural forms and uses.

5

Housing Provision through Permitted Development Vertical Extensions

5.1 Introduction and research aims

The backlog of required housing in Great Britain (GB) is estimated to be 4.75 million households (4 million in England alone), requiring the generation of 380,000 homes a year (340,000 in England) for the next 15 years (Bramley, 2018). This is significantly greater than the government's current target of 300,000 new homes per year (The Conservative Party, 2019)[6] and almost double the average annual supply since 2000 (Ministry of Housing Communities and Local Government, 2021). In addition to generating such large numbers of housing, further complications arise from the fact that housing provision in high-density urban centres is increasingly being viewed as preferential to more traditional low-density suburban clusters. This is a result of their ability to enhance economic productivity (Arbabi, Mayfield, & McCann, 2020) and access to services (Transport for New Homes, 2020; Royal Town Planning Institute, 2018), whilst also providing infrastructure more efficiently and reducing transport emissions (Resch et al., 2016; Arbabi & Mayfield, 2016; Nichols & Kockelman, 2015; Norman, MacLean, & Kennedy, 2006; Newman & Kenworthy, 1989).

In recognition of the potential for vertical extensions to generate housing whilst increasing residential density and reducing embodied carbon emissions, a series of permitted development rights (PDRs) were introduced in 2020 (Ministry of Housing Communities and Local Government, 2020a; The Town and Country Planning (General Permitted Development) (England) (Amendment) (No. 2) Order 2020; The Town and Country Planning (Permitted Development and Miscellaneous Amendments) (England) (Coronavirus) Regulations 2020). As detailed below, these facilitate the extension of existing houses, commercial buildings and blocks of flats by up to two storeys without the requirement for planning permission (The Town and Country Planning (General Permitted Development) (England) (Amendment) (No. 2) Order 2020; The Town and Country Planning (Permitted Development and Miscellaneous Amendments) (England) (Coronavirus) Regulations 2020). Instead, only a streamlined prior approval process is required, with the eligibility for extension, and number of storeys that may be added, being dependent upon building characteristics such as age, location and listed status.

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[6] At the time of writing the target to deliver 300,000 new homes a year remains mandatory. This is despite indication on 05/12/2022 that this may be made advisory as part of the forthcoming Levelling Up and Regeneration Bill (Department for Levelling Up Housing and Communities, 2022b).

Prior to their introduction, the Ministry of Housing, Communities and Local Government (MHCLG), now the Department for Levelling Up, Housing and Communities (DLUHC) conducted a monetised cost-benefit analysis of vertical extension PDRs (Ministry of Housing Communities and Local Government, 2020b). As summarised in Chapter 2 and detailed in Section 5.2.8, this first derived the number of eligible properties from the English Housing Survey (EHS) (Ministry of Housing Communities and Local Government, 2017) and rateable property statistics (Valuation Office Agency, 2020), before successively converting this into potential, feasible and likely numbers of deliverable dwellings. Typical of top-down approaches, this procedure experiences a number of methodological deficiencies, including: the neglect of location, listed-status and height-based restrictions; employment of numerous unjustified assumptions; and poor spatial resolution.

Similar deficiencies are seen in further works assessing the potential for vertical extensions beyond the building scale, with these too employing top-down (Spirkova et al., 2021), or archetype-based bottom-up (Aparicio-Gonzalez, Domingo-Irigoyen, & Sánchez-Ostiz, 2020; HTA Design, 2016) approaches over geographically restricted regions (Chapter 2). Because of this, the true potential for at-scale vertical extension in the UK, whether delivered through PDRs or otherwise, remains unknown. As well as in terms of the number of possible extensions, there is also no current understanding of the spatial distribution of these between and within the UKs cities, meaning that it is unclear whether vertical extension PDRs are effective in promoting their intended morphological change of increased residential density in urban areas.

To address these knowledge gaps, this chapter considers ***how much space may be provided by residential vertical extensions, and how this is distributed at the city and national level***. In achieving this, three objectives are defined.

a.) Develop a bottom-up assessment framework to identify properties eligible for extension and the number of storeys that may be added.

b.) Apply the framework to estimate the amount of housing that may be generated by permitted development extensions at the property, neighbourhood, city and national level.

c.) Assess the distribution of extension potential between and within England's major cities.

5.2 An overview of permitted development rights for vertical extensions and their uptake and assessment to date

Understanding and overcoming the methodological deficiencies outlined in Section 2.6, and thus answering RQ3, requires a more nuanced appreciation of permitted development rights (PDRs) for vertical extensions. The following subsections therefore provide further detail on PDRs in England, as well as the introduction, scope and current uptake of those relating specifically to the vertical extension of existing buildings. An in-depth appraisal of previous work from the Ministry of Housing, Communities and Local Government (MHCLG) assessing the potential impact of vertical extensions is also presented in Section 5.2.8, revealing methodological deficiencies throughout and acting as an initial benchmark against which the potential for extension identified in Section 5.4 may be compared.

5.2.1 Overview

In England, PDRs refer to the ability to deliver specific types of development without the need for planning permission. First introduced in 1995 (The Town and Country Planning (General Permitted Development) Order 1995), two of the most commonly exercised and well-known PDRs enable the alteration and enlargement of existing dwellings, typically through conversion of loft space or sideways extension. Similar PDRs also exist to enable the change of use of certain buildings (The Town and Country Planning (General Permitted Development) (England) Order 2015). Instead of the traditional planning process, PDR developments are subject to a streamlined prior approval process in which the proposal is assessed against a set of pre-defined criteria (e.g. considering the buildings location, use, and age). Because of this, PDRs are less onerous for both the applying developer and local planning authority (LPA), resulting in reduced time and financial costs. The non-subjective nature of the criteria assessed in the prior approval process also means that PDRs offer greater reassurance to developers in terms of the likelihood of success.

5.2.2 Development and introduction

First indication of a potential PDR for vertical extensions was made in the 2017 “Fixing our broken housing market” whitepaper from the Department for Communities and Local Government. This recognised the need for increased residential density in city-centres and near transport hubs, acknowledged the ability of vertical extensions to deliver this, and announced intention to consult on associated amendments to the National Planning Policy

Framework (NPPF) (Department for Communities and Local Government, 2017). Views on proposed PDRs for the creation of new dwellings above existing houses, freestanding blocks of flats and commercial buildings were subsequently sought in the 2018 consultation on planning reforms to support the high street and increase housing delivery (Ministry of Housing Communities and Local Government (MHCLG), 2018).

Although recognising the benefits of increased residential density through vertical extensions, response to this consultation was generally negative, with less than half of respondents supporting the introduction of such PDRs (MHCLG, 2019). In the case of dwelling extension, cited reasons for this include negative impacts on neighbour amenity and the character of residential areas, requirement for additional parking and increased conversion of dwellings to houses of multiple occupancy (MHCLG, 2019). Additional concerns were raised regarding nuisance for occupiers of dwellings above commercial buildings of certain uses (e.g. laundrettes, restaurants or cafes), and the unsustainability of housing provision in certain locations (e.g out of town offices or retail estates) (MHCLG, 2019). Because of this case-by-case variation in suitability for extension, and the range of storeys that may reasonably be added to different typologies in different locations, more than half of respondents felt that PDRs were not the correct instrument by which vertical extensions should be delivered (MHCLG, 2019). Instead, as the case-specific suitability of vertical extensions necessitates their individual consideration by the LPA, a preference for full planning permission or Local Development Orders (MHCLG, 2019) was expressed by many. For the same reason, respondents stated that, if a PDR *was* to be introduced, prior approval processes should be used to explicitly consider the extent and design of the development (MHCLG, 2019).

Despite a lack of support, the government announced its intention to proceed with the introduction of vertical extension PDRs (MHCLG, 2019), with six new PDR classes being created in 2020 (MHCLG, 2020). As detailed in Table 5.1, the first of these relates to the extension of existing dwellings, and thus is made in an amendment to Part 1 of Schedule 2 of the 2015 Town and Country Planning General Permitted Development Order (GPDO) (The Town and Country Planning (General Permitted Development) (England) (Amendment) (No. 2) Order 2020). The five remaining PDR classes enable the generation of *new* dwellings, and so are inserted in Part 20 of Schedule 2 of the same statutory instrument (HM Government, 2020b).

	Part	**Class**

Permitted development type		
Enlargement of a dwelling by construction of additional storeys.	1	AA
New dwelling(s) on detached blocks of flats.	20	A
New dwelling(s) on detached buildings in commercial or mixed use		AA
New dwelling(s) on attached buildings in commercial or mixed use		AB
New dwelling(s) on attached buildings in use as dwelling(s).		AC
New dwelling(s) on detached buildings in use as dwelling(s).		AD

Table 5.1 - Vertical extension PDRs classes for different development types, and the corresponding part of the GPDO in which they are introduced

5.2.3 Property eligibility

As shown in Table 5.2, a property's eligibility for PDR extension is subject to a set of restrictions based upon its location (e.g. not within a national park, conservation area or 3km of an aerodrome); age (e.g. not built before July 1948 or after March 2018); and protection status (e.g. not a listed building or scheduled monument) (The Town and Country Planning (General Permitted Development) (England) (Amendment) (No. 2) Order 2020; The Town and Country Planning (Permitted Development and Miscellaneous Amendments) (England) (Coronavirus) Regulations 2020). Each PDR class also requires existing properties to be of a specific use (e.g. residential, non-residential or mixed) and type (e.g. flat or dwellinghouse) as well as either detached, semi-detached or terraced (The Town and Country Planning (General Permitted Development) (England) (Amendment) (No. 2) Order 2020; The Town and Country Planning (Permitted Development and Miscellaneous Amendments) (England) (Coronavirus) Regulations 2020) (Table 5.2).

	Part 1	**Part 20**				
Eligibility Criterion	**Class AA**	**Class A**	**Class AA**	**Class AB**	**Class AC**	**Class AD**
Not in a national park	✓	✓	✓	✓	✓	✓
Not in a world heritage site	✓	✓	✓	✓	✓	✓
Not in an area of outstanding natural beauty	✓	✓	✓	✓	✓	✓
Not in a conservation area	✓	✓	✓	✓	✓	✓
Not in a site of special scientific interest (SSSI)	✓	✓	✓	✓	✓	✓
Not within 3km of an aerodrome		✓	✓	✓	✓	✓
Not a scheduled monument		✓	✓	✓	✓	✓
Not in a safety hazard area[a]		✓	✓	✓	✓	✓
Not in a military explosives area[a]		✓	✓	✓	✓	✓
Constructed after 1948[b]	✓	✓	✓	✓	✓	✓
Constructed before 2018[b]	✓	✓	✓	✓	✓	✓
Not listed		✓	✓	✓	✓	✓
In residential use	✓	✓			✓	✓
In non-residential or mixed use[b]			✓	✓		
Is a house	✓				✓	✓
Is a block of flats		✓				
Is of 3 or more storeys		✓	✓			
Is detached	✓		✓			✓
Is semi-detached	✓			✓	✓	
Is terraced	✓			✓	✓	

[a] Omitted from analysis due to unavailability of data.

[b] Discrepancy between UKBuildings age classes and PD criteria (Section 5.3.3).

Table 5.2 - Criteria required to be satisfied for eligibility to each PDR class. (Footnotes provide details of where consideration of these vary between the GPDO and the methodology employed in Section 5.3).

5.2.4 Scope of extension

If eligible, the degree by which a property may be extended is limited by its existing and prospective storey number and potential extended height. This is to reduce overlooking and the loss of light of adjacent properties, as well as alteration of the character of the surrounding area (The Town and Country Planning (Permitted Development and Miscellaneous Amendments) (England) (Coronavirus) Regulations 2020). Up to two storeys may be added to existing properties of two or more storeys, with a maximum of one storey being addable to properties smaller than this (The Town and Country Planning (General Permitted Development) (England) (Amendment) (No. 2) Order 2020; The Town and Country Planning (Permitted Development and Miscellaneous Amendments) (England) (Coronavirus) Regulations 2020). Extended properties must also be no more than 18m tall, with this being relaxed to 30m for detached properties (Part 20: Class A) (Part 20: Class AA) as a result of their requirement to be three or more storeys prior to extension (Table 5.2). Limits are also placed on the height of the extension itself, with respective maxima of 3.5m and 7.0m for existing properties of one or greater storeys. In all cases, the internal floor to ceiling height of each extended storey must also be 3m or less, and not exceed the minimum internal floor to ceiling height of the existing property (The Town and Country Planning (General Permitted Development) (England) (Amendment) (No. 2) Order 2020; The Town and Country Planning (Permitted Development and Miscellaneous Amendments) (England) (Coronavirus) Regulations 2020). A summary of the requirements for each PDR is given in Table 5.3.

	Part 1	**Part 20**				
Extendibility Criterion	**Class AA**	**Class A**	**Class AA**	**Class AB**	**Class AC**	**Class AD**
No. of extension storeys ≤ no. of existing storeys	✓	✓	✓	✓	✓	✓
Internal floor-ceiling height of extended storeys ≤ minimum internal floor-ceiling height of extended storeys	✓	✓	✓	✓	✓	✓
Internal floor-ceiling height of extended storeys ≤ 3m	✓	✓	✓	✓	✓	✓
Extension height ≤ 3.5m per storey	✓			✓	✓	✓
Extended height ≤ 18m	✓			✓	✓	✓
Extension height ≤ 7.0m in total		✓	✓			
Extended height ≤ 30m		✓	✓			
Extended height ≤ 3.5m above tallest adjoined property	✓[a]			✓	✓	

[a] Requirement to consider minimum building height does not apply to detached properties.

Table 5.3 - Criteria required to be satisfied by extension under each PDR class.

5.2.5 Additional permitted works

Vertical extension PDRs also allow works facilitating the delivery and usage of the extended storeys, such as the strengthening of walls and/or foundations. In developments generating new dwellings (Part 20: Class A-AD), works to install or replace services (e.g. water, gas and electricity); provide access (including means of escape) and construct ancillary facilities (e.g. storage or waste areas) are also permitted (The Town and Country Planning (General Permitted Development) (England) (Amendment) (No. 2) Order 2020; The Town and Country Planning (Permitted Development and Miscellaneous Amendments) (England) (Coronavirus) Regulations 2020). Rooftop plant may be replaced under PDRs for properties upon which it is expected to be found, i.e. detached blocks of flats (Part 20: Class A) and commercial and mixed-use properties (Part 20: Class AA and AB) (The Town and Country Planning (Permitted Development and Miscellaneous Amendments) (England) (Coronavirus) Regulations 2020).

Facilitating works are themselves subject to a set of restrictions, with no externally-visible support structures or strengthening beyond the building's curtilage being permitted (The Town and Country Planning (General Permitted Development) (England) (Amendment) (No. 2) Order 2020; The Town and Country Planning (Permitted Development and Miscellaneous Amendments) (England) (Coronavirus) Regulations 2020). Work pertaining to service or access provision (i.e. where new dwellings are to be generated) and ancillary facilities must take place within the existing building’s curtilage. These must also not be placed in front of the building’s principal elevation, or a side elevation adjacent to a highway, with modifications to rooftop plant being required to result in no increase in height (The Town and Country Planning (General Permitted Development) (England) (Amendment) (No. 2) Order 2020; The Town and Country Planning (Permitted Development and Miscellaneous Amendments) (England) (Coronavirus) Regulations 2020).

5.2.6 Prior approval

Before attempting to vertically extend an existing building under PDRs, a prior approval application must be submitted to the relevant LPA. Amongst other elements, this includes a written description of the proposed development and scaled site- and floor-plans detailing: “dimensions and proposed use of each room, the position and dimensions of windows, doors and walls, and the existing and proposed elevations of the building” (The Town and Country Planning (General Permitted Development) (England) (Amendment) (No. 2) Order 2020). Flood- and fire-risk assessments are also required to be submitted where applicable, (e.g. in Flood Zone 1 and 2, or where the extended building exceeds 18m) (The Town and Country Planning (General Permitted Development) (England) (Amendment) (No. 2) Order 2020; The Town and Country Planning (Permitted Development and Miscellaneous Amendments) (England) (Coronavirus) Regulations 2020).

Following receipt of a prior approval application, the LPA must supply occupiers of properties adjoining the proposed development with a written description of this, including its maximum extended height. Adjoined occupiers then have a minimum of 21 days to submit any representations (comments or objections) relating to this. These representations are considered by the LPA alongside the development’s impact on surrounding vistas, transport networks and defence assets (The Town and Country Planning (General Permitted Development) (England) (Amendment) (No. 2) Order 2020), with relevant external bodies (e.g. Highways England, the Civil Aviation Authority and Historic England) being consulted where required (The Town and Country Planning (General Permitted Development) (England) (Amendment) (No. 2) Order 2020). Occupier and neighbour amenity are also considered in terms of internal natural light, external appearance, privacy, and the impact of its surroundings (e.g. commercial or industrial activity) on prospective occupiers.

Significantly quicker than for full planning permission, applicants must be informed of the outcome of a prior approval application within just eight weeks, beyond which it is granted by default (The Town and Country Planning (General Permitted Development) (England) (Amendment) (No. 2) Order 2020). An application may only be refused if the property is ineligible (Table 5.2), the proposed development does not comply with extension criteria (Table 5.3) or based upon any of the above considerations.

5.2.7 Uptake

Although data on the number of PDR vertical extensions delivered to date is not available, uptake may be measured through the number of prior approval applications received, and granted, by LPAs across England. Data for the period from the introduction of the PDRs to the end of March 2022 (Department for Levelling Up Housing and Communities, 2022a) is given in Table 5.4.

		Number of Prior Approval Applications		
PDR Class	**Development Type**	**Submitted**	**Granted**	**Refused**
Part 1 AA	Enlargement of a dwelling by construction of additional storeys.	523[1]	244 (47%)	260 (50%)
Part 20 A	New dwelling(s) on detached blocks of flats.	161[1]	53 (33%)	104 (64%)
Part 20 AA	New dwelling(s) on detached buildings in commercial or mixed use	43	15 (35%)	28 (65%)
Part 20 AB	New dwelling(s) on attached buildings in commercial or mixed use	26	6 (23%)	20 (77%)
Part 20 AC	New dwelling(s) on attached buildings in use as dwelling(s).	11	8 (73%)	3 (27%)
Part 20 AD	New dwelling(s) on detached buildings in use as dwelling(s).	26	12 (46%)	14 (54%)
	Total:	790[1]	338 (43%)	429 (54%)

[1] A number of submitted applications are not recorded as either granted or refused. This represents situations where prior approval application was submitted but not required, or where the local planning authority has misclassified an application.

Table 5.4 - Number of prior approval applications submitted, granted and refused under each vertical extension PDR class between July 2020 and March 2022.

A total of 790 prior approval applications for vertical extension PDRs have been submitted in England to date, significantly below the rate predicted by the Ministry of Housing Communities and Local Government (MHCLG) (Ministry of Housing Communities and Local Government, 2020b). This indicates limited uptake in comparison with expectation, as well as similar PDRs promoting housing provision through adaptive building reuse (e.g. office to residential conversions) (Department for Levelling Up Housing and Communities, 2022a). Owing to its likely influence on uptake, the impacts of the COVID-19 pandemic should be recognised here, with the limited uptake of vertical extension PDRs perhaps being contributed to a more widespread decline in construction activity between July 2020 and March 2022.

Beyond this, because of the unavailability of data for non-PDR vertical extensions, it is unclear how far limited uptake results from a general lack of interest in vertical extensions, or specifically their delivery through PDRs. As discussed in consultation responses and the MHCLG impact assessment, disinterest in vertical extensions for owner-occupiers may include the desire to avoid overlooking and, in the case of detached properties, maintain exclusivity (Ministry of Housing Communities and Local Government, 2018c, 2019a). Such desires are also exemplified by the preference for dwelling expansion rather than the generation of new residential units (Table 5.4), representing a potential shortfall of the introduced PDRs with respect to their ability to generate housing. In the case of privately rented properties, reasons for the lack of appetite are less apparent, with the general consensus being that vertical extensions represent a good opportunity to maximise the value of an existing asset at a minimised cost (Gillott, Davison, & Densley Tingley, 2022b; Ministry of Housing Communities and Local Government, 2019a, 2020b; Department for Communities and Local Government, 2017). In such cases it may be PDRs specifically that are the issue, with developers instead opting for vertical extension through the standard planning process. Reasons for this may include the highly restrictive nature of PDRs, both in terms of height and permitted works, or, as alluded to in responses to the 2020 public consultation (Ministry of Housing Communities and Local Government, 2019a), the onerous nature of the prior approval process. These factors may contribute to limited uptake by giving the view that traditional planning permission allows for greater freedom and ease of extension, at minimal time and financial cost.

Less than half of submitted prior applications have been granted (Table 5.4) to date, indicating limited success even where uptake has occurred. Although it may genuinely be the case that just 43% of proposed PDR extensions satisfy the prior approval process, this is unlikely to be the case *if* all eligibility criteria (Table 5.2) have been met. Because of this, limited success may instead be a result of developer confusion regarding the eligibility of properties, and the erroneous application for prior approval where the necessary criteria (Table 5.2) are not met. Developer confusion surrounding vertical extension PDRs is further exemplified by the submission of a number of prior approval applications for developments for which this was not required (Table 5.6), increasing the likelihood that misunderstanding amongst developers has contributed to low success rates. It may also be the case that LPAs are themselves unclear on what constitutes eligibility under each PDR class or, as alluded to in the consultation process (Ministry of Housing Communities and Local Government, 2019a), have insufficient resources to effectively assess prior approval applications. Such a situation may therefore have resulted in the incorrect refusal of a number of prior approvals that were in fact satisfactory.

5.2.8 MHCLG impact assessment

In 2020, the Ministry of Housing, Communities and Local Government (MHCLG), now the Department for Levelling Up, Housing and Communities (DLUHC) conducted a monetised cost-benefit analysis of PDRs for the generation of new dwellings above existing buildings (Ministry of Housing Communities and Local Government, 2020b). As part of this, the total number of eligible properties was estimated and used to calculate potential, feasible and likely numbers of deliverable dwellings. This employed a top-down approach based upon total numbers of residential and commercial properties from the English Housing Survey (EHS) (Ministry of Housing Communities and Local Government, 2017) and rateable property statistics (Valuation Office Agency, 2020). Because of this, spatial considerations were limited simply to properties either within or outside London. The top-down methodology followed eight distinct steps, as detailed below, with the numbers of properties identified as eligible at each stage being summarised at the end of this subsection.

Step 1: Disaggregation of attached/detached commercial properties and dwellings in terraces of uniform/variable height

Owing to a cited lack of more appropriate weightings, commercial properties were first categorised as detached or terraced based upon the proportions recorded for blocks of flats in the EHS (Ministry of Housing Communities and Local Government, 2017). Although separate percentages are used within and outside London (78% and 76% respectively) this assumption of proportionality across building uses is unjustified, and thus potentially inaccurate. Because of PDRs' use of more detailed property typologies than are provided by EHS and rateable property statistics, terraced dwellings also are disaggregated further, assuming an 80:20 split between those in blocks of uniform and variable height. No justification for this is provided beyond 'a high chance that entire row of terraces may be the same height', however, casting uncertainty over its validity.

Step 2: Adjustment for conservation areas

To account for properties that are not eligible for PDR extension, total values are reduced by the percentage of dwellings currently in conservation areas within and outside London (16% and 3% respectively (Bottrill, 2005)). This carries the assumption that all property uses and types are equally likely to be within a conservation area and applies a single percentage factor for all areas outside London, both of which are unjustified and potentially invalid. A large number of PDR eligibility criteria (e.g. listed status or location in a national park, AONB or within 3km of an aerodrome) are also omitted from this step, having potentially significant implications on the estimated potential.

Step 3: Estimation of property extendibilities

The number of extendible properties is estimated from eligible property numbers using assumed percentages of each typology to which different numbers of storeys may be added (Table 5.5). These explicitly take account of the 18m and 30m total height restrictions and limiting of extensions to 3.5m above adjoining properties, whilst restrictions on single-storey and total extension heights are assumed to be satisfied (Table 5.3) (The Town and Country Planning (General Permitted Development) (England) (Amendment) (No. 2) Order 2020; The Town and Country Planning (Permitted Development and Miscellaneous Amendments) (England) (Coronavirus) Regulations 2020).

Property Type	Percentage deemed extendible	Storeys deemed addable
Uniform terraced dwelling	100%	1
Variable terraced dwelling	100%	2
Tall terraced dwelling	100%	1
Semi-detached dwelling	50%	2
Tall semi-detached dwelling	100%	1
Detached dwelling	100%	2
Bungalow	100%	1
Detached commercial property	50%	2
Terraced commercial property	100%	2

Table 5.5 - Proportion of each property type deemed extendible by different numbers of storeys (Ministry of Housing Communities and Local Government, 2020b).

Because of the restriction of extensions to ≤ 3.5m above adjoining properties (Table 5.3), terraced dwellings in blocks of uniform height are deemed extendible by just one storey. Two storeys are erroneously assumed addable to *all* terraced dwellings in blocks of variable height, despite this requiring variation of at least one storey and the tallest property in each block being limited to a one storey extension. No justification for 100% of tall, terraced dwellings being assumed extendible by one storey, or their consideration separately from general terraced dwellings, is provided (Ministry of Housing Communities and Local Government, 2020b).

As 68% of semi-detached dwellings comprise two storeys (Ministry of Housing Communities and Local Government, 2017), it is assumed likely that adjoining properties are of the same height and thus extendible by a single storey. This is used to justify 100% of tall semi-detached dwellings being extendible by one storey, whereas a stated lack of relevant data results in the arbitrary assumption that two storeys may be added to 50% of semi-detached dwellings. Although these approaches have the same outcome, with the former being potentially more reasonable, both lack appropriate justification and thus certainty of validity.

Detached bungalows and multi-storey dwellings are assumed to be extendible by one and two storeys respectively, based upon the extension's restrictions to the number of existing storeys and the assumption that the 18m maximum height limit is satisfied. Similarly as for semi-detached dwellings, a lack of data for detached commercial properties results in the arbitrary assumption that 50% of properties are extendible by two storeys, with this again being unjustified. All terraced commercial properties are deemed to be extendible by two storeys as a result of the perception that these are highly likely to experience height variation across adjoining properties. As with variable terraced dwellings this is unjustified and would require an existing height variation of at least one storey, of which the likelihood in reality is unknown.

Step 4: Adjustment for regional economic activity

Having estimated the number of properties that may be extended, an additional adjustment is made to 'capture the fact that the PDR is more likely to be used in London'. This is based upon a previously identified relationship between GDP per capita and construction activity (Department for Communities and Local Government, 2013), and sees extendible building numbers outside London reduced by the proportion for which GDP outside London is lower than within (33%) (Sundling, Blomsterberg, & Landin, 2018). Aside from its use in previous PDR impact assessments, no justification is given for this adjustment which, considering the unique nature of vertical extension PDRs, is unlikely to be valid. The placement of this step in the calculation of total extendible properties is also misleading as it considers the *likelihood* of PDRs being exercised rather than simply the *potential* for this.

Step 5: Adjustment for pre-war properties

Similarly as for properties within conservation areas (Step 2), adjustments are then made to discount properties constructed before 1948. This is carried out using separate percentage reductions for residential (39%) and commercial (33%) properties, derived from the EHS (Ministry of Housing Communities and Local Government, 2017) and non-domestic stock statistics (Valuation Office Agency, 2020) respectively. Despite assuming all property types are equally likely to have been constructed pre- or post-war, and that this is the case for the entire country, this adjustment is largely valid. It is however unclear why this adjustment was completed following estimation of extension potential (rather than as an initial step as per conservation areas), with this placement making the effect of the erroneous adjustment for regional economic activity somewhat unclear.

Step 6: Conversion into potential deliverable dwellings

Next, based upon floorspace and storey number data from Energy Performance Certificates (EPCs) (Department for Levelling Up Housing and Communities, 2020), the average footprint of existing dwellings is taken to be the same as the average floorspace of a new flat, resulting in the assumption that each extended storey yields one new dwelling. A similar methodology is applied for commercial buildings, with average floorspace data from EPCs and an assumed average height of four storeys leading to the assertion that each extended storey above a commercial building generates three new dwellings. The accuracy of EPC data and validity of the four-storey average height assumption in this process are uncertain, potentially resulting in large inaccuracies. Stipulation that all exercised PDRs will deliver flats is also a potential oversimplification, with consideration of numbers of people housed perhaps being more appropriate because of its preclusion of speculation on dwelling size. Upper and lower bounds for the numbers of dwellings delivered above each property type are calculated using corresponding minimum (one storey) and maximum (Table 5.5) numbers of addable storeys. This lower bound is said to represent the situation where developers opt not to extend a property by its full potential.

Step 7: Adjustment for feasibility of extensions

Reportedly accounting for the feasibility of an extension taking place, *demand* for PDR vertical extensions is modelled using MHCLG statistics on the proportion of new addresses being delivered on existing residential (13%) and commercial (12%) sites (Ministry of Housing Communities and Local Government, 2019b). Upper and lower feasibility adjustment factors are obtained from these percentages using ±½, with this being said to account for uncertainty in *supply* of properties eligible for PDR extension and the degree by which they may be extended. The least and greatest number of dwellings deliverable above each property type are then calculated by multiplying the previous lower and upper bounds by their corresponding feasibility adjustment factor. This founding assumption that demand for PDR extensions is proportional to the percentage of new dwellings delivered on existing residential sites, and the arbitrary assumption that supply uncertainty results in variation of ±½, are unjustified and potentially invalid. This is because PDR vertical extensions are inherently different to existing methods of housing provision, requiring consideration of unique factors such as reserve structural capacity and buildability in order to accurately assess their feasibility.

Step 8: Adjustment for likelihood of uptake

Despite feasibility purportedly being accounted for through consideration of supply and demand (as in Step 7), the number of dwellings delivered above each property type is next adjusted to 'convert them to a realistic estimate of development likely to come forward over the next ten years'. This process is said to be based on 'reasonable assumptions in line with the scale of other permitted development rights' and sees seemingly arbitrary uptake percentages of 2-10% being applied to different property types, with a ±½ methodology again giving lower and upper bounds. Lower, middle and upper uptake factors are then multiplied by corresponding minimum, average and maximum numbers of deliverable dwellings, giving a range for the amount of housing likely to be generated by the PDR overall.

Identified potential

The MHCLG impact assessment concludes by providing a best estimate of 78,000 new dwellings generatable through PDR vertical extensions over the next 10 years (Ministry of Housing Communities and Local Government, 2020b). The number of properties identified as eligible following each of the above steps is detailed in Table 5.4, giving an overall estimate of 53,000.

			Number of deliverable dwellings	
Step	**Description**	**Number of properties**	**Lower bound**	**Upper bound**
1	All properties	20,476,528	-	-
2	Adjustment for conservation areas	19,701,133	-	-
3	Non-extendible properties removed	16,624,262	-	-
4	Adjustment for regional economic activity	11,623,180	-	-
5	Adjustment for property age	7,096,144	-	-
6	Conversion into deliverable dwellings	-	7,531,482	11,538,705
7	Adjustment for extension feasibility	919,004	490,434	2,255,375
8	Adjustment for likelihood of uptake	53,370	14,889	189,542

Table 5.6 - Number of eligible properties and corresponding deliverable dwellings identified following completion of steps 1-8 (as above).

In addition to the issues discussed above, including the unjustified assumption of attached:detached and uniform:variable building proportions (Step 1) and the failure to recognise the unique nature of vertical extension PDRs (Steps 7 and 8), the MHCLG impact assessment has a number of methodological deficiencies. These include the neglect of a number of location-based eligibility criteria (e.g. removal of buildings within national parks, world heritage sites, areas of outstanding natural beauty, SSSI) and listed or scheduled monument status (Table 5.2), as well as extendibility restrictions on individual storey and total building height (Table 5.3). Indicated by the repeated reference to 'internal sense testing', it is likely that these omissions were made as a result of the lack of necessary aggregated data (i.e. statistics on the percentage of buildings within the above areas). This is characteristic of an overarching issue with the use of top-down assessment methodologies where *all* buildings are successively filtered to identify those eligible and extendible by different degrees. Use of top-down approaches such as this also results in further concerns regarding the archetypal and spatial disaggregation of the identified extension potential.

Although split into different building uses (i.e. residential and commercial), types (i.e. dwellings and blocks of flats) and attachment status (i.e. attached, semi-detached and terraced) (Table 5.5), the MHCLG impact assessment fails to correctly disaggregate by PDR class as defined by the GPDO (Table 5.1) (The Town and Country Planning (General Permitted Development) (England) (Amendment) (No. 2) Order 2020; The Town and Country Planning (Permitted Development and Miscellaneous Amendments) (England) (Coronavirus) Regulations 2020). This means that it is not possible to directly compare the potential for extension under different PDR classes as would be required for appraisal of their relative effectivity. Of greatest issue here is the resultant inability to consider differences in the potential for extension under Part 1: Class AA (dwelling enlargement) or Part 20: Class AC/AD (generation of new dwellings), meaning that the effects of the more lenient requirements of Part 1 (Table 5.2) remain unknown.

Spatial disaggregation of buildings in the MHCLG impact assessment is limited to those within or outside London, with this categorisation being made primarily to allow for adjustment based upon differences in economic activity within these respective areas (Step 4). This means that the spatial distribution of the potential for PDR vertical extension is not considered, in terms of how this is spread both between and within England's cities. As such, the impact assessment is unable to assess the true potential for vertical extension with respect its intended aim of increasing residential density in city centres and close to key transport links.

5.3 Methodology

5.3.1 Overview

To meet the aims stated in Section 5.1, three distinct stages are followed, the first of which is concerned with the collection of data and its preparation for subsequent analysis (Section 5.3.2). Following this, a bottom-up assessment framework is developed and applied to assess the eligibility of individual properties under each PDR class, as well as the associated potential for housing delivery at the neighbourhood and city levels. An overview of this process is given in Figure 5.1, with further details being included in Section 5.3.3. Following this, a series of neighbourhood-level analyses are conducted in order to consider the spatial distribution of extension potential and how this interacts with other socioeconomic factors to influence the uptake of PDRs (Section 5.3.4).

Figure 5.1 - Overview of the developed bottom-up assessment framework. Further details may be found in Section 5.3.3.

5.3.2 Data collection and preparation

Data sources

The primary dataset used in the development and application of the bottom-up assessment framework is the "UKBuildings" GIS (geographic information system) package from Verisk 3D Visual Intelligence (licence no. 5560) (Geomni, 2020). This comprises geospatially located polygons and a set of basic building attributes (e.g. building use, footprint and height) for all buildings in Great Britain. A richer set of attributes (e.g. structural form, listed status, and number of storeys) is also provided for residential buildings, as well as non-residential buildings within "urban extents" (defined as towns and cities with populations over 10,000 (Geomni, 2021)). As well as for buildings (defined as "a continuous structure used for residential or non-residential purposes"), UKBuildings contains polygons representing individual properties (defined as "a whole or part of a building with a consistent use, owner or occupant") (Geomni, 2021). Similarly as with detailed attributes, whilst all residential buildings are disaggregated into individual properties, this is only the case for non-residential buildings within urban extents. Beyond urban extents non-residential properties are instead represented by geospatially located points, to which relevant attributes are assigned.

To model the location-based restrictions imposed by PDRs (Table 5.2), GIS packages detailing the extents of National Parks (Natural England, 2021a), Areas of Outstanding Natural Beauty (AONB) (Natural England, 2020), Sites of Special Scientific Interest (SSSI) (Natural England, 2021b), World Heritage Sites (Historic England, 2021), and Scheduled Monuments (Historic England, 2021) have been acquired from Natural England and Historic England under Open Government Licence. The extent of aerodromes are derived from the Ordnance Survey (OS) MasterMap Topography Layer (Ordnance Survey, 2021) (procured through Digimap's OS Collection educational license (EDINA, 2022)), with conservation area extents being taken from a third party dataset (Hall, 2021) which supplements Historic England data (Historic England, 2021) (again under Open Government Licence) with that from individual LPAs. For use in subsequent spatial analyses, travel to work area (Office for National Statistics, 2017a), LSOA boundary (Office for National Statistics, 2016), and built up area (Office for National Statistics, 2017b) datasets are obtained from Office for National Statistics (ONS).

Data trimming

For computational efficiency in subsequent steps, the UKBuildings dataset was initially trimmed to contain only the areas considered as part of this study. Owing to PDRs applying exclusively to England, this includes eight out of the UK's eleven 'Core Cities' (Birmingham, Bristol, Leeds, Liverpool, Manchester, Newcastle, Nottingham, Sheffield), which are responsible for more than 25% of economic output (Core Cities UK). These are supplemented with England's largest and most populous city, London, to give nine cities overall. To ensure consideration of all areas in which housing provision may reasonably be attributed to a nearby city, boundaries are defined using statistically derived travel to work areas (TTWA), rather than administrative alternatives (e.g. city council or local authority). These are widely used statistical boundaries and represent the area around a city where the bulk of the resident population (75%) also work within the same area (Office for National Statistics, 2011).

Removal of non-residential properties sharing a building

Beyond urban extents, the proportion of a building's footprint attributable to each contained property may not be accurately determined at scale. Multiple non-residential properties contained within a single building are thus excluded from this analysis. This process is carried out using QGIS and sees property points removed where two or more intersect a single building polygon. Across the nine considered cities, this process results in 68% of non-residential properties being retained. Following this step, non-residential attributes assigned to the trimmed UKBuildings points layer are assigned to the corresponding building polygon to give a single consolidated layer for subsequent analysis.

Determination of property attachment

Although required for the application of height restrictions as in Table 5.2, UKBuildings does not differentiate between attached and detached properties in non-residential use. Unique Building Numbers (UBNs) are instead used for this purpose, with all non-residential properties sharing a UBN being appended with a new attribute classifying them as *attached.* Properties not sharing a UBN were otherwise considered *detached* and a corresponding indicator assigned.

Assignment of block height

For attached properties, consideration of the maximum height of all adjoining properties is required as per the conditions in Table 5.3. To allow for this the maximum height of all properties sharing a UBN is first calculated. This may then be assigned as a new ‘block height’ attribute to all properties with that UBN.

5.3.3 Bottom-up extendibility assessment framework

Property eligibility

To allow eligibility to be determined, a set of attributes corresponding to the criteria in Table 5.2 are first assigned to each property. These initially take a base value of 0 (indicating non-compliance), which is replaced by an indicator value of 1 where a specific criterion is met. This process is carried out using QGIS for spatial criterion (e.g. ‘not within a national park’), with attribute-based (e.g. ‘not a listed building’) being considered using Python.

As indicated in footnotes to Table 5.2, there are a number of instances in which assessment of eligibility criteria does not exactly match that as stated in the GPDO (The Town and Country Planning (General Permitted Development) (England) (Amendment) (No. 2) Order 2020; The Town and Country Planning (Permitted Development and Miscellaneous Amendments) (England) (Coronavirus) Regulations 2020). This includes a discrepancy between the actual (1945-2019) (Geomni, 2020) and desired (1948-2018) (The Town and Country Planning (General Permitted Development) (England) (Amendment) (No. 2) Order 2020; The Town and Country Planning (Permitted Development and Miscellaneous Amendments) (England)

(Coronavirus) Regulations 2020) construction dates for which buildings are deemed eligible, as well as potential misalignments between UKBuildings and PDR use categories. Because of the unavailability of such sensitive data, locations of safety hazard and military explosives areas are also not considered in this study, though numbers of properties in such areas is assumed to be minimal.

A set of six eligibility attributes representing each of the PDR classes are then assigned to all properties, again taking an initial value of 0. Using a series of combination filters in Python, this is replaced by an indicator value of 1 where a property satisfies the combination of criteria required by a PDR class (Table 5.2). It should be noted here that, whilst uses and attachment types preclude a single property from being eligible under multiple classes within Part 20, it is possible for a property to be eligible under Part 1: AA and Part 20: AC-AD, as a result of these both pertaining to existing houses (Table 5.2).

Property extendibility

For properties eligible under any class, the number of storeys that may be added is then assessed considering the criteria in Table 5.3. This process is again completed in Python, with attributes indicating permissible extension of 0, 1 or 2 storeys under Parts 1 and 20 of the GPDO being appended to each property. Existing building height and storey number attributes from UKBuildings are used for this purpose, with the floor to ceiling height of each added storey being taken as 2.3m, as recommended by nationally described space standards (Department for Housing Communities and Local Government, 2015). An additional 0.4m is assumed for floor thickness in the extended portion, representing typical beam depth in a 1-2 storey construction and giving a total storey height of 2.7m. It should be noted here that no specific allowance is made for a dedicated service void, based on the likelihood of extensions employing local central heating rather than shared mechanical ventilation.

Generated floor area and equivalent people housed

The number of storeys that may be added above each property is next multiplied by its footprint area, taken from UKBuildings (Geomni, 2020), to give the total floor area yielded by its extension. This is then contextualised as an equivalent number of people that may be housed, using a nominal value of $39m^2$ of floorspace per person. Such a value is taken from the nationally described space standards by which PDR extensions must comply, representing the minimum area required to be provided for a single person living in a one bed dwelling (Department for Housing Communities and Local Government, 2015). As less space per person is required as cohabitation increases, this provides a lower bound estimate for the number of people housed by each extension. This process is completed prior to aggregation to the neighbourhood and city levels, with equivalent people housed being rounded down to the nearest whole number, in order to avoid excess floor area from individual properties being accounted as additional dwellings. Alternative approaches through which space requirement and typical dwelling sizes may be considered, with potential greater accuracy, are discussed in Section 5.4.5.

Aggregation to neighbourhood and city level

To enable floor areas and numbers of people housed to be aggregated beyond the property level, the neighbourhood and city containing each property are assigned to each property as two additional attributes. Similarly as for eligibility criteria, this process is completed in QGIS using the select by location tool and a largest overlap approach. For consistency with travel to work areas and to ensure comparability with additional datasets (e.g. census data and similar), neighbourhoods are defined as Lower Super Output Areas (LSOAs). These are widely used statistical boundaries, with each LSOA containing an average of approximately 1,500 residents or 650 households (Office for National Statistics, 2011).

5.3.4 Neighbourhood level analysis

Distance from city centre

To act as an initial assessment of the spread of extension potential in England’s major cities, the relationship between the LSOA extendibility and distance from the respective city centre is investigated. This first requires calculation of the distance between the population-weighted centroid of each LSOA and the centre of its containing city in QGIS. As a widely accepted indicator, the location of the primary train station is used to represent the centre of each city, with this also being more relevant to urban densification than other alternatives (e.g. central business district) in terms of access to public transport.

To investigate patterns between extension potential and distance from the city centre, LSOAs are aggregated into 2km bands, and the total number of people housed within each band calculated. This distance is selected to give sufficient spatial resolution (i.e. ≥ 10 bands) within the smallest city whilst ensuring a reasonable number of bands (i.e. ≤ 20) across the largest.

5.4 Results and discussion

5.4.1 Eligible properties

Figure 5.2 details the percentage of total properties in each city that are eligible for extension under each PDR. This excludes properties discounted in Section 5.3.2 as a result of them occupying an unknown portion of a shared building.

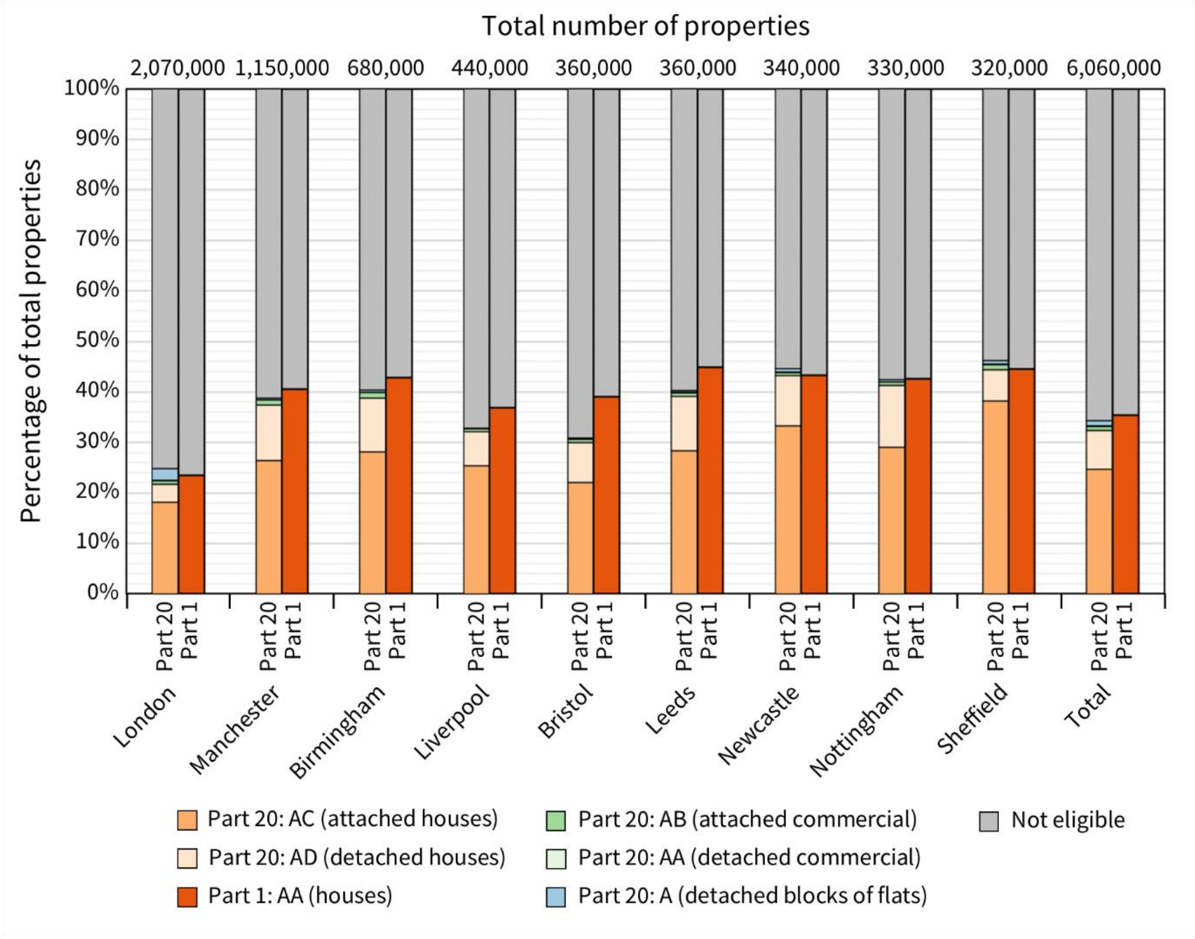

Figure 5.2 - Percentage of total properties within each city eligible for extension under each PDR class.

It can be seen from Figure 5.2 that between 25% (London) and 46% (Sheffield) of properties are eligible for extension under Part 20 of the GPDO (The Town and Country Planning (General Permitted Development) (England) Order 2015) (extension for new dwellings), with the average value across all cities being 34%. Corresponding minimum, maximum and average values for eligibility under Part 1 (extension for dwelling enlargement) are 23% (London), 45% (Sheffield and Leeds) and 35%. This represents significant potential for both new unit generation (2,078,101 eligible properties) and dwelling enlargement (2,144,357 eligible properties), but results in a greater number of properties being eligible for the latter despite only being applicable to houses. No clear pattern between the proportion of total properties that are eligible and city size (total number of properties) or geographical location are apparent.

Although percentages of properties eligible for extension under Part 1 and 20 are similar for most cities, those for Part 1: AA (enlargement of existing houses) are consistently greater than the corresponding percentage for new unit generation (Part 20: Classes AC *and* AD). This is caused by the less stringent restrictions applied to Part 1 PDRs, such as the permissibility of listed properties (Table 5.2), resulting in a large number of houses being deemed extendible for dwelling enlargement but not the generation of new units. Such a pattern is most apparent for Bristol, in which 39% and 30% of properties may be extended for house enlargement (Part 1: Class AA) and the generation of new units above existing houses (Part 20: AC and AD) respectively (Figure 5.2). Combined with the fact that all houses eligible for new unit generation are also eligible to be enlarged (Table 5.2), this prioritisation of dwelling enlargement suggests that PDRs are perhaps more promotive of enhancing the size and value of existing properties than they are of increasing housing supply. This is a direct contradiction of their intended aim, and is further exemplified by the fact that more than 2/3 of prior approval applications submitted have been for dwelling enlargement under Part 1 of the GPDO (The Town and Country Planning (General Permitted Development) (England) Order 2015).

The negative effects of prioritising dwelling enlargement are likely to be exacerbated by the fact that houses (Class AC and AD) make up the vast majority of properties eligible for extension under Part 20 (Figure 5.2). Across all cities, 32% of total properties (1,963,742) are eligible under Classes AC and AD (Figure 5.2). This represents 94% of the properties eligible under Part 20 overall, as shown in Figure 5.3. Corresponding minimum and maximum values of 87% and 98% can be seen for London and Liverpool, with all other individual cities seeing majorities of 96% or above, suggesting that PDRs promote housing provision above existing houses to a significantly greater degree than they do commercial properties and blocks of flats. This has scope to be both a positive or negative aspect of PDRs depending on the specific case, perhaps ensuring houses are not generated in unsuitable business or retail parks but also potentially encouraging further housing provision in poorly connected suburban clusters with minimal service provision.

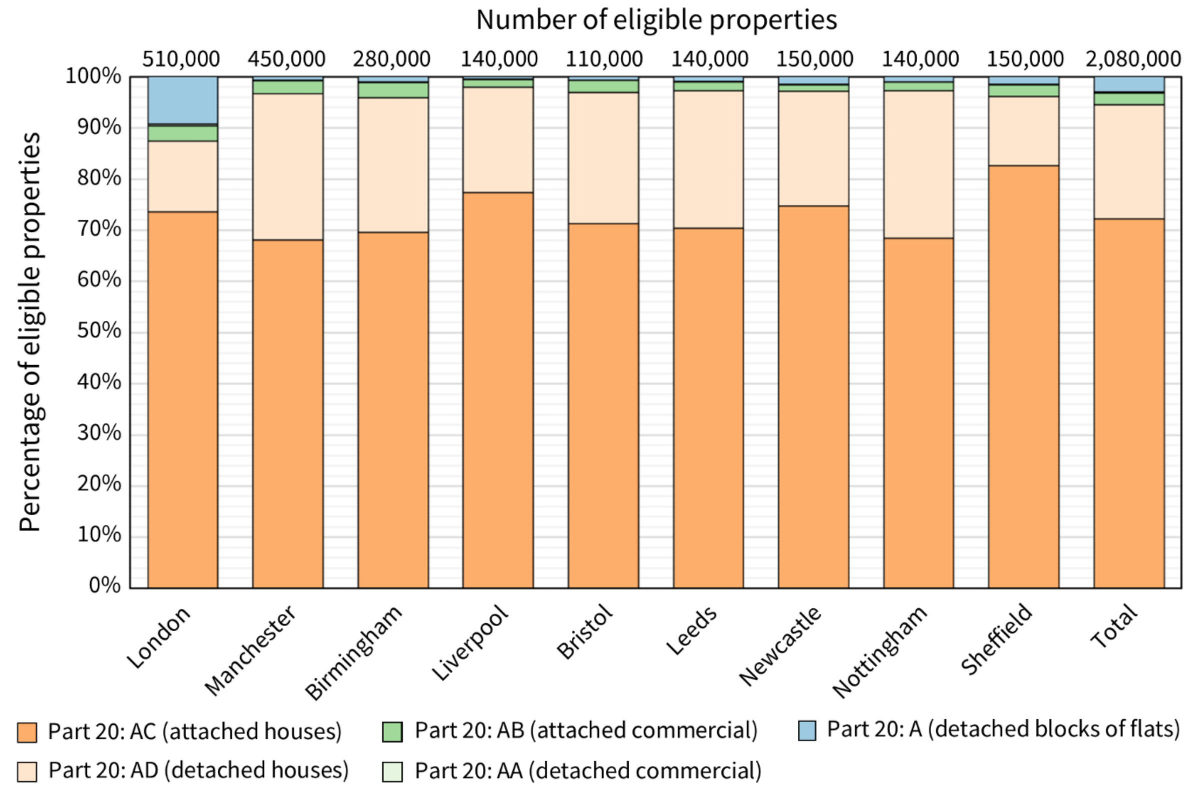

Figure 5.3 - Percentage of properties eligible under Part 20 of the GPDO within each considered city and PDR class.

Houses' dominance of eligible properties is indicative of the typically diminutive number of commercial properties (Part 20: Class AA and AB) and blocks of flats (Part 20: Class A) eligible for extension, with these typologies contributing just 52,341 and 62,018 properties across all cities (1% of total properties each). As the Part 20 eligibility criteria for commercial properties (Class AA and AB) and detached blocks of flats (Class A) are otherwise identical to those for houses (Class AC and AD), this minimal number of eligible properties is likely to be caused in part by their requirement to be three or more storeys prior to extension (Table 5.3). It is also the case that there are smaller numbers of these typologies overall, and that they perhaps have an increased likelihood of being located within city centres where conservation areas are more prevalent. It should be noted here however that the small number of eligible commercial properties (Class AA and AB) and detached blocks of flats (Class A) does not necessarily preclude these typologies from contributing to housing supply, with those that *are* eligible being likely to be larger and extendible by a greater number of storeys than a typical house.

Figure 5.3 reveals London to follow a different pattern to all other cities in terms of the contribution of detached blocks of flats (Class A), with these making up 9% of the city's

513,731 eligible properties. This means that 47,597 blocks of flats are identified as eligible for extension in London, representing 77% of the total number across all nine cities. A similar, yet less extreme, pattern is also observed for commercial buildings (Class AA and AB) (Figure 5.3), for which London contributes 16% of the total across all cities. Further review of Figure 5.3 shows that, whilst the proportion of eligible properties that are *attached* houses (Class AC) is similar in London to all other cities, it is the proportion of *detached* houses (Class AD) that is reduced in order to account for the increased number of detached blocks of flats (Class A) and commercial properties (Class AA and AB). This suggests that the distribution of detached housing typologies in London is simply skewed towards blocks of flats, and/or that detached houses within London are more likely to be ineligible (e.g. due to being listed, constructed before 1948, or located within a conservation area or near an aerodrome) (Table 5.2).

In the case of both houses (Class AC and AD) and commercial properties (Class AA and AB), those that are attached (Class AC and AB) contribute a significantly greater proportion of total eligible properties than those that are detached (Figure 5.3). This is demonstrated by contributions of 72% and 22% of the properties eligible across all cities for attached (Class AC) and detached (Class AD) houses respectively. As eligibility criteria are otherwise identical for attached and detached properties of the same use (Table 5.2), the greater proportion of eligible attached properties is perhaps because there are simply a greater number of this typology, and/or because they are less likely to have ineligible characteristics (e.g. being listed, constructed before 1948, or located within a conservation area or near an aerodrome) (Table 5.2). It is also worthy to note that the dominance of *attached* commercial properties is observed despite the omission of those occupying an unknown portion of a shared building (Section 5.3.3), potentially suggesting this disparity to be more extreme in reality.

Despite there being no clear pattern between the number of properties within each city and the proportion of these that are eligible (Figure 5.2), the rank order of the number of eligible properties within each city differs from that for total property number (Figure 5.3). This is shown by Leeds, Newcastle and Sheffield having greater numbers of eligible properties than the next largest city (by total number of properties) (Figure 5.3) as a result of their increased proportion of eligible properties and similar city size (Figure 5.2).

5.4.2 Property extendibility

Figure 5.4 shows the majority of eligible properties to be extendible when subjected to the height restrictions in Table 5.3. For both new unit generation (Part 20) and dwelling enlargement (Part 1), 83% of the properties eligible across all cities may be extended by at least one storey, representing 1,724,023 and 1,781,433 properties respectively. This means that properties identified as eligible are deemed non-extendible in less than 1 in 5 cases considering the restrictions in Table 5.3. Across all cities, 24% of properties eligible for new dwelling generation (Part 20), and 23% of properties eligible for existing dwelling enlargement (Part 1), are extendible by the full two storeys, representing 507,391 and 501,421 properties respectively. The remaining 59% (1,216,632) and 60% (1,293,410) are therefore extendible by a single storey, meaning that, whilst most eligible properties *are* extendible, this is most often only by one storey.

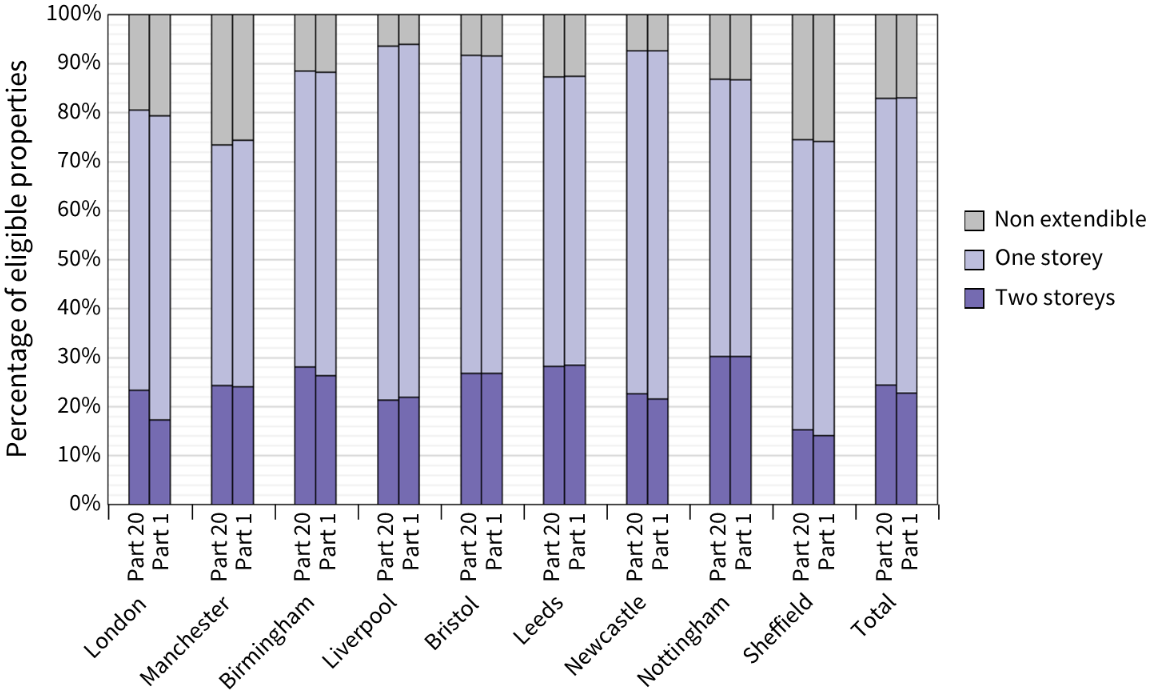

Figure 5.4 - Proportion of properties eligible under Parts 20 (new unit generation) and 1 (dwelling enlargement) of the GPDO extendible by different numbers of storeys within different cities

For different cities, extendibility is fairly consistent for properties eligible for new unit generation (Part 20) and dwelling enlargement (Part 1), as a result of the minimal influence of the small number of commercial properties and blocks of flats eligible under Part 20 (Figure 5.3). As a result of it containing a greater proportion of these typologies, the largest percentage difference between extendibility for new unit generation and dwelling enlargement is seen for London (Figure 5.4).

Minimum and maximum percentages of eligible properties that are extendible for new unit generation (Part 20) are seen in Manchester (73%) and Liverpool (94%), with these cities also experiencing minimum and maximum values for dwelling enlargement (Part 1) (74% and

94% respectively) (Figure 5.4). This is likely to be a result of the urban form of these cities, with Manchester having a greater proportion of buildings infringing one or more height restriction (Table 5.3). As Manchester and Liverpool experience similar proportions of eligible properties that are extendible by two storeys (Figure 5.4), it may be suggested that its decreased overall extendibility is because of infringements preventing non-extendible buildings being extended by a single storey, rather than those extendible by a single storey being extended by two.

5.4.3 Generated floorspace and number of people housed

Numbers of properties eligible under Part 20 of the GPDO (The Town and Country Planning (General Permitted Development) (England) Order 2015) (Figure 5.2) and their associated extendibilities (Figure 5.4) combine to result in the generatable floor areas and equivalent numbers of people housed in Figure 5.5 and Figure 5.6. In total, 176km^2 of new dwellings may be generated through vertical extension across the nine considered cities. This is sufficient space to house 3,767,178 people in single person dwellings of 39m^2 (Figure 5.6), as required by nationally described space standards (Department for Housing Communities and Local Government, 2015) and calculated as in Section 5.3.3. As a result of their similar extendibilities (Figure 5.4) the amount of floorspace that may be generated in each city follows a similar rank order as for numbers of eligible properties (Section 5.4.1). Exceptions here include Sheffield, which, as a result of limited extendibility (Figure 5.4), only contributes 6% (10km^2 = 220,865 people) of total generated floor area despite having the 5th most eligible properties. Conversely, despite having the second smallest number of eligible properties (139,246), 7% of total floor area (12km^2 = 253,374 people) is generated in Nottingham as a large number of these are extendible by two storeys (Figure 5.4).

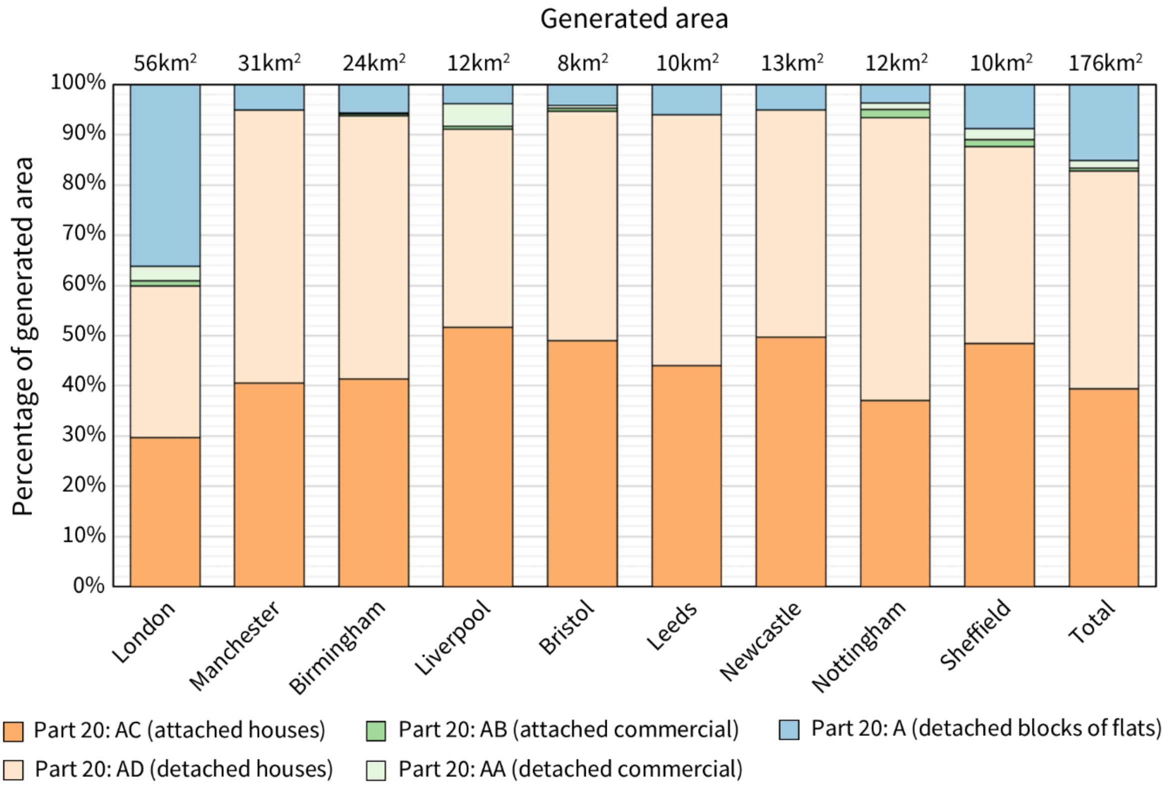

Figure 5.5 - Proportion of total generatable floorspace contributed by each Part 20 PDR class within each considered city. Total floor areas generatable within each city are shown to the top of the figure.

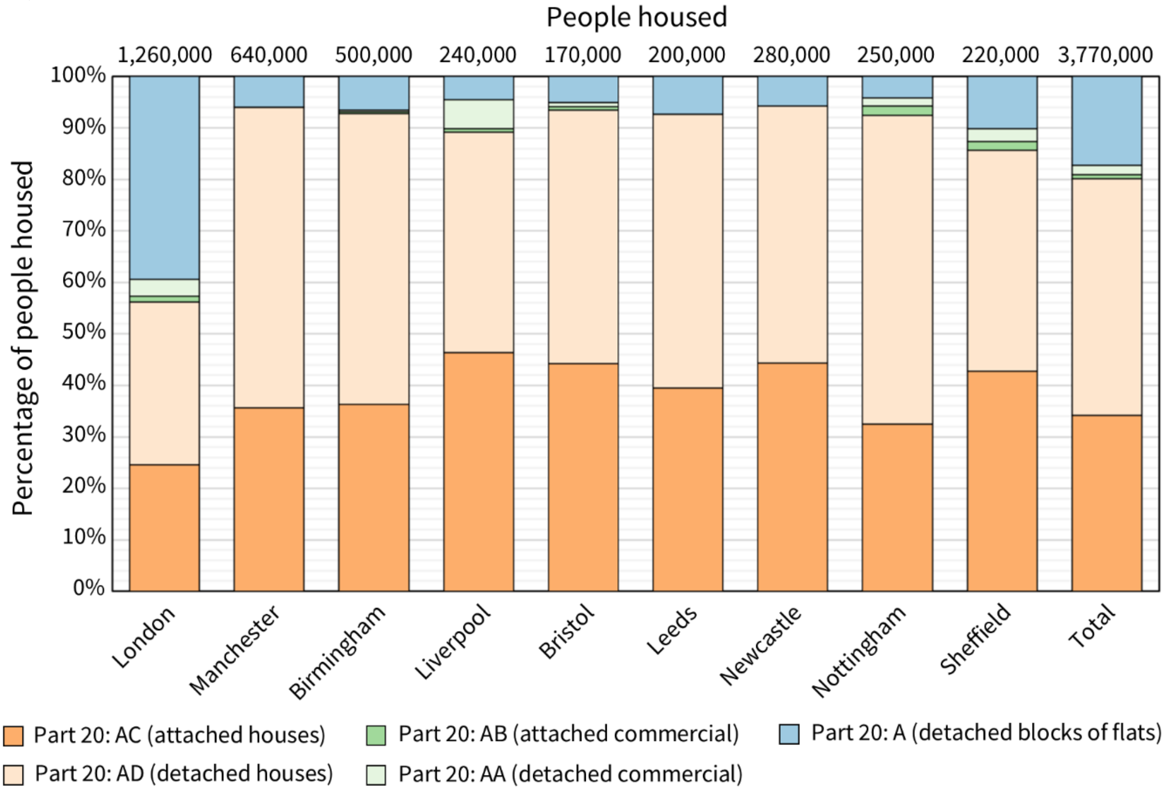

Figure 5.6 - Proportion of total people housed by extensions above Part 20 PDR extensions within each considered city. Total numbers of people housed within each city are shown to the top of the figure.

Figure 5.5 also reveals that the majority of floor space generatable within each city is above existing houses (Class AC and AD), with minimum, maximum and average values being 60% (London), 95% (Newcastle) and 83%. In total 146km^2 of floorspace may be generated above the 1,963,742 houses eligible for extension (Figure 5.3), representing sufficient space for 3,019,864 people in single person dwellings (Figure 5.6). Of this, 76km^2 (=1,733,736 people) may be delivered above *detached* houses, with the remaining 70km^2 (=1,286,128 people) being above those that are attached. Detached houses therefore make the single largest contribution to generatable floorspace across all cities (43%), and the majority of that attributed to houses (53%), exhibiting a reversal in the trend seen for numbers of eligible properties (Figure 5.3). Owing to the otherwise identical height restrictions applied to detached and attached houses (Table 5.3), this difference in majority contribution may be attributed in part to the restriction of extension of attached properties to $\leq$ 3.5m above the tallest adjoining property. It is also likely that detached houses have a larger footprint on average, combining with increased extendibility to generate greater floor areas on average. Because of the calculation of equivalent residential units at the property level (Section 5.3.3), detached houses dominate this to a greater degree still, with 46% of generatable single person dwellings (1,733,736 units) being above this typology (Figure 5.6).

Similarly as for houses, the increased extendibility and average footprint of *detached* commercial properties sees them contribute a greater proportion of generated floor area (Figure 5.5) than number of eligible properties (Figure 5.3). Despite this, as a result of the smaller numbers of these properties, this effect is significantly less extreme, with *attached* commercial properties still making a larger floor area contribution than those that are detached in both Birmingham and Nottingham (Figure 5.5). It is also revealed by Figure 5.5 and Figure 5.6 that commercial properties fail to contribute to floor area generation and resultant dwelling generation. This is contributed to both by the limited number of this typology that are eligible within the city (Figure 5.2) and their limited extendibility considering the restrictions in Table 5.3.

The fact that detached blocks of flats typically have larger footprints than other typologies, and are not subject to restrictions based upon adjoining properties (Table 5.3), means that they are able to contribute significantly to floorspace generation (Figure 5.5) despite representing a small number of eligible properties (Figure 5.3). Across all cities, blocks of flats contribute 15% (27km^2) of generatable floorspace (Figure 5.5), enough to house 652,229 people (Figure 5.6). As this is possible above just 62,018 eligible properties (6% of the total across all typologies), the extension of blocks of flats perhaps poses the most feasible opportunity for housing delivery: with only a small number of successful projects yielding a large number of residential units. This contrasts with the larger number of smaller extensions required for a comparable contribution above existing houses, for which appetite is already known to be minimal (Table 5.4). Despite this heightened opportunity for the extension of blocks of flats, the spatial distribution of housing potential between cities becomes problematic when considering this typology in isolation. This is exemplified by the fact that 76% of the floor area generated above blocks of flats (20km^2) is within London (Figure 5.5), as a result of it containing a higher proportion of a larger number of eligible properties (Figure 5.3).

To contextualise the identified potential for housing provision through PDR vertical extension, the estimated housing demand within each considered city is provided in Table 5.7. These are taken from the most current local plan available for each city (Liverpool City Council, 2022; Sheffield City Council, 2022; The Greater London Authority, 2021; Nottingham City Council, 2020; Leeds City Council, 2019; Birmingham City Council, 2017; Newcastle and Gateshead Council, 2015; Manchester City Council, 2012; Bristol City Council, 2011) and are thus reported in terms of required numbers of dwellings[7]. To facilitate comparison with the potential supply through PDR extension, these values have also been converted into equivalent numbers of people in Table 5.7 using the national average household size of 2.4 people (Office for National Statistics, 2022).

City	Local plan housing demand (dwellings)	Local plan housing demand (equivalent people)	Potential supply through PDR extension (people)	Potential oversupply (%)
London	522,870	1,254,888	1,260,000	0%
Manchester	60,000	144,000	640,000	344%
Birmingham	51,100	122,640	500,000	308%
Liverpool	34,780	83,472	240,000	188%
Bristol	29,000	69,600	170,000	144%
Leeds	51,925	124,685	200,000	60%
Newcastle	30,000	72,000	280,000	289%
Nottingham	17,150	41,160	250,000	507%
Sheffield	35,700	85,680	220,000	157%

Table 5.7 - Comparison of local plan housing demand and the vertical extension potential identified in each considered city.

Potential for housing supply through PDR extension is revealed to be greater than estimated demand across all cities, with this oversupply being reported in Table 5.7 as a percentage of

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[7] Local plans are prepared by individual local authorities to set out long-term strategic development plans and policies for the consideration individual development proposals.

estimated demand. Oversupply is revealed to vary greatly between the considered cities, ranging from 0% in London to 507% in Nottingham, with there being no clear relationship between this and city size, extension potential or estimated housing demand (Table 5.7). As such, although indicating possibility within individual cities, Table 5.7 does not imply that housing demand may be met through PDR vertical extension at the national scale. It should also be recalled that that the housing supply values in Table 5.7 represent an upper bound estimation of the potential for vertical extension, with the number of feasible extensions likely to take place in reality perhaps being significantly below this.

When considering estimated demands and resultant oversupply percentages in Table 5.7, it is also important to recognise a number of methodological restrictions in their derivation. This includes their conversion from dwellings to people assuming national average household sizes; inconsistent projection periods across different local plans; and disparity between the geographical extent concerned by each local plan and the travel to work areas used in Section 5.3.

5.4.4 Spatial distribution of extension potential

To investigate the distribution of extension potential within each city, Figure 5.7 shows the number of people that may be housed at different distances from the city centre, defined as the primary train station (as in Section 5.3.4). The number of people that may be housed within 2km wide bands are summed for this purpose, with each bar in Figure 5.7 representing the number of people housed within concentric rings around the city centre. Alternatively, Figure 5.8 shows the cumulative number of people housed at increasing distance from each city centre, using pre-banded, LSOA-level data in this case. In both cases, for consistency with Figure 5.2 and Figure 5.6, cities are plotted in order of decreasing number of properties, with this not necessarily following the same rank order as maximum distance from city centre. As with Figure 5.3 to Figure 5.6, only extensions for the generation of new dwellings (i.e. under Part 20 of the GPDO) are considered here. It should also be recalled that city boundaries are defined as travel to work areas (as in Section 5.3.2), and noted that all cities are plotted on x-axis of the same scale, despite their varied geographical extent.

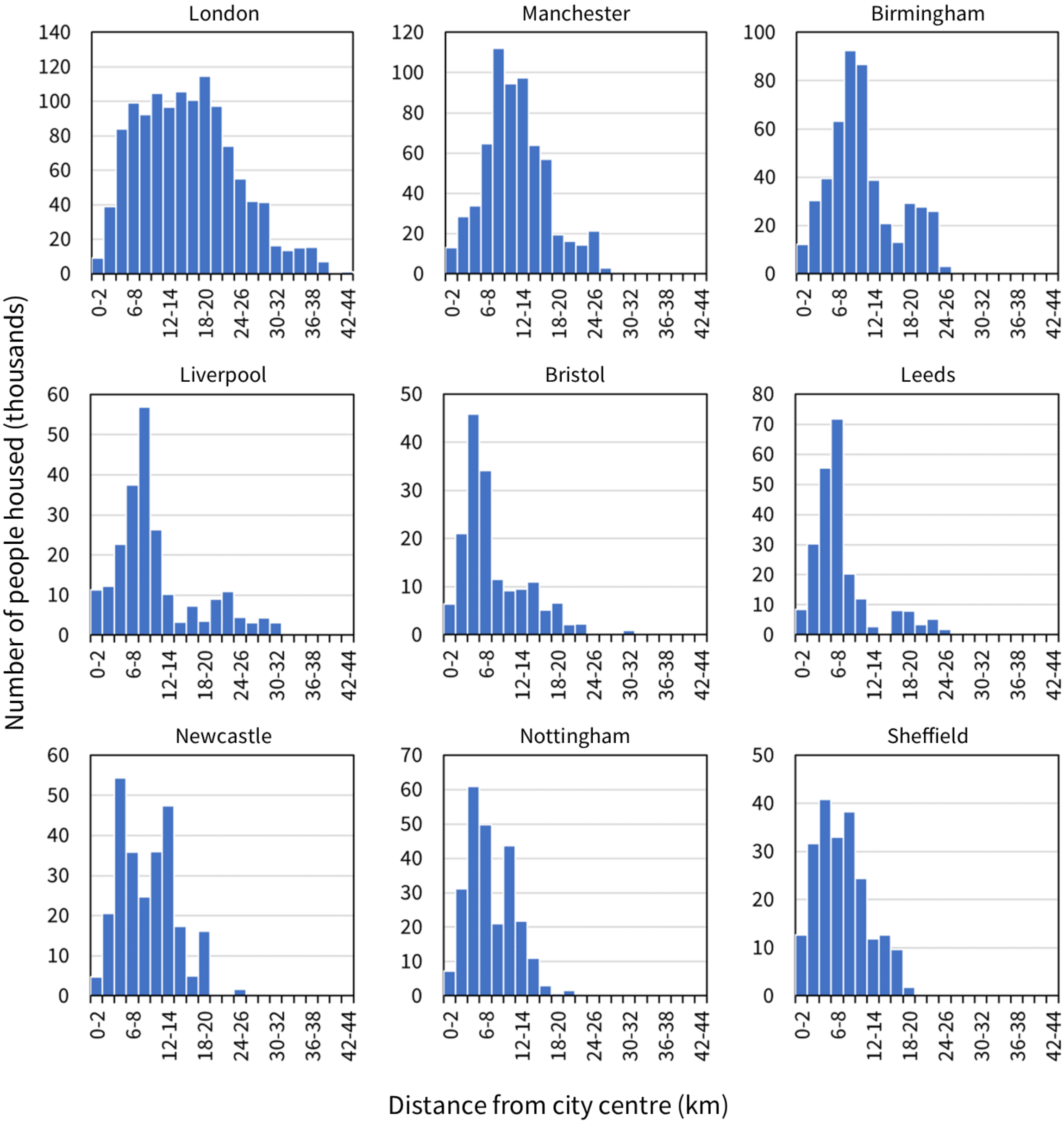

Figure 5.7 - Number of people that may be housed through PDR vertical extension at different distances from each considered city centre.

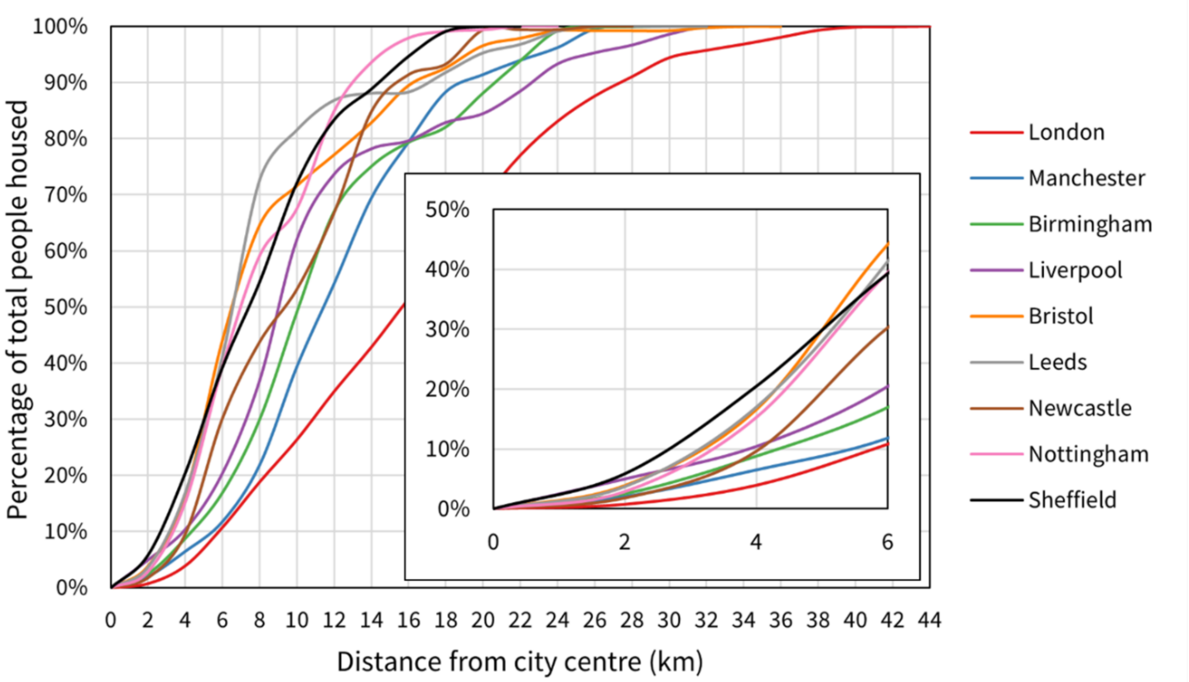

Figure 5.8 - Cumulative number of people that may be hosued through PDR vertical extension at increasing distance from each considered city centre.

Albeit to varying extents, Figure 5.7 shows extension potential within all cities to follow the same general pattern. This is characterised by an initially small number of people housed immediately adjacent to the primary train station, with housing potential then increasing to a peak value, before decreasing more gradually as the cities' extremities are neared. Contextually, this may be thought of as limited potential for housing delivery through vertical extension PDRs *within* city centres, an above average potential immediately beyond this, and gradually reducing potential in decreasingly urbanised areas at increasing distance from the city centre. In the case of Birmingham, Liverpool and Leeds there is also a secondary, yet significantly smaller, peak towards the outskirts of the city, with this perhaps representing the inclusion of smaller satellite conurbations within the considered travel to work area.

In the case of the smallest city, Sheffield, the dramatic increase in extendibility with distance is characterised by just 6% of people (12,690) being housed within 2km of the city centre, and 15% (31,708 people) within the 2-4km range (Figure 5.7 and Figure 5.8). Beyond this distance, contributions of more than 30,000 people (14%) are made by all 2km bands less than 10km from the city centre (Figure 5.7), with this initially rapid increase and elongated peak resulting in 2/3 of Sheffield's extension potential falling between 2 and 10km (Figure 5.8). This shows that, despite comparatively limited potential for housing generation within Sheffield city centre, the majority of generatable dwellings are within the city boundary.

Although extension potential within city centres is lower than in surrounding areas, this is not to say that it is insignificant, with the 12,690 people able to be housed within 2km of Sheffield city centre representing nearly 1/3 of Sheffield's 2038 housing target (Sheffield City Council, 2020).

Although over a geographical area of more than twice the size, a similarly rapid increase in extension potential is seen in the case of London. This is shown by just 1% of its housing potential (9,035 people) being within 2km of the city centre, whereas 3% (38,906 people) and 7% (83,947 people) are within 2-4km and 4-6km bands respectively (Figure 5.7 and Figure 5.8). From this point, more than 7% of housing potential is contributed by each 2km band within 22km from the city centre, resulting in almost 75% of generated housing falling between 4 and 22km. This again reveals the vast majority of housing potential to fall within existing built up areas within London travel to work area, despite extendibility surrounding the primary train station being comparatively limited.

As exemplified for the smallest and largest considered cities, the majority of potential for housing delivery is focussed beyond areas which may be assumed suitable for housing provision as a result of inherently high density, connectivity and access to services. The majority of extension potential is however within existing built up areas, meaning there is a likelihood of this being the case. From these results it may be concluded that, whilst vertical extension PDRs do serve to promote the densification of urban centres as intended, they promote increased provision within suburban areas to a greater degree, with this potentially exacerbating issues associated with suburban sprawl and increasing the number of people living within poorly connected, low-density settlements with poor access to services.

5.4.5 Limitations and Future Work

This work relies upon input data from a number of external datasets. Most notably, this includes Verisk UKBuildings, for which key property attributes (e.g. age and use) and geometries (e.g. footprint and height) are derived from aerial and ground imagery, LiDAR, as well as third party datasets including OpenStreetMap, Ordnance Survey Open Map and Energy Performance Certificates (EPCs) (Geomni, 2021). Despite this general indication of the processes through which property attributes are determined, no methodological details or associated accuracies are given. This means that, although likely to be satisfactory as a result of internal verification, the accuracy of data inputted into the assessment framework is largely unknown. To investigate the effects of potential input inaccuracy on outputs from the assessment framework, input uncertainties would first be required to be quantified, most likely necessitating an independent desk-based or fieldwork investigation. Having quantified input uncertainties, their propagation through the assessment framework may be assessed in a subsequent sensitivity analysis. As well as input datasets, the sensitivity of the assessment framework to a number of underlying assumptions should also be considered. This may include, for example, the nominal storey height of 2.7m (Section 5.3.3), the allocation of 39m^2 of floor area per person, or disparities between assumed gross area (i.e. footprints) and true net values.

Although only intended to identify the *potential* for housing delivery through permitted development vertical extensions, there is scope to expand the developed framework to consider additional influencing factors. Examples of these include reserve structural capacity, buildability and financial viability, as well as key aspects of the prior approval process (e.g. flood risk, fire safety and highways impact) (Chapter 2). By considering such factors, the expanded assessment framework may be used to derive more accurate estimations of the number of properties for which PDR extension is *feasible* or even *likely*, as well as the associated floorspace generated and equivalent number of people housed. A similar approach may also be applied to consider non-PDR extensions in terms of their potential, feasibility and likelihood of delivery, as well as alternative adaptive reuse strategies (e.g. change of use) delivered under PDRs or otherwise.

When considering the spatial distribution of extension potential, this work uses a neighbourhood's proximity to the city centre as an indicator for its suitability for housing provision in terms of connectivity and service provision. Although typically valid, as key services and transport infrastructure are concentrated within city centres, this neglects to consider the presence of intra-city public transport systems (e.g. buses and trams) and the specific location of key services (e.g. schools, hospitals and shops). Future work may therefore investigate the connectivity of, and service provision within, individual LSOAs as a means of more accurately determining their suitability for housing provision. This would facilitate more detailed consideration of the ability of PDR extensions in delivering new housing in the most suitable locations.

As a result of consideration of extension potential at the LSOA level, for which a wide range of statistics are available, there is also scope for assessment of variation in the extendibility of neighbourhoods with other socioeconomic factors. For example, the relationship between extendibility and various deprivation metrics may readily be considered, both as a means of investigating presently limited uptake and to convert identified potential for extension into those that are feasible or more likely.

5.5 Conclusions

This chapter successfully develops a bottom-up assessment framework to identify individual eligible properties, quantify their extendibility and aggregate this over multiple spatial scales. The framework has been successfully applied to estimate the quantity of housing that could *potentially* be generated under PDR vertical extensions in England's Core Cities at the property, neighbourhood and city level. Around 1/3 of considered properties are revealed to be eligible for PDR extension for both the generation of new residential units (Part 20 of the GPDO) and the enlargement of existing dwellings (Part 1 of the GPDO). Considering the inclusion of non-residential properties in the former of these cases (Part 20), this indicates more houses to be eligible for dwelling enlargement than for new unit generation, perhaps promoting enhanced space provision above increased housing supply. The effects of this are exacerbated by the fact that 94% of the 2,020,000 total properties eligible under Part 20 are existing houses (Class AC-AD), with commercial properties (Class AA-AB) and blocks of flats (Class A) making minimal contributions of 3% each. London differs from all other cities in this respect, however, with blocks of flats (Class A) making up 9% of eligible properties (47,597). Although some variation is seen between Core Cities and Parts 1 and 20 of the GPDO, the majority (~3/5) of eligible properties are extendible by a single storey, with the remaining 2/5 being split equally between those that are not extendible or extendible by the full two storeys. This results in the potential to generate 176km^2 of new useable floorspace under Part 20 of the GPDO overall, representing sufficient space to house almost 3.8 million people

Potential for housing delivery under PDR is distributed between cities with loose proportionality to their size (in terms of total numbers of buildings), resulting in the three largest cities (London, Manchester and Birmingham) contributing 64% of all deliverable dwellings. As a result of their typically larger building footprint, blocks of flats contribute 652,229 (17%) of total deliverable dwellings above just 62,018 eligible properties, perhaps representing a 'quick win' in terms of housing generation through vertical extension. Uneven spatial distribution of this typology across England may become problematic here, however, with London contributing 76% of associated dwellings.

Quantities of generated housing have also been estimated at the neighbourhood level in order to consider the intra-city distribution of extension potential. In general, city centres are revealed to have poor potential for housing generation through PDR vertical extensions, with this growing to a peak value with increasing distance from the city centre before decaying more gradually as the city's extremities are approached. In general, whilst this may not be concluded to inherently promote housing delivery in low-density suburban areas with poor service provision and/or connectivity, this may well be the case considering the significantly greater potential for PDR extension in areas of greater distance from city centres. Notwithstanding this, and despite comparatively low potential for PDR extension within city centres, the numbers of houses capable of being generated in such areas are not insignificant and may still contribute sufficiently to increased housing supply. From this it may be concluded that vertical extension PDRs possess the *potential* to contribute to increased housing supply in high density urban centres, as well as in low-density suburban settlements and that further work is required in order to assess the feasibility and/or likelihood of extensions taking place in these respective localities.

The bottom up assessment framework developed in this study is transferable to different locations, applicable at various spatial scales, and may be easily adapted to consider additional influencing factors or adjacent contexts. Potential future applications therefore include assessment of extension potential in non-UK contexts, at the national or regional level, or considering the influence of factors such as buildability and reserve structural capacity. Similarly, the developed framework may be applied to consider neighbouring adaptive reuse strategies (e.g. change of use), whether deliverable under PDR or otherwise. This inherent flexibility represents a contribution to knowledge beyond the stated aims of the study, enabling a better understanding the potential to meet future societal needs whilst transitioning to a circular economy.

6

Discussion and Conclusion

6.1 Overview

Chapter 1 outlined the significance of decarbonising the built environment in limiting global average temperature increase to 2°C. The increasing relevance of embodied carbon was also noted, as well as the ability for this to be reduced by limiting material extraction and waste generation through transition to a circular economy. From this, the resultant importance of building reuse was shown, with vertical extensions being noted as capable of facilitating this whilst also meeting the needs of a growing population. Vertical extensions' particular suitability for housing delivery was also outlined, resulting from their ability to increase residential densities within urban centres. Despite recognition of the suitability of vertical extensions, exemplified by a number of successful projects and the introduction of associated PDRs, the true potential for this construction technique remained unknown. This was noted to be because of a limited understanding of the factors influencing uptake of vertical extensions, including in terms of reserve structural capacity and planning constraints, as well how these interact to influence the ability for extensions to take place at various spatial scales. The work presented in this thesis has thus served to meet the overarching aim of ***understanding the potential for future space provision through the vertical extension of existing buildings.***

In Chapter 2, existing studies pertaining to the vertical extension of existing buildings were revealed to be limited in number and scope, representing a series of fragmented inward looking perspectives from various different communities. The small number of previous context-specific studies were found to be methodologically restricted, indicating the need for a more developed, holistic and context-centric consideration of the potential for the vertical extension of existing buildings. Various relevant works from adjacent contexts were also reviewed, including circular economy in the built environment, adaptable buildings and structural underutilisation, though the transferability of their findings remained unclear.

Assessing the relative importance of factors identified in surrounding contexts is one of a series of objectives completed in Chapter 3 to ***better understand the key factors influencing the uptake of vertical extensions, and how this may be enhanced in the future*** (RQ1). This takes the form of a sequential, explanatory mixed-methods study, comprising a survey and interviews, to: (a) assess awareness and experience of vertical extensions amongst construction sector stakeholders, (b) identify context-specific factors influencing the uptake of vertical extensions and assess the relative importance of those from surrounding contexts, and (c) understand the causes and interrelation of influencing factors and suggest recommendations to enhance uptake. From this, the key driver of vertical extension is identified as its potential to increase a building's value, with reduced environmental impacts being viewed only as a secondary benefit. Confusion regarding, and resultant difficulty justifying, the presence of reserve structural capacity in existing buildings is identified as the primary barrier to vertical extensions, contributed to by the unavailability of design information, inexperience of engineers and limited consideration of future reuse in new build design. Combined with other technical barriers, this results in technical enablers consistently being viewed as most important, although a number of important legal, economic and cultural enablers are also identified. Taking account of the relative importance of identified drivers, barriers, and enablers, a series of recommendations to enhance future uptake are posed, including the increased education of structural engineers for building reuse, adjustment of VAT rates for refurbishment projects, mandatory whole life carbon assessments and consideration of the circular economy across all stakeholder groups.

Uncertainty in Chapter 3 regarding the presence of reserve structural capacity within existing buildings echoes the variation in strengthening requirements observed in previous work (Chapter 2) and completed extension projects (Gillott, Davison, & Densley Tingley, 2022a). Although likely to be present as a result of well-documented sources of underutilisation, resultant reserve structural capacity within existing buildings is not addressed in previous work, which instead focuses on improved utilisation in new build design (Chapter 2). As such, Chapter 4 considers ***how much reserve capacity different underutilisation sources introduce in existing buildings, and how far this facilitates their extension*** (RQ2). This is achieved by considering vertical load transfer in columns through the application of a series of scenarios, each representing a single underutilisation source, to a wide variety of hypothetical steel-framed buildings. Analysing each of these combinations in terms of utilisation and reserve capacity enables Chapter 4 to meet its objectives of (a) assessing the influence of different sources of overdesign on the utilisation of columns in existing steel-framed buildings, and (b) identifying the reserve capacity associated with this in terms of a permissible load increase. Through comparison with per-storey loads for four different extension solutions, Chapter 4 was also able to (c) contextualise identified reserve capacities in terms of their potential to facilitate extension. In meeting these objectives, different amounts of reserve capacity were found to result from each source of underutilisation as well varied frame configurations. An average reserve capacity of 10% is found even in minimum-weight

Eurocode designs, with this increasing for those using superseded codes of practice; employing conservative, defensive or rationalised design processes; or assuming enhanced imposed loads. For designs using superseded British Standards, though to represent the majority of the UK's buildings stock, extension is found to be possible in up to 74% of cases.

As identified in Chapter 2, much of the work considering vertical extensions represents a series of fragmented perspectives completed in adjacent contexts. Because of this, minimal consideration of the at-scale potential for extension has been made previously, with this being overshadowed by methodological deficiencies in instances where it has taken place. For this reason, Chapter 5 considers ***how much space may be provided by residential vertical extensions, and how this is distributed at the city and national level*** (RQ3). Owing to the influence of planning constraints identified in Chapter 3, and the limited uptake of vertical extension PDRs in Chapters 2 and 3, this is carried out in the context of PDR vertical extensions for housing generation in England. In meeting the above aim, Chapter 5 satisfies its objectives of (a) developing a bottom-up assessment framework to identify properties eligible for extension and the number of storeys that may be added and (b) applying this to estimate the amount of housing that may be generated by permitted development extensions at the property, neighbourhood, city and national level. Around 1/3 of all properties are revealed to be eligible, representing the *potential* to generate 176 km^2 of new useable floorspace (equivalent to 3.75 million people), across nine major cities in England. Despite the vast majority of this potential being above existing houses, as a result of their greater number, blocks of flats are revealed to contribute 15% of generatable floor area above just 6% of eligible properties. Considering the relative ease of extending this typology, and its increased prevalence in urban centres, this may therefore represent 'quick win' on which future policy emphasis should be placed.

Chapter 5 also meets its objective to (c) apply spatial analysis methods to assess the distribution of extension potential between and within England's cities. The percentage of properties eligible for extension within cities varies between 73% and 94%, meaning that, although influenced somewhat by differing urban form, extension potential is generally distributed between cities based upon their total number of properties. Across all cities, there is typically a below-average extension potential within both the city centre and rural areas, with the ability for housing generation thus being greatest in the suburbs. Although there is still significant potential for housing delivery within city centres, this pattern suggests that PDRs are perhaps unlikely to be as effective in promoting urban densification as intended.

6.2 Contribution to knowledge

For the first time, the work contained within this thesis considers the vertical extension of existing buildings from a holistic and context-centric perspective. In doing so, a significant *potential* to meet housing needs through extension of the UK's building stock is illustrated. Whilst various barriers to this are identified, extensions are revealed to generally be technically feasible through the identification of sufficient reserve capacity in a large number of cases. To address the remaining barriers, and otherwise incentivise extension, this work also presents a series of recommendations for construction sector policy and practice as well as future research.

The primary knowledge contributions in Chapter 3 are the identification of context-specific factors influencing adoption of vertical extensions and the rating of those from relevant adjacent contexts. Beyond this, it also serves to give a measure of industry awareness of, and engagement with, vertical extensions for the first time. By identifying drivers, barriers and enablers of vertical extensions, Chapter 3 also identifies key areas for future research, with the most pertinent of these subsequently being addressed in Chapters 4 and 5.

Chapter 4 identifies the influence of a range of common design inefficiencies on column utilisation within existing buildings. This initial contribution to knowledge is advanced by the novel quantification of resultant reserve structural capacity, as well as estimation of the associated potential for vertical extension. Aside from these findings, the developed assessment framework represents a further contribution to knowledge, with this being suitable for future advancement and modification to address additional building typologies or adaptive reuse strategies.

Although previously estimated with limited accuracy for different geographic regions, Chapter 5 represents the first comprehensive, bottom-up assessment of the potential for vertical extension. Its primary knowledge contribution is thus an accurate evaluation of the potential for PDR extensions in England, with this also being completed at a higher spatial resolution than seen previously. A secondary contribution is made by the developed bottom-up methodology. For the first time, this facilitates the rapid identification of vertical extension potential over large geographical areas and at high spatial resolution, in terms of numbers of eligible properties, addable storeys, generatable floor areas and equivalent people housed. The developed assessment framework is thus suitable for future adaptation to consider additional influencing factors, including those identified in Chapter 3, as well as the potential of alternative PDRs or adaptive reuse more widely.

6.3 Industrial and policy implications

In addition to its direct contributions to knowledge, the work contained within thesis has a number of implications for both policy and industrial practice. Perhaps the most apparent of these are the explicit recommendations made in Chapter 3 to enhance uptake of vertical extensions and adaptive reuse more widely. These include (1) the enhanced education of engineers on adaptive reuse, (2) adjustment of VAT rates for refurbishments, (3) mandatory whole life carbon assessments/benchmarking and (4) industry-wide promotion of CE (e.g. through local plan requirements). Although resulting from the conducted mixed methods study, such recommendations sit within wider efforts being made by a number of industry groups, including The Joint Board of Moderators for Engineering Degree Programmes (2021), The Architects' Journal (2019), The UK Green Building Council (2021), Part Z (2022) and The Greater London Authority (2021).

Consideration of reserve structural capacity as a percentage of Eurocode-compliant design loads in Chapter 4 facilitates examination of the '10% permissible load increase' rule identified in Chapter 3. This goes some way in verifying the reliability of this current benchmark, and is thus of direct relevance to current industrial practice. By considering 12 design scenarios, Chapter 4 also offers initial indication of the potential presence of additional benchmark values for buildings designed with different known inefficiencies as identified to be required in Chapter 3. Representing the majority of the UK building stock, and having a median reserve capacity of around 20% (Chapter 4), buildings designed using superseded British Standards are perhaps most pertinent here.

Chapter 5 reveals huge disparity between the potential for vertical extension PDRs and their current uptake, highlighting current planning policy to be ineffective in promoting housing provision through vertical extensions. It is also revealed by that, despite promoting urban densification as intended, the majority of potential for PDR vertical extension falls within sub-urban areas, thus potentially promoting housing provision in low-density and poorly connected areas with minimal service provision. Vertical extension PDRs are also identified to offer greater potential for the enlargement of existing dwellings than the generation of new units, further contradicting their stated aims. Together, these three aspects highlight significant drawbacks with current PDRs for vertical extensions, with future modification (e.g. adjustment of eligibility criteria) being recommended for a more effective and targeted approach. One such modification includes a focus on detached blocks of flats, as a result of their identified potential to deliver a large amount of housing relative to their number, and increased prevalence within urban areas.

6.4 Limitations and future work

In addition to those resulting from methodological detail, as outlined within each respective chapter, it is important to appreciate limitations associated with the scope of this work, which aimed to understand the potential for future space provision through the vertical extension of existing buildings. By analysing potentially the most significant factors of reserve structural capacity and planning constraints, a substantial contribution to this has been made in terms of extensions that are technically and legally possible. Despite this, and although identified and discussed, the effects of a number of additional factors influencing the potential for space provision through vertical extension have not been evaluated. It is also the case that it is only the *potential* for vertical extensions that has been enumerated in this work, with no consideration being made of the wider feasibility or likelihood of extensions taking place.

For these reasons, future work to understanding vertical extensions should build upon the holistic and context-centric approach adopted in this thesis to consider additional factors influencing its potential, as well as those dictating extensions that are most feasible or likely to materialise. In addition to advancement of the methodologies employed in understanding structural and planning aspects, as outlined in Chapters 4 and 5 respectively, consideration of a number of factors outlined within Chapters 2, 3 and 5 will be required for this purpose. This may include the buildability and financial viability of extensions, as well as location-based factors such as service provision and socioeconomic status. Following analysis of the influence of these aspects, they may then be integrated into the existing bottom-up assessment framework to provide a more refined and realistic indication of the true potential for vertical extension.

As well as being improved to more closely consider the potential for vertical extension, the developed assessment framework may also be used to consider adjacent contexts such as change-of-use or component-level reuse. In combination, this will facilitate a more holistic assessment of the potential to meet future built environment needs whilst reducing material consumption and waste generation through transition to a circular economy.

In addition to more widely considering the ability to meet future societal needs through adaptive reuse, further work should build upon that in Chapter 3 to better understand approaches to realising the potential identified herein.

6.5 Conclusion

Vertically extending existing buildings can generate new useable floorspace whilst reducing resource extraction, waste generation and associated carbon emissions. This work advances understanding of the potential for future space provision through the vertical of existing buildings by identifying and addressing key influencing factors, including reserve structural capacity and associated planning constraints.

Through a sequential explanatory mixed methods study considering the views of a wide range of stakeholders, key drivers, barriers and enablers of vertical extension are identified and their relative influence assessed. This reveals the ability to increase the value of a building to be the primary driver, with environmental benefits being viewed simply as a secondary benefit. Technical barriers including identifying reserve capacity, working within spatial constraints, and the unavailability of design information are identified as the most inhibitive, but are thought to be rooted in the nature of the construction sector rather than indicate infeasibility. Recommendations to overcome these barriers and otherwise promote extension include increased education of engineers, adjustment of VAT tariffs, mandatory whole-life carbon assessments, and industry-wide engagement with the circular economy.

The influence of common design inefficiencies on structural utilisation within existing buildings has been assessed through the application of 12 different scenarios to a range of hypothetical multi-storey steel frames. Column utilisation is found to vary greatly depending upon the design and appraisal process used, with the highest median value for a least-weight Eurocode-compliant design being just 0.91. This suggests an average reserve capacity in existing Eurocode-compliant buildings of at least 10%, with those designed to superseded codes of practice or using conservative or defensive approaches giving permissible load increases of up to 1/3. In terms of potential for extension, even least-weight Eurocode designs may be extended without the requirement for strengthening in 9%–36% of cases, depending upon structural form and use.

To estimate the potential for vertical extension beyond the single-building scale, a bottom-up assessment framework has been developed. This identifies the extendibility of individual buildings, before aggregating this to various spatial scales (e.g. neighbourhoods, cities and nations) for subsequent analysis. The developed framework has been applied to identify over 2 million properties eligible for PDR extension in nine major cities in England, with this being capable of generating 176km^2 of new useable floorspace to house almost 3.8 million people. Enabled by the framework's high spatial resolution, the distribution of extension potential within and between the considered cities has also been assessed. This reveals extension potential to be somewhat proportional to the total number of properties within a given city, and that extension potential within suburbs is greater than in city centres or more rural areas.

Together, this work offers the first holistic and context-centric perspective of the vertical extension of existing buildings. It illustrates a significant potential to meet housing needs through PDR vertical extensions and that, although a number of technical and non-technical barriers remain, reserve structural capacity is likely to be present within a large number of buildings.

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A1

Survey Questions

Survey Flow

1. Participant Information and Consent (2 Questions)
2. Participant Details (4 Questions)
3. Standard: Awareness/Definition (3 Questions)

If: *"Are you aware of the vertical extension of existing buildings as a method of construction?": 'Yes' = selected*

and *"To which stakeholder group do you belong?": 'Research and Development (industry based)' = not selected*

and *"To which stakeholder group do you belong?": 'Research (academia)' = not selected*

- Participant Experiences (13 Questions)

4. Financial/Economic (6 Questions)
5. Legislation, Policy and Assessment (4 Questions)
6. Sectoral/Cultural (4 Questions)
7. Technical and Informational (5 Questions)
8. Additional Comments (1 Question)
9. Future Correspondence (1 Question)

Survey Questions

Start of Block: Participant Information and Consent

The Vertical Extension of Existing Buildings

This survey has been constructed and published by the Department of Civil and Structural Engineering (CSE) at The University of Sheffield.

To ensure confidentiality, all responses are collected, stored and analysed anonymously except where a participant elects to provide an email address at which to be contacted regarding future research. In this case, only the primary researcher will have access to this information which is to be used for this purpose only.

With the exception of instances where free text responses are quoted directly, survey responses will be aggregated in any resulting publications. In all cases the personal information of participants (e.g. name and email address) will remain undisclosed to ensure anonymity.

By clicking **'I agree'** you are consenting to the responses submitted in this form being used by the University of Sheffield's Department of CSE as per the above conditions (clicking 'I disagree' will result in the termination of this survey response).

This also acknowledges that you understand that taking part in this survey is voluntary, and that you may request the withdrawal of your responses within two weeks of their submission.

○ I agree (1)

○ I disagree (2)

Skip To: End of Survey If "By clicking 'I agree' you are consenting to the responses submitted in this form being used by the University of Sheffield's Department of CSE as per the above conditions (clicking 'I disagree' will result in the termination of this survey response" = I disagree

End of Block: Participant Information and Consent

Start of Block: Participant Details

What is your current job title?

____

To which stakeholder group do you belong? (select one)

○ Local Planning/Development (11)

○ Client (1)

○ Project Management (2)

○ Sustainability Consultant (3)

○ Architect (4)

○ Structural Engineer (5)

○ Mechanical and Electrical Engineer (6)

○ Contractor (7)

○ Subcontractor (8)

○ Quantity Surveyor (9)

○ Research and Development (industry based) (10)

○ Research (academia) (13)

○ Other (please specify) (12) ____

How long have you worked within the construction sector?

○ Less than 5 years (1)

○ 5-9 years (2)

○ 10-19 years (3)

○ 20-50 years (4)

○ More than 50 years (5)

Approximately how many staff does your company employ?

○ Less than 10 (1)

○ 10-49 (2)

○ 50-249 (3)

○ More than 250 (4)

End of Block: Participant Details

Start of Block: Awareness/Definition

Are you aware of the vertical extension of existing buildings as a method of construction?

○ Yes (1)

○ No (2)

Display This Question:

If "Are you aware of the vertical extension of existing buildings as a method of construction?" = No

The vertical extension of existing buildings refers to the process of adding additional storeys to an existing structure in order to yield new usable floorspace.

Display This Question:

If "Are you aware of the vertical extension of existing buildings as a method of construction"?" = Yes

What do you believe is meant by the term 'vertical extension of existing buildings'?

____

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End of Block: Awareness/Definition

Start of Block: Participant Experiences

Of the projects you have been involved in, how many times has vertical extension been considered as a preliminary design option?

○ Don't know (0)

○ 0 (0)

○ 1 (1)

○ 2 (2)

○ 3 (3)

○ 4 (4)

○ 5 (5)

○ More than 5 (6)

Display This Question:

If "Of the projects you have been involved in, how many times has vertical extension been considered..." = 0

Please summarise the reasons why vertical extension has never been considered as a preliminary design option on projects you have been involved in.

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Display This Question:

If "Of the projects you have been involved in, how many times has vertical extension been considered..." = 1

Or "Of the projects you have been involved in, how many times has vertical extension been considered..." = 2

Or "Of the projects you have been involved in, how many times has vertical extension been considered..." = 3

Or "Of the projects you have been involved in, how many times has vertical extension been considered..." = 4

Or "Of the projects you have been involved in, how many times has vertical extension been considered..." = 5

Or "Of the projects you have been involved in, how many times has vertical extension..." = More than 5

Please summarise the reasons why vertical extension was considered as a preliminary design option on these projects.

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Display This Question:

If “Of the projects you have been involved in, how many times has vertical extension been considered...” != 0

Of the projects you have been involved in, how many times has vertical extension been implemented as the preferred solution?

○ Don't know (0)

○ 0 (0)

○ 1 (1)

○ 2 (2)

○ 3 (3)

○ 4 (4)

○ 5 (5)

○ More than 5 (6)

Display This Question:

If “Of the projects you have been involved in, how many times has vertical extension been...” = 1

Or “Of the projects you have been involved in, how many times has vertical extension been...” = 2

Or “Of the projects you have been involved in, how many times has vertical extension been...” = 3

Or “Of the projects you have been involved in, how many times has vertical extension been...” = 4

Or “Of the projects you have been involved in, how many times has vertical extension been...” = 5

Or “Of the projects you have been involved in, how many times has vertical extension been...” = More than 5

Please summarise the reasons why vertical extension was selected in preference of alternative options on these projects.

____

Display This Question:

If "Of the projects you have been involved in, how many times has vertical extension been..." = 0

And "Of the projects you have been involved in, how many times has vertical extension..." = More than 5

Of the projects you have been involved in where vertical extension was considered as a preliminary design option, why has this never been implemented as the preferred solution?

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Display This Question:

If "Of the projects you have been involved in, how many times has vertical extension been..." = 0

And "Of the projects you have been involved in, how many times has vertical extension been..." = 1

Or If

"Of the projects you have been involved in, how many times has vertical extension been..." = 0

And "Of the projects you have been involved in, how many times has vertical extension been..." = 2

Or If

"Of the projects you have been involved in, how many times has vertical extension been..." = 0

And "Of the projects you have been involved in, how many times has vertical extension been..." = 3

Or If

"Of the projects you have been involved in, how many times has vertical extension been..." = 0

And "Of the projects you have been involved in, how many times has vertical extension been..." = 4

Or If

"Of the projects you have been involved in, how many times has vertical extension been..." = 0

And "Of the projects you have been involved in, how many times has vertical extension been..." = 5

Of the {PIPED NUMBER} projects you have been involved in where vertical extension was considered as a preliminary design option, why has this never been implemented as the preferred solution?

____
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____

Display This Question:

If "Of the projects you have been involved in, how many times has vertical extension been..."= 5
And "Of the projects you have been involved in, how many times has vertical extension been..."= 4
Or "Of the projects you have been involved in, how many times has vertical extension been..." = 5
And "Of the projects you have been involved in, how many times has vertical extension been..."= 3
Or "Of the projects you have been involved in, how many times has vertical extension been..." = 5
And "Of the projects you have been involved in, how many times has vertical extension been..." = 2
Or "Of the projects you have been involved in, how many times has vertical extension been..." = 5
And "Of the projects you have been involved in, how many times has vertical extension been..."= 1

Or If

"Of the projects you have been involved in, how many times has vertical extension been..."= 4
And "Of the projects you have been involved in, how many times has vertical extension been..." = 3
Or "Of the projects you have been involved in, how many times has vertical extension been...". = 4
And "Of the projects you have been involved in, how many times has vertical extension been..."= 2
Or "Of the projects you have been involved in, how many times has vertical extension been..." = 4
And "Of the projects you have been involved in, how many times has vertical extension been..."= 1

Or If

"Of the projects you have been involved in, how many times has vertical extension been..." = 3
And "Of the projects you have been involved in, how many times has vertical extension been..."= 2
Or "Of the projects you have been involved in, how many times has vertical extension been..."= 3
And "Of the projects you have been involved in, how many times has vertical extension been..." = 1

Or If

"Of the projects you have been involved in, how many times has vertical extension been..."= 2
And "Of the projects you have been involved in, how many times has vertical extension been..."= 1

Of the {PIPED NUMBER} projects you have been involved in where vertical extension was considered as a preliminary design option, why was this only implemented as the preferred solution in {PIPED NUMBER} cases?

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Display This Question:

If "Of the projects you have been involved in, how many times has vertical extension been..." = More than 5

And "Of the projects you have been involved in, how many times has vertical extension been..."= 5

Or "Of the projects you have been involved in, how many times has vertical extension been..." = More than 5

And "Of the projects you have been involved in, how many times has vertical extension been..." = 4

Or "Of the projects you have been involved in, how many times has vertical extension been..." = More than 5

And "Of the projects you have been involved in, how many times has vertical extension been..."= 3

Or "Of the projects you have been involved in, how many times has vertical extension been..." = More than 5

And "Of the projects you have been involved in, how many times has vertical extension been..." = 2

Or "Of the projects you have been involved in, how many times has vertical extension been..."= More than 5

And "Of the projects you have been involved in, how many times has vertical extension been..." = 1

Of the projects you have been involved in where vertical extension was considered as a preliminary design option, why was this only implemented as the preferred solution in {PIPED NUMBER} cases?

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Display This Question:

If "Of the projects you have been involved in, how many times has vertical extension been..."= 1

And "Of the projects you have been involved in, how many times has vertical extension been..."= 1

Or If

"Of the projects you have been involved in, how many times has vertical extension been..."= Don't know

And "Of the projects you have been involved in, how many times has vertical extension been..."= 1

Or If

"Of the projects you have been involved in, how many times has vertical extension been..."= 1

And "Of the projects you have been involved in, how many times has vertical extension been..."= Don't know

How would you rate your experience working on a vertical extension project?

○ Extremely negative (1)

○ Somewhat negative (2)

○ Neither positive nor negative (3)

○ Somewhat positive (4)

○ Extremely positive (5)

Display This Question:

If "Of the projects you have been involved in, how many times has vertical extension been..."= 2

Or "Of the projects you have been involved in, how many times has vertical extension been..." = 3

Or "Of the projects you have been involved in, how many times has vertical extension been..." = 4

Or "Of the projects you have been involved in, how many times has vertical extension been..."= 5

Or "Of the projects you have been involved in, how many times has vertical extension been..."= More than 5

Or "Of the projects you have been involved in, how many times has vertical extension been..." = 2

Or "Of the projects you have been involved in, how many times has vertical extension been..."= 3

Or "Of the projects you have been involved in, how many times has vertical extension been..."= 4

Or "Of the projects you have been involved in, how many times has vertical extension been..."= 5

Or "Of the projects you have been involved in, how many times has vertical extension been..."= More than 5

How would you rate your experience working on vertical extension projects?

○ Extremely negative (1)

○ Somewhat negative (2)

○ Neither positive nor negative (3)

○ Somewhat positive (4)

○ Extremely positive (5)

Display This Question:

If "Of the projects you have been involved in, how many times has vertical extension been..."= 1

Or "Of the projects you have been involved in, how many times has vertical extension been..."= 2

Or "Of the projects you have been involved in, how many times has vertical extension been..."= 3

Or "Of the projects you have been involved in, how many times has vertical extension been..."= 4

Or "Of the projects you have been involved in, how many times has vertical extension been..."= 5

Or "Of the projects you have been involved in, how many times has vertical extension been..."= More than 5

Or "Of the projects you have been involved in, how many times has vertical extension been..."= 1

Or "Of the projects you have been involved in, how many times has vertical extension been..."= 2

Or "Of the projects you have been involved in, how many times has vertical extension been..."= 3

Or "Of the projects you have been involved in, how many times has vertical extension been..."= 4

Or "Of the projects you have been involved in, how many times has vertical extension been..."= 5

Or "Of the projects you have been involved in, how many times has vertical extension been...". = More than 5

Do you wish to take part in a vertical extension project again?

○ Yes (1)

○ No (2)

Display This Question:

If "Of the projects you have been involved in, how many times has vertical extension been..." = 0

And "Of the projects you have been involved in, how many times has vertical extension been..." = 0

Or "Of the projects you have been involved in, how many times has vertical extension been..."Don't know

And "Of the projects you have been involved in, how many times has vertical extension been..."= Don't know

Or "Of the projects you have been involved in, how many times has vertical extension been..." = Don't know

And "Of the projects you have been involved in, how many times has vertical extension been..."= 0

Or "Of the projects you have been involved in, how many times has vertical extension been..."= 0

And "Of the projects you have been involved in, how many times has vertical extension been..." = Don't know

Given the opportunity, would you wish to take part in a vertical extension project?

○ Yes (1)

○ No (2)

End of Block: Participant Experiences

Start of Block: Financial/Economic

How do you perceive the **design** costs of a vertical extension scheme in comparison with a new-build project of the same usable floor area?

○ Significantly lower (1)

○ Lower (2)

○ The same (3)

○ Higher (4)

○ Significantly higher (5)

How do you perceive the **construction** costs of a vertical extension scheme in comparison with a new-build project of the same usable floor area?

○ Significantly lower (1)

○ Lower (2)

○ The same (3)

○ Higher (4)

○ Significantly higher (5)

How do you perceive the **material** costs of a vertical extension scheme in comparison with a new-build project of the same usable floor area?

○ Significantly lower (1)

○ Lower (2)

○ The same (3)

○ Higher (4)

○ Significantly higher (5)

How do you believe **total** project costs influence the adoption of vertical extension at present?

○ Significant barrier (1)

○ Barrier (2)

○ No influence (3)

○ Enabler (4)

○ Significant enabler (5)

How important do you believe the following are in increasing the uptake of vertical extensions?

	Not at all important (1)	Slightly important (2)	Of average importance (3)	Very important (4)	Extremely important (5)
Financial incentives (e.g. tax exemption for renovation projects/levies for new-build projects) (1)	○	○	○	○	○
Financial support from national/local government (2)	○	○	○	○	○
Vertical extension-specific insurance policies (7)	○	○	○	○	○
Other (please specify) (8)	○	○	○	○	○

Please provide additional information and justifications for your responses to this section of the survey here.

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End of Block: Financial/Economic

Start of Block: Legislation, Policy and Assessment

How do you believe current government policy and legislation influences the adoption of vertical extension?

○ Significant barrier (1)

○ Barrier (2)

○ No influence (3)

○ Enabler (4)

○ Significant enabler (5)

How do you believe current local planning policy influences the adoption of vertical extension?

○ Significant barrier (1)

○ Barrier (2)

○ No influence (3)

○ Enabler (4)

○ Significant enabler (5)

How important do you believe the following are in increasing the uptake of vertical extension?

	Not at all important (1)	Slightly important (2)	Of average importance (3)	Very important (4)	Extremely important (5)
Legislative change (permitted development style planning waiver) (3)	○	○	○	○	○
Relaxation of planning requirements (7)	○	○	○	○	○
Mandatory whole-life environmental impact assessments (1)	○	○	○	○	○
Greater acknowledgement/reward of vertical extension in assessment/certification schemes (e.g. BREEAM, LEED, regenerate) (2)	○	○	○	○	○
Other (please specify) (8)	○	○	○	○	○

Please provide additional information and justifications for your responses to this section of the survey here.

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End of Block: Legislation, Policy and Assessment

Start of Block: Sectoral/Cultural

How do you believe the nature of the construction sector as a whole influences the uptake of vertical extension?

○ Significant barrier (1)

○ Barrier (2)

○ No influence (3)

○ Enabler (4)

○ Significant enabler (5)

How do you believe the company culture of your current employer influences the uptake of vertical extension?

○ Significant barrier (1)

○ Barrier (2)

○ No influence (3)

○ Enabler (4)

○ Significant enabler (5)

How important do you believe the following are in increasing the uptake of vertical extension?

	Not at all important (1)	Slightly important (2)	Of average importance (3)	Very important (4)	Extremely important (5)
Experiences of colleagues (1)	○	○	○	○	○
Corporate social responsibility of employers (8)	○	○	○	○	○
Personal moral obligation of employees (7)	○	○	○	○	○
Long term partnerships/collaborations between planning departments, developers and consultants/contractors (2)	○	○	○	○	○
Education/training on environmental considerations within the construction industry (3)	○	○	○	○	○
Awareness raising campaigns/promotion to the general public (4)	○	○	○	○	○
Other (please specify) (10)	○	○	○	○	○

Please provide additional information and justifications for your responses to this section of the survey here.

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End of Block: Sectoral/Cultural

Start of Block: Technical and Informational

Do you believe engineers are suitably equipped to **design** for vertical extension projects at present?

○ Yes (30)

○ No (31)

Do you believe contractors/subcontractors are suitably equipped to **deliver** vertical extension projects at present?

○ Yes (30)

○ No (31)

Do you believe the **technologies, products and systems** required by vertical extension projects are available at present?

○ Yes (30)

○ No (31)

How important do you believe the following are in increasing the uptake of vertical extension?

	Not at all important (1)	Slightly important (2)	Of average importance (3)	Very important (4)	Extremely important (5)
Design tools, guidance, and training (9)	○	○	○	○	○
Development of standard solutions and details (3)	○	○	○	○	○
Contractor/subcontractor/operative training (1)	○	○	○	○	○
Information/data regarding structural performance (2)	○	○	○	○	○
Demonstration projects and case studies (4)	○	○	○	○	○
Data and tools to assess material, energy and waste benefits (7)	○	○	○	○	○
Consideration of future extension in new-build projects (11)	○	○	○	○	○
Other (please specify) (12)	○	○	○	○	○

Please provide additional information and justifications for your responses to this section of the survey here.

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End of Block: Technical and Informational

Start of Block: Additional Comments

Thank you for taking part in this survey.

If you have any additional comments that you feel have not been adequately addressed, please provide these here.

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End of Block: Additional Comments

Start of Block: Future Correspondence

It may be the case that further investigation of the themes uncovered by this survey is required as part of this research. If you would be willing to participate in subsequent surveys, interviews or focus groups please provide your contact details below. If you do not wish to be contacted, please skip to the next question.

(please note: these details will be used for contact purposes only and the personal information of participants will remain undisclosed in all publications)

○ Name (1) ____

○ Email Address (2) ____

End of Block: Future Correspondence

A2

Interview Question Guide

Interview Question Guide

Housekeeping/Introduction

- Thank you for agreeing to take part in this interview regarding the vertical extension of existing buildings today. I want to take this opportunity to remind you that you have previously provided consent for (select those that apply):
    - *Audio to be recorded during this interview.*
    - *Audio and video to be recorded during this interview.*
    - *You also indicated that a 3rd party automated service may be used to be used to transcribe this recording.*
- Please adjust your video settings to reflect this, and I will begin recording the session.
- This interview is being used for the purposes outlined in the participant information sheet only, and all the information you share today will remain anonymous in any resulting publications.
- There are no right/wrong answers to any question, and the aim of this interview is to uncover your personal viewpoint regarding the themes explored.
- You do not need prior knowledge or experience of the themes explored, and where this is the case, you are encouraged to provide insights regarding your perception of these
- The interview is expected to finish before HH:MM, but you may stop the interview whenever you wish by indicating this to me.
- Are there any questions before we start?

Demographics (only if not answered survey)

- Stakeholder group
- Job title
- Company size
- Years in industry

Definition, Drivers and Benefits

- What does vertical extension mean to you?
- Why do you think vertical extension is something that people are interested in doing?
- Benefits (l*ower embodied carbon, reduced material usage, no demolition)*
    - *How?*
    - *Why?*
    - *What?*
    - *Who?*
- Drivers (*lack of space, generation of new space, increase in density, existing building occupied)*
    - *How?*
    - *Why?*
    - *What?*
    - *Who?*

Barriers and Enablers

- Thinking about the construction industry as a whole, what do you think are the main (3?) barriers to the adoption of vertical extension?
- How does this act as a barrier?
- Why is this barrier more important than others?
- Who or what is creating this barrier? *(specific stakeholder, internal to the company, industry-wide, policy driven)*
- What are the options for overcoming this barrier?
  - *Finance*
  - *Legislation*
  - *Clear industry guidance*
  - *Economies of scale*
  - *Demonstration of feasibility*
- In your opinion, what is the most effective of these options?
- Which types of buildings/projects do you think might be best/worst suited to vertical extension?
  - *Structural forms*
  - *Typologies*
  - *Uses*
  - *Locations*
  - *Ages*

Personal Experience

- What is your past involvement in vertical extension projects?
  - If no involvement: why do you think you have never been involved in a vertical extension project?
- Of the projects you have been involved in, how many were at preliminary design stages and how many were carried through to completion?
- Of those that lost out - what was selected in place of vertical extension and why?
- Of those that didn't - why was vertical extension selected in place of alternatives?
- Which of these projects do you think you learnt most from?
- Could you give an overview of the project? (*Total budget, location, building type, date.)*
- What was your role in the project? (*Construction manager, Structural engineer etc.)*
- How many storeys was the exiting building and how many were added?
- What was the key driver/motivation for the use of vertical extension?
- How was the ability of the existing structure to resist the new loads determined/verified? (*full analysis, rule of thumb etc.*)
- What level of structural intervention (if any) was required?
- Did you encounter any issues during the design/delivery of the scheme?
- Overall, what was your experience of carrying out a vertical extension? (*Prompt: was it easy? Hard? Well-received? How did you work with other stakeholders to deliver this? Were there any barriers? How were they overcome?)*
- Were any of the barriers discussed earlier encountered in this project?
- Are there any lessons you learnt from this experience carrying out a vertical extension scheme?
- Are there any other projects you have learnt a lot from?

Stakeholder Groups

- Which stakeholder groups do you believe act as the most significant barrier to vertical extension?
  - Why?
  - How?
- Which stakeholder groups do you believe play the most significant role in enabling vertical extension?
  - Why?
  - How?
- What do you believe *STAKEHOLDER GROUP OF INTERVIEWEE* can do to enable or promote vertical extension going forward?
- Which stakeholder group(s) do you believe hold the most responsibility for promoting low carbon techniques such as vertical extension?

Uncertainty

- A recurring theme from existing work is the uncertainty and project-to-project variability of vertical extensions – do you see this is as a significant barrier?
- What could be done to overcome this barrier (*e.g reduce the variability OR overcome the variability*)

Permitted Development Rights

- Are you aware of the recent changes made to permitted development rights?
- What do they mean for vertical extension?
- Do you think this will serve to significantly promote vertical extensions?
- What else could be done to promote the adoption of vertical extensions?

Closing Remarks

- Is there anything else you would like to add/any insights you would like to share with us regarding the vertical extension of existing buildings?
- Contact me for questions/comments.
- Finally, would you be happy for us to contact you in the future with short follow-up questions if necessary?
- Thank you and goodbye.

Notes

Additional Probing Phrases

- Can you give me an example of that?
- Is this something you’ve experienced first-hand?

Tips

- Ask one question at a time no ‘and’
- Write down new questions that arise - don’t interject
- Ask follow up questions

A3

Underutilisation and Reserve Capacity Assessment Parameters

Assessment Parameters

Scenario No.	Design Approach	Reappraisal Approach	Permanent Load (kN)	Imposed Load (kN)	Permanent Load Partial Factor	Imposed Load Partial Factor	Permanent Load Reduction Factors	Imposed Load Combination Factor	Target UR	Material Strength (MPa)
1	BS449 (least weight)	Eurocode compliant	3.7-3.9	3.5	1.40	1.60	0	0	NA	355
2	BS5950 (least weight)		3.7-3.9	3.5	1.40	1.60	0	0	1.0	355
3	Eurocode (least weight)		3.7-3.9	3.3	1.35	1.50	0.925	0.7	1.0	355
4	Eurocode (no reduction factors (ξ, ψ))		3.7-3.9	3.3	1.35	1.50	0	0	1.0	355
5	Eurocode (no reduction factors (α_a, α_n))		3.7-3.9	3.3	1.35	1.50	0.925	0.7	1.0	355
6	Eurocode (defensive)		3.7-3.9	3.3	1.35	1.50	0.925	0.7	0.80	355
7	Eurocode (rationalised)		3.7-3.9	3.3	1.35	1.50	0.925	0.7	0.49	355
8	Eurocode (overspecified imposed loads)		3.7-3.9	4.63	1.35	1.50	0.925	0.7	1.0	355
9	Eurocode compliant (least weight)	Eurocode (experienced imposed loads)	3.7-3.9	0.5	1.35	1.50	0.925	0.7	1.0	355
10		Eurocode (residential imposed loads)	3.7-3.9	2.0	1.35	1.50	0.925	0.7	1.0	355
11		Eurocode (average material strength)	3.7-3.9	3.3	1.35	1.50	0.925	0.7	1.0	402
12		Eurocode (reduced partial factors (γ))	3.7-3.9	3.3	1.10	1.50	0	0	1.0	355

A4

The Potential of Vertical Extensions: A Case Study Analysis (Conference Paper)

This appendix contains a reproduction of the following work, as accepted for publication and currently in print:

Gillott, C., Davison, B. and Densley Tingley, D. (2022). The Potential of Vertical Extensions: A Case Study Analysis. *IOP Conference Series: Earth and Environmental Science*.

The Potential of Vertical Extensions: A Case Study Analysis

Charles GILLOTT, Buick DAVISON, Danielle DENSLEY TINGLEY,

Abstract

There is a global imperative to reduce greenhouse gas emissions as a means of mitigating climate change. Buildings are responsible for almost 40% of carbon emissions, exemplifying the importance of decarbonising the built environment to limit global temperature increase. As a result of the increasing awareness of the importance of embodied carbon, transition towards a circular economy within the construction sector is key in its decarbonisation The adaptive re-use of existing buildings has a significant role to play through reduced material consumption and waste generation and prolonged building lifespans. One adaptive reuse strategy, the vertical extension of existing buildings, serves to achieve this whilst meeting growing demand for space within already dense cities. This paper reviews seven instances of vertical extension in the UK and Ireland, exploring the specific motivations for, and technical details of, each. These are compared to reveal the suitability of vertical extension to a range of building archetypes, and the case-by-case variability with which both structural appraisal and remediation are required.

Keywords: adaptation, reuse, circular economy, embodied, whole-life, carbon, vertical extension

Introduction

Decarbonisation of the Construction Sector

In 2015, attendees of the United Nations Framework Convention on Climate Change signed the Paris agreement. This outlines “aims to strengthen the global response to the threat of climate change”, including “holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C” [1]. In 2020 the UK responded to this in their Nationally Determined Contribution by “committing to reduce economy-wide greenhouse gas emissions by at least 68% by 2030, compared to 1990 levels” [2].

With buildings alone being responsible for 38% of global carbon emissions [3], decarbonisation of the built environment represents a significant challenge that must be addressed. In the UK this is recognised by numerous declarations of climate emergency from within the sector, including those by architects, designers, engineers, project managers, surveyors, developers, contractors, suppliers, students and academics [4]. The importance of decarbonising the built environment is also noted by the UK government's "Ten Point Plan for a Green Industrial Revolution" [5].

Embodied Carbon and the Circular Economy

Although historically overlooked in prioritisation of operational carbon emissions, considering the carbon embodied within the built environment is becoming increasingly important. This refers to emissions during the extraction of materials and manufacture of components; transportation and construction processes; and end of life phases. Embodied carbon is known to contribute 11% of the whole-life carbon of buildings [6], with this value expected to increase with time in line with improvements in operational performance and decarbonisation of the electricity grid. Reductions in embodied carbon also allow significant *upfront* savings to be made before a building's occupation (whereas operational benefits must be accrued over a building's lifespan), consistent with the urgency with which the sector must decarbonise.

As embodied carbon depends upon material extraction and waste generation, strategies to reduce this are consistent with those to transition towards a circular economy. This moves away from a linear model of consumption in which resources are extracted, manufactured, used and discarded, to one where focus is placed on retaining materials within the technosphere for as long as possible, and at their highest possible value. As explained by Bocken et al., this includes strategies that: slow resource flows through the design of long-life goods and product life extension; narrow resource flows through more efficient design; and close resource flows through reuse and recycling [7].

As a result of the growing emphasis on transitioning towards a circular economy in the built environment, different strategies to achieve this have been suggested by various organisations. These generally consider adaptability, design for deconstruction, circular material selection and resource efficiency, with building lifespan extension also being prioritised in some cases [8].

Adaptive Reuse and Vertical Extension

One approach to building lifespan extension is adaptive reuse, which serves to slow resource flows and ensure a maximum amount of material is retained in the built environment at its highest possible level. Adaptive reuse refers to the modification of existing buildings to meet new needs and mitigates sources of embodied carbon by reducing material extraction; component manufacture; transportation and construction processes; and waste generation. The benefits of adaptive reuse in achieving a circular economy and decarbonising the construction sector are increasingly being recognised by industry such as in the Architects Journal's 'RetroFirst' campaign. This aims to "prioritise retrofit over demolition and rebuild" [9] and has been signed by more than 200 organisations.

Whilst specific use requirements of buildings may vary with time (as seen with decreased requirement for office space following the COVID-19 pandemic), net demand for useable floorspace is expected to increase, in line with a growing population. Within cities this increase in demand is expected to be more extreme, with the percentage of the global population living within urban areas predicted to rise from 55% in 2018 to 68% in 2050 [10].

The vertical extension of existing buildings therefore represents an adaptive reuse strategy in which required additional space may be generated simultaneously with decarbonisation of the construction sector. Additional benefits associated with vertical extension include the increase in density this facilitates, and its ability to create mixed-use spaces. Both of these aspects are known to be conducive to a sustainable urban form.

Vertical Extension Case Studies

Seven instances of vertical extension in the UK and Ireland have been reviewed, focussing on specific motivations for, and technical details of, each project. This explores the key drivers of vertical extension for a range of design scenarios and building archetypes, as well as the degree of structural appraisal and remediation required in each instance. A summary of each of the case studies, outlining key details, may be seen in Table 1. Unless otherwise stated, all information contained within each case study is derived from the corresponding source in Table 1, or through informal exchanges with relevant parties.

Overview of considered case studies, showing key details of each.

Building Name	Location	Original No. of Storeys	Storeys Added	Original Use	New Use	Existing Form	Extended Form
Southbank Tower [11]	Southwark, London	31	11	Office	Residential	Concrete frame	Steel frame & concrete core
Crown House [12]	Sheffield	6	3	Office	Residential	Steel frame	Steel frame
Lister Mill [13]	Bradford	5	1	Mill	Residential	Masonry, cast iron & concrete	Prefabricated timber & steel
Arnold House [14]	Shoreditch, London	4	3	Office	Office, retail	Concrete frame	Steel frame
The Department Store [15]	Brixton, London	3	1	Retail	Office, retail	Masonry	Oak frame
1 Triton Square [16]	Camden, London	5	3	Office	Office, retail, gym	Concrete frame	Steel frame
Clerys Department Store [17]	Dublin	4	3	Retail	Retail, office, restaurant	Concrete frame	Steel frame

Southbank Tower

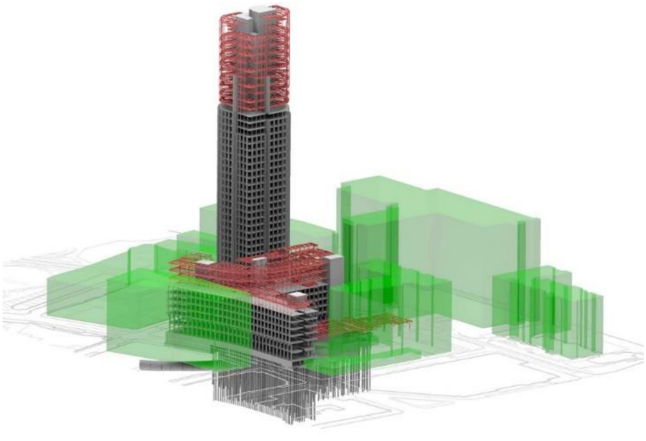

Figure 1 - 3D model of the Southbank Tower extension, showing the original structure (grey), additional steelwork (red) and surrounding buildings (green). (© AKT II)

As part of a wider refurbishment and office-to-residential conversion, 11 storeys were added to this 1970's reinforced concrete (RC) tower. Utilising reserve capacity in the existing concrete core, this has been extended, and a steel frame cantilevered from this using steel tension hangers (Fig. 1). As a result of consolidation of the founding clay, loads experienced by the structure's piled foundations were permissibly increased by up to 25%, negating the requirement for their strengthening.

To ensure occupant comfort despite the 1/3 increase in height, Computational Fluid Dynamic (CFD) analysis of the extend structure was carried out. This resulted in the linkage of the tower and surrounding podium structures (Fig. 1) as a means of resisting increased wind loads. Three additional storeys were added to these structures themselves, generating additional office and roof garden space [18].

Crown House

Figure 2 - Rendered image of the completed office-to-residential conversion, lateral (rear) and vertical (front) extension of Crown House, Sheffield. (© RG Group).

As part of an office-to-residential conversion and wider redevelopment, this steel framed building has been extended by three storeys to generate 181 student properties. A further 172 beds have been contributed by two new build blocks of eight and nine storeys (Fig. 2).

To allow for this, reserve capacity resulting from the less onerous design load associated with the change of use was utilised. This supplemented by removal of the existing upper floor and inefficiencies in the original design. Renovation and refurbishment of the existing structure was also required, including the steel frame and internal fit out [19]. The existing steel frame was extended vertically, following the same grid as the existing building [20].

Owing to time constraints associated with the annual rental period for student properties [19], and the sites proximity to a major transport route [20] (Fig. 2), the scheme was required to move from planning to construction stages in just 13 weeks.

Lister Mills

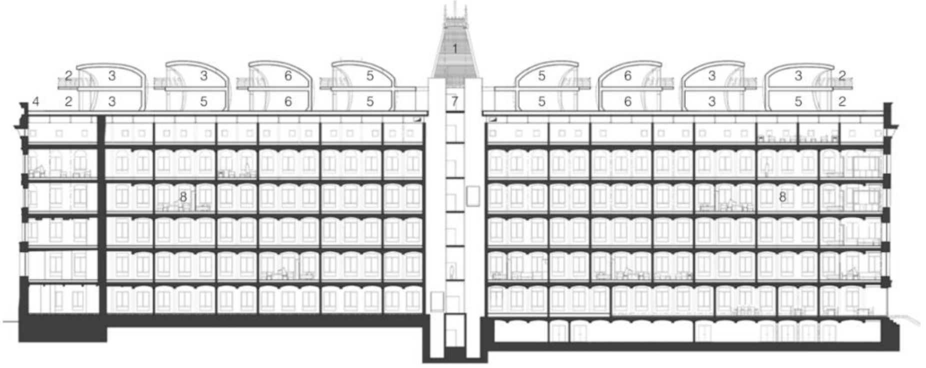

Figure 3 - Section drawing of the refurbished Lister Mills building, showing the completed rooftop development. (© David Morley Architects).

Lister Mills in Bradford was built in 1873 using a cast iron frame with an ornate stonework façade. This supports brick-lined concrete floors and brickwork internal walls. Following the closure of the mill in 1992, the building became derelict before being refurbished and extended in 2001 for residential use. As a result of low land values in Bradford, cost was a major constraint on this project, as was the roof width of just 19m.

Rather than a single structure, as with other case studies, individual units were created at roof level (Fig. 3) to be accessed by a shared staircase. Owing to the limited budget, constrained site and requirement for a lightweight solution, prefabricated timber cassettes wrapped around a lightweight steel frame were selected for use. These were prefabricated off-site and craned to roof level for assembly, negating the need for temporary works. For further financial savings and ease of construction, each of the ten cassettes are identical, comprising eight curved plywood I-beams joined by OSB noggins and braced with an OSB outer skin. The rooftop units are supported by a new concrete slab, transferring loads to a set of steel universal beams. These replace the original cast iron roof trusses in being slotted into existing notches within the stone piers. Construction of the new roof was completed first to allow for the separation of the extension works and refurbishment of the existing building.

Arnold House

Figure 4 - Image of the extended and upgraded form of Arnold House showing continuity between new and existing structures. (© Allsop).

Originally built as a concrete framed warehouse in the 1960s and converted into office space in the 1990s [21], Arnold House struggled to attract tenants in the mid-to-late-2010s despite its desirable location in Shoreditch. This was because of its dated interior and the fact it only had one elevator, as well as its poor operational performance as a result of single glazing and lack of air conditioning.

The building therefore underwent extensive renovation and vertical extension in order to increase its lettable value in line with that of the surrounding area. As a result of its original use as a warehouse, Arnold House was particularly suitable for this, because of reserve structural capacity and the large floor-to-ceiling height desired in modern offices.

Three steel-framed storeys were added to the existing structure, and a rear extension constructed to result in a 50% increase in floor area to 75,000 ft^2. New cores and additional lifts were also added to improve circulation and provide access to the extended portion [21]. Further improvements included new glazing, re-cladding of existing facades [21] (Fig. 4), the installation of an air conditioning system, construction of a landscaped roof terrace, and inclusion of cycle storage and changing facilities. In addition to office space, the ground floor level now hosts cafés, restaurants and retail units [21].

The Department Store

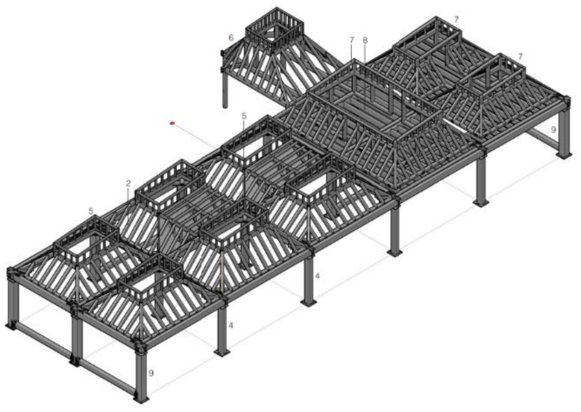

Figure 5 - 3D model of the oak-framed rooftop extension to The Department Store, Brixton. (© Carpenter Oak).

Built in 1906 as one of England's first steel-framed buildings, this Edwardian department store has previous uses including office and retail. When acquired in 2015, it was in a state of disrepair following numerous conversions and the degradation of the structure with time. Now, as part of a wider refurbishment and retrofit, a fifth storey, set back from the building's roofline, has been constructed.

This uses an oak frame (Fig. 5), with 450 mm diameter oak columns resting on the original steel columns at 5375 x 7300 mm centres. Each of these are hewn from a single 'green' oak trunk, with these being cored to allow for the insertion of an adjustable 75mm stainless steel tension rod. These are then connected to 350 mm deep oak beams to form the roof structure (Fig. 5).

In order to construct the extension, a crawler crane was dismantled and reconstructed on the existing roof. This was then used to lift components from street level and arrange these as required on the rooftop. At present, the refurbished department store is used as office space, with retail units at the ground floor. The new extension itself is used as a rooftop bar and restaurant.

1 Triton Square

Built in the 1990s, this building originally took the form of a 6-storey, 72m x 72m, office building, following a 9m x 9m structural grid. This comprised an RC frame, with braced, steel-frame cores placed at each corner for lateral stability. As a result of the over-conservativity of the initially assumed design actions and oversized stair cores, this was particularly suitable for vertical extension.

To streamline the structural appraisal process, the capacity of elements experiencing no increase in design load were not considered, with all other elements being re-analysed using modern codes of practice. This allowed the reduction of assumed imposed loads from 5 kN/m^2 to 4 kN/m^2. The stability offered by the concrete frame was also considered in the re-appraisal, where neglected in original calculations.

Despite these measures, a number of existing concrete columns required strengthening using a 125-150 mm thick RC encasement or fibre reinforced plastic (FRP) wrapping. Depending upon their anticipated failure mode, existing steel columns were either encased in concrete or strengthened using steel plates, with the original diagonal braces being replaced to enhance overall stability. Supplementary piles were added within the basement and tied to existing piles using a new concrete raft. Within the extended portion of the building, lightweight composite steel/concrete floors are supported on a traditional steel frame.

The above remediation measures result in an embodied carbon over the new floor area of 390 kgCO2e/m2, which is higher than the targeted benchmark value of 350 kgCO2e/m2. Through reusing the existing building however, 1,900 t of steel and 35,000 t of concrete were saved. When the embodied carbon of new material is considered over the entire building's floor area, the revised value is 136 kgCO2e/m2.

Clerys Department Store

Figure 6 - Rendered cross-section of the refurbished Clerys Department Store showing the increased structural grid of the upper storeys and terraced extension. (© Visual Lab).

Originally constructed in the 1920s, this concrete framed building housed a department store until its closure in 2015. In this time, it saw numerous adaptations, including the infilling of an atrium in the 1940s, and an initial rooftop extension in the 1970s. In 2020, work began to refurbish the building as part of a wider regeneration initiative. This includes the deconstruction of previous adaptations, and the addition of three new storeys.

Because of a lack of reserve capacity, the extended portion of the building was required to be structurally independent. This has resulted in the insertion of additional columns following the existing 6m x 7m grid. These fabricated I-section columns are split at each floor level and joined using stiffened splice plates to straddle the existing concrete beams. Micro-piles and raft foundations are used to support these columns at ground level. A steel frame construction is used for the new storeys, with these deviating from the existing structural grid through the use of cellular beams up to 14m in length (Fig. 6). This allows them to be used as adaptable office space and a rooftop restaurant, whilst existing storeys are used for retail.

Discussion

Motivations for Vertical Extension

Though present in all cases, the environmental benefits discussed in Section 1 are most prevalent as a motivation for 1 Triton Square (Section 2.6), for which they are explicitly stated as the primary driver. Beyond this, financial incentives for adaptive reuse and vertical extension are also reported, as with the desired increase in lettable value for both Crown House (Section 2.2) and Arnold House (Section 2.4) and.

Opting for vertical extension because of a tight project timeline is explicitly stated in the case of Crown House (Section 2.2), with programme benefits being cited in a number of additional instances. This exemplifies the ability of vertical to reduce project programme in comparison with the alternative of demolition and reconstruction. The less intensive construction process also makes vertical extension more suitable for constrained sites, as suggested for Crown House (Section 2.2), Lister Mills (Section 2.3) and The Department Store (Section 2.5). This enables the increase in value of an asset to which access is temporally or spatially limited, with the craning of materials and components to roof level commonly being employed to facilitate this.

In the case of more historically and architecturally significant structures, such as Lister Mills (Section 2.3) and Clerys Department Store (Section 2.7), vertical extension is also revealed to be a useful tool in the conservation of heritage. This is because it allows space provision in key locations to be brought in line with current requirements, without the need for demolition. Linked to this is the ability of vertical extension to act as a catalyst for wider regeneration, as is observed to be the case for Southbank Tower (Section 2.1), Lister Mills (Section 2.3) and Clerys Department Store (Section 2.7).

Existing and Extended Building Archetypes

The applicability of vertical extension to a range of building archetypes is illustrated by the above case studies. Although examples of the extension of former retail (Sections 2.5 and 2.7), and industrial buildings (Section 2.3) are discussed, cases of vertical extension are shown to primarily take place on existing offices (Tab. 1). This may be because of increasing vacancy rates in such buildings, or because of the inherent adaptability of offices as a result of their open structural grids and large imposed design loads.

Cases of both across- and within- use extension are discussed, further demonstrating the applicability of vertical extension to a wide range of scenarios. Office-to-residential conversions are revealed to be particularly common, potentially resulting from the ability to deliver such schemes under permitted development rights [22]. The ability of vertical extension to deliver high-density mixed-use spaces (Section 1) is also reiterated, with a number of instances of office- or residential- over-retail extensions being discussed (Tab. 1). Opportunity to integrate leisure offerings such as bars and restaurants is also shown in a number of case studies, utilising the inherent ability of vertical extensions to provide architecturally interesting forms and reveal previously unseen rooftop views.

As well as various use-types, different existing and extension materials and forms are utilised in the above case studies. Existing concrete frames are shown to be most commonly extended (Tab. 1), potentially resulting from the fact these make up a large portion of the current building stock and represent typical ‘engineered’ structures for which reserve capacity may be identified. This may also be because these structural forms are most often used for office buildings, which are noted above to be most commonly extended. In addition to concrete framed structures, extensions are shown to be suitable for steel frames (Section 2.2), and buildings with various load bearing masonry elements (Sections 2.3, and 2.5), reiterating the flexibility of this construction type.

The extended storeys of the above case studies are dominated by steel frame constructions (Tab. 1), but also include instances of prefabricated (Section 2.3) and ‘heavy’ (Section 2.5) timber structures. This is likely to result from the fact that these materials are more lightweight than concrete or masonry alternatives, which is of great importance when attempting to utilise scarce reserve capacity. Steel and timber structures also offer additional benefits in that they can be designed to use purely mechanical fixings, which require no ‘wet’ trades and are particularly suited to adaptation and prefabrication [23].

The projects discussed in Section 2 also show a range of different approaches to the addition of new storeys. This includes projects in which a similar aesthetic is employed within the original and extended portions (e.g. Crown House and Arnold House) as well as those in which effort is made to differentiate between the new and existing portions (e.g. Lister Mills). The former of these approaches is revealed to typically be used in the extension of more recent and utilitarian buildings, whilst the latter is employed on those of greater architectural significance.

Structural Assessment and Remediation

The level of structural appraisal carried out for each of the projects in Section 2 is shown to vary on a case-by-case basis. This ranges from the full assessment of the building’s extended form using finite element analysis (e.g. Southbank Tower), to more simplistic checks based on comparisons of existing and extended loads. Between these extremes are examples such as 1 Triton Square (Section 2.6), where individual elements experiencing an increase in load are checked, whilst all others are assumed to offer sufficient resistance.

Following these assessments, different degrees of structural remediation are shown to be required by the above case studies. This includes instances of simplistic (e.g. Crown House etc.) and complex (e.g. Triton Square) elemental strengthening, as well as more novel support systems (e.g. Southbank Tower and Clerys Department Store). The required degree of structural intervention is shown to result both from the ability to identify reserve capacity within the structure, and its condition. For example, Crown House only required minimal localised strengthening as a result of its decrease in assumed imposed loads and good structural health, whereas more intense interventions were required for derelict structures such as Clerys Department Store.

In most instances, the capacity of existing foundations is deemed to be insufficient, requiring the strengthening of these or the construction of supplementary piles (e.g. 1 Triton Square and Clerys Department Store). In some cases, however (e.g. Southbank Tower), consolidation of founding soils from the weight of the original building is used to justify an increase in soil strength and thus the resistance offered by existing piles.

As a result of the increase in building height associated with a vertical extension, the increased lateral loads compared with the original building need to be considered, particularly where a large number of storeys are added. In the case of Southbank Tower, where the buildings height was increased by 1/3, this required CFD analysis to accurately determine the wind loading for use in structural appraisal. The requirement for remediation in this case was the linkage of the tower and surrounding podium structures (Section 2.1), though other lateral stability increases have been achieved through the replacement of steel bracing and consideration of hitherto ignored stiffness (e.g. 1 Triton Square), as well as the construction of new cores (e.g. Arnold House).

The nature of vertical extensions, in that they increase loads experienced at the existing roof level, dictate that strengthening or replacement of this element is often required. This is shown to be true in the case of Lister Mills, for which new load transfer structures were introduced to transmit loads to existing members. In some cases however, such as Crown House, the loads associated with the existing structure may be transferred directly to existing column ends, with imposed floor loads being supported by the original roof structure.

Conclusions

The above case studies reveal vertical extension to be a versatile construction method capable of adding new useable floorspace to a variety of existing building archetypes. This includes traditional load bearing masonry structures, as well as more recent ‘engineered’ structures such as steel and concrete frames. Although most commonly carried out on existing offices, extensions are also shown to be applicable to residential, retail, and industrial building. Both within- and across- use adaptations are included, with the generation of mixed-use spaces being common.

As well as the embodied carbon and circular economic benefits discussed in Section 1, additional motivations for vertical extension are revealed to include: the ability to increase asset value at a reduced project cost; reductions in project programme; suitability for constrained sites; and the preservation of heritage.

Depending upon the form and condition of the existing building, different degrees of structural appraisal and remediation are required. This ranges from full finite element and CFD analysis, to element-wise capacity checks. Superstructure remediation is shown to vary from localised strengthening (where single elements are insufficient), to the construction of complex load transfer structures (where the extended portion is required to be structurally independent). The requirement for substructure strengthening also varies on a case-by-case basis, dependent upon capacity of the existing foundations and the anticipated increase in load.

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