This is a repository copy of *Reserve capacity and vertical extension potential in steel framed buildings*.

White Rose Research Online URL for this paper:
https://eprints.whiterose.ac.uk/215516/

Version: Accepted Version

Article:

Gillott, C. orcid.org/0000-0001-5706-7909, Davison, B. and Densley Tingley, D. (2025) Reserve capacity and vertical extension potential in steel framed buildings. Proceedings of the Institution of Civil Engineers: Structures and Buildings, 178 (3). pp. 235-247. ISSN 0965-0911

https://doi.org/10.1680/jstbu.24.00010

© 2024 The Author(s). Except as otherwise noted, this author-accepted version of a journal article published in Proceedings of the Institution of Civil Engineers: Structures and Buildings is made available via the University of Sheffield Research Publications and Copyright Policy under the terms of the Creative Commons Attribution 4.0 International License (CC-BY 4.0), which permits unrestricted use, distribution and reproduction in any medium, provided the original work is properly cited. To view a copy of this licence, visit http://creativecommons.org/licenses/by/4.0/

Reuse

This article is distributed under the terms of the Creative Commons Attribution (CC BY) licence. This licence allows you to distribute, remix, tweak, and build upon the work, even commercially, as long as you credit the authors for the original work. More information and the full terms of the licence here: https://creativecommons.org/licenses/

Takedown

If you consider content in White Rose Research Online to be in breach of UK law, please notify us by emailing eprints@whiterose.ac.uk including the URL of the record and the reason for the withdrawal request.

eprints@whiterose.ac.uk
https://eprints.whiterose.ac.uk/

Reserve capacity and vertical extension potential in steel framed buildings

Charles Gillott*[1], Buick Davison[1], Danielle Densley Tingley[1]
*c.gillott@sheffield.ac.uk, Sir Frederick Mappin Building, Mappin Street, S1 3JD.
[1]Department of Civil and Structural Engineering, The University of Sheffield, Sheffield, England.

Abstract

Reusing existing buildings is key in transitioning to a circular economy and meeting associated decarbonisation targets. Many adaptive reuse strategies, including vertical extensions, result in increased loads that are required to be resisted by reserve structural capacity and/or strengthening. Previous work identifies structural underutilisation within existing buildings and suggests numerous sources of this. However, understanding of associated contributions to reserve capacity and how this influences a building's ability to be extended is limited. To address this, 11 scenarios, each modelling a different source of underutilisation, have been developed and applied in the design and reappraisal of 11,252 hypothetical steel framed office buildings. An average reserve capacity of 10% is found in optimal Eurocode designs, rising to around 20% for British Standards and over 30% in the conservative or defensive application of Eurocodes. Office to residential conversions are shown to unlock an average reserve capacity of more than 20%. Across the 11 scenarios, between 9% and 89% of considered cases are shown to be extendable without the need for strengthening. This demonstrates potentially significant extension potential within steel framed buildings, but that this varies with frame configuration, design/appraisal approach, and the extension's use and structural material.

1 Introduction

Buildings are responsible for 34% of global energy consumption and 37% of associated greenhouse gas (GHG) emissions (United Nations Environment Programme, 2022). An increasing portion of this is in the form of embodied carbon (UK Green Building Council, 2021), resulting from the extraction and manufacture of materials and components; construction, maintenance and demolition of buildings; and processing and disposal of waste (RICS, 2017). A circular economy (CE) aims to reduce embodied GHG emissions by *narrowing, slowing* and *closing* resource flows, including through efficient design, lifespan extension and reuse and recycling (Bocken *et al.*, 2016). In the built environment, strategies to achieve this include: the optimisation of structures and components; design for longevity, adaptability and deconstructability; the (adaptive) reuse of existing buildings; and the specification of reused/reusable components and recycled/recyclable materials (Astle *et al.*, 2023; Gillott *et al.*, 2023).

In the past, structural engineering practice and related research has typically focussed on the *narrowing* of resource in-flows, through structural optimisation, and the *closing* of waste out-flows, through component reuse and recycling (Drewniok *et al.*, 2020; Dunant *et al.*, 2018). More recently, however, the benefits of *slowing* material flows through the reuse of entire buildings has come to the fore, leading to increasing research interest (Gosling *et al.*, 2013; Rockow *et al.*, 2021; Sundling,

2019) and both sectoral (Architects' Journal, 2019) and governmental (The Greater London Authority, 2021) support.

Where a building's reuse results in an increase in experienced loads (e.g. through change of use or vertical extension), these are required to be resisted by reserve capacity within the existing structure and/or its strengthening (Gillott *et al.*, 2022a; Pattison, 2021). As suggested by work considering reinforced concrete structures (Mei *et al.*, 2024), identifying underutilisation in case study buildings (Dunant *et al.*, 2018; Moynihan and Allwood, 2014), and documenting known sources of overdesign (Beal, 2011; Drewniok and Orr, 2018; Dunant *et al.*, 2018; Gibbons, 1995; Gibson *et al.*, 1995; Kala, 2007; Moynihan and Allwood, 2014; Orr, 2018; Orr *et al.*, 2019; Orr and Drewniok, 2018), such reserve capacity is likely within at least some existing buildings (Gillott *et al.*, 2022b).

1.1 Limit state design and structural utilisation

'Limit state' design, as employed in Eurocodes, ensures that the design value for the effect of actions on a member (E_d) does not exceed the corresponding design value for resistance (R_d) or relevant serviceability criteria (C_d). In Eurocodes, design values for action effects (E_d) are determined by applying a series of partial (e.g. γ_G and γ_Q), combination (e.g. ψ) and reduction (e.g. ξ) factors to characteristic actions (e.g. permanent, G, and imposed loads, Q) based upon their likelihood of simultaneous occurrence (British Standards Institution, 2011). The conservative Equation 1 (6.10) is typically used here, with the alternative of the least favourable of Equations 2 (6.10a) and 3 (6.10b) being less common in practice (British Standards Institution, 2011). Design values for member resistance (R_d) are calculated using characteristic material properties (e.g. yield strength) and an associated partial factor (γ_M) (British Standards Institution, 2005).

$$E_d = \sum_{j\geq 1} \gamma_{G,j} G_{k,j} + \gamma_P P + \sum_{i>1} \gamma_{Q,i} Q_{k,i} \tag{1}$$

$$E_d = \sum_{j\geq 1} \gamma_{G,j} G_{k,j} + \gamma_P P + \gamma_{Q,1} \psi_{0,1} Q_{k,1} + \sum_{i>1} \gamma_{Q,i} \psi_{0,i} Q_{k,i} \tag{2}$$

$$E_d = \sum_{j\geq 1} \xi_j \gamma_{G,j} G_{k,j} + \gamma_P P + \gamma_{Q,1} Q_{k,1} + \sum_{i>1} \gamma_{Q,i} \psi_{0,i} Q_{k,i} \tag{3}$$

Calibration of partial, combination and reduction factors using 'long experience of building tradition' and 'statistical evaluation of experimental data and field observations' (British Standards Institution, 2011), results that designs in which $E_d \leq R_d$ and $E_d \leq C_d$ have a suitably low probability of failure and are thus deemed compliant. This relationship may alternatively be presented as E_d/R_d or $E_d/C_d \leq 1$, where E_d/R_d and E_d/C_d define member 'utilisation ratios' (URs) for ultimate and serviceability limit states (ULS and SLS) respectively (Moynihan and Allwood, 2014).

1.2 Sources of reserve capacity in existing buildings

Mounting impetus for material efficiency has resulted in a number of studies considering both the extent and cause of underutilisation within structural engineering design. This includes the work of Moynihan & Allwood (2014) who, through the structural appraisal of 23 real-world steel framed case studies, identify the average UR of 12,787 beams and 2,347 columns to be just 0.40 and 0.49. Around 10% of this underutilisation is suggested to result from the limited number of catalogue sections available for specification (Moynihan and Allwood, 2014), with the remainder being attributed to the rationalisation of designs to enhance simplicity and reduce costs (Gibbons, 1995; Gibson *et al.*, 1995). A second study identifies an average mass-weighted UR of 0.65 across 30 case study buildings (Dunant *et al.*, 2018), but observes no correlation between the level of design rationalisation and member underutilisations. Instead, as the distribution of URs exhibits a distinct peak around 0.8, the authors attribute the observed underutilisation to the 'defensive design practice' of avoiding URs ≈ 1 (Dunant *et al.*, 2018).

A subsequent industry survey, conducted as part of the MEICON (Minimising Energy in Construction) project, also suggests design rationalisation and the targeting of URs between 0.75-0.80 to be commonplace in structural engineering design (Orr, 2018; Orr *et al.*, 2019). Additional work within the same project considers disparities between imposed loads *adopted* in the design process, *recommended* in codes of practice and *experienced* by buildings in reality (Drewniok and Orr, 2018; Orr and Drewniok, 2018). This finds the area-averaged imposed load used across the design of 95 buildings to be 4.63kN/m^2 (Orr and Drewniok, 2018), whilst the average value experienced across 13 prior studies is just 0.63kN/m^2 (Drewniok and Orr, 2018). Considering Eurocode-recommend office loading of 2.5-4.2kN/m^2 (British Standards Institution, 2002), this represents a potential source of reserve capacity in buildings designed more conservatively than, or even in accordance with, current codes of practice. Reserve capacity may also be identified through a building's reappraisal using loads associated with a less onerous use class, for example as part of an office to residential conversion.

Although partially accounting for decreased design uncertainty (e.g. in material and dimensional variation), the increasing efficiency of design codes over time (Beal, 2011) represents a potential additional source of reserve capacity. This includes the switch between permissible stress (e.g. BS449) (British Standards Institution, 1969) and limit state approaches (e.g. BS5950) (British Standards Institution, 2001), as well as the subsequent adoption of Eurocodes (British Standards Institution, 2011). Perhaps the most obvious of these temporal disparities is in partial factors for permanent and imposed loads (γ_G and γ_Q), taken as 1.40 and 1.60 in BS5950 (British Standards Institution, 2001) and 1.35 and 1.50 in Eurocodes (British Standards Institution, 2011). Additional optional factors for combinations of variable actions (ψ) and the reduction of permanent (ξ) and imposed loads acting over large areas (α_a) or numbers of storeys (α_n) are also offered by Eurocodes (British Standards Institution, 2011). This represents potential to identify reserve capacity even in buildings designed to current codes of practice, though the frequency of omission of such factors is unknown.

Reserve capacity may also be identified through the reappraisal of existing buildings using a modified Eurocode approach. This includes reduction of the partial factor for permanent loads (γ_G) to 1.10 (shown to be permissible where imposed:total load = 0.15-0.55) (Kala, 2007) and the use of tested material strengths in place of characteristic values (Melcher *et al.*, 2004; Orr, 2019).

1.3 Aims and objectives

Despite existing studies' documentation of numerous sources of structural underutilisation, few quantify the impact of these, and typically do so in terms of their compound effect in real-world structures (Dunant *et al.*, 2018; Moynihan and Allwood, 2014). The majority of work is also concerned with enhancing material efficiency in the design of new buildings (e.g. through structural optimisation) (Drewniok *et al.*, 2020; Dunant *et al.*, 2018; Moynihan and Allwood, 2014), rather than utilising reserve capacity in existing buildings as part of their adaptive reuse. Partially as a result of this, focus is placed upon beam elements (Drewniok *et al.*, 2020; Dunant *et al.*, 2018; Moynihan and Allwood, 2014), further overlooking the potential for reserve column capacity as required for vertical extension.

Where the influence of different underutilisation sources on column capacity has been considered, this is only in terms of URs and potential load increases in reinforced concrete structures (Mei *et al.*, 2024). Owing to their prevalence in the UK (British Constructional Steelwork Association, 2021), inherent suitability for adaptation (Astle *et al.*, 2023) and experience of a majority of underutilisation sources (Section 1.2), this study focusses on braced, multi-storey, steel framed office buildings.

To address the above knowledge gaps and enhance understanding of structural underutilisation, reserve capacity and vertical extension potential in existing buildings, this study (1) quantifies the impact of different known sources of underutilisation in braced steel framed columns; (2) identifies associated reserve capacities in terms of permissible load increase; (3) contextualises this as a resultant potential for vertical extension in terms of the number of addable storeys.

2 Methodology

To assess the effect of individual sources of reserve capacity across a broad range of buildings, the adopted methodology applies a suite of 11 underutilisation scenarios (Section 2.1) in the design and subsequent reappraisal of 11,252 hypothetical braced steel frame office configurations (Section 2.2). For each of the 123,772 discrete combinations, the optimal (i.e., least-mass) design is first generated using the relevant design approach, before being reassessed using the associated appraisal approach to calculate an adjusted design effect and/or resistance (Figure 1). Associated utilisation ratios and reserve capacities are then calculated (Section 2.3), and finally contextualised as a potential for vertical extension using typical per-storey loads (Section 2.4). For efficiency, this entire process is executed computationally in MATLAB (Mathworks, 2021), with a sub-sample of frame configuration and underutilisation scenario combinations being verified by traditional hand calculation.

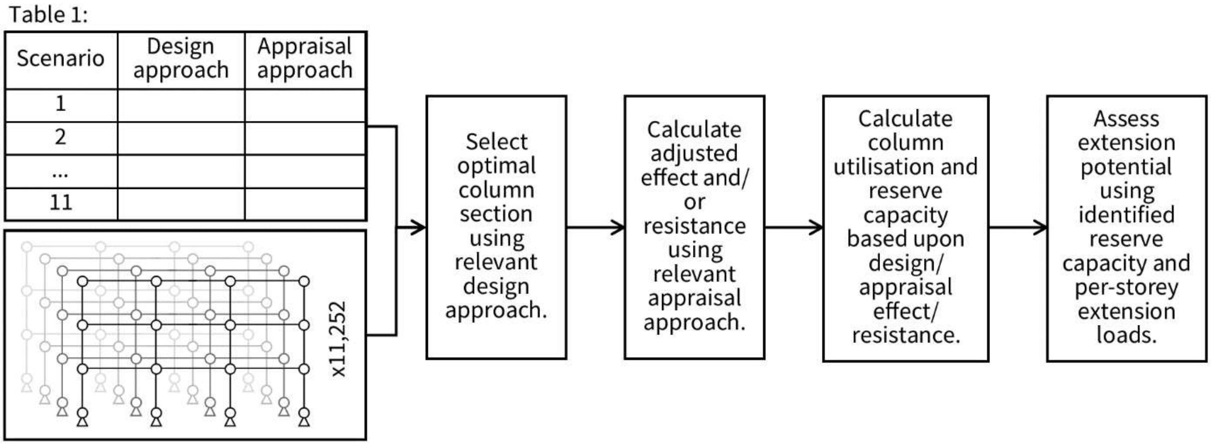

Figure 1 – Developed methodological framework to assess utilisation, reserve capacity and extension potential within multi-storey framed buildings.

2.1 Underutilisation scenarios

To represent the underutilisation sources identified in Section 1.2, a set of 11 scenarios have been developed (Table 1). These each comprise a design and appraisal approach, at least one of which follows optimal Eurocode compliance in order to isolate consideration of a single utilisation source. Scenarios 1-7 represent underutilisation arising from buildings' original over-design, namely the use of superseded design codes (Scenarios 1-2); the application of current codes conservatively (Scenarios 3-4) or defensively (Scenario 5); the over-specifying of assumed loads (Scenario 6); and the use of catalogue sections (Scenario 7). Scenarios 8-11 represent underutilisation unlocked through a building's novel reappraisal, including using average-experienced imposed loads (Scenario 8); as part of an office-residential conversion (Scenario 9; and using tested material strengths (Scenario 10) or reduced partial factors (Scenario 11). Details of the parameters used in each design and appraisal approach are given in Table 2 and Table 3 respectively.

Scenario No.	**Design Approach**	**Appraisal Approach**
1	BS449: Optimal compliance	Eurocode: Optimal compliance
2	BS5950: Optimal compliance	
3	Eurocode: Omitting reduction / combination factors (ξ, ψ)	
4	Eurocode: Omitting imposed load reduction factors (α_a, α_n)	
5	Eurocode: Targeting UR=0.8	
6	Eurocode: Using over-specified imposed loads	
7	Eurocode: Optimal compliance	
8		Eurocode: Using experienced imposed loads
9		Eurocode: Using residential imposed loads
10		Eurocode: With average material strength
11		Eurocode: With reduced partial factor for permanent loads (γ)

Table 1 – Developed underutilisation scenarios and associated design and appraisal approaches.

Design Approach	**Permanent floor load, G_k (kN/m^2)**	**Imposed floor load, Q_k (kN/m^2)***	**Partial factor for permanent loads, γ_G**	**Partial factor for imposed loads, γ_Q**	**Permanent load reduction factor, ξ**	**Imposed load combination factor, ψ**	**Target UR**	**Material strength (MPa)**
BS449: Optimal compliance	3.7-3.9[†]	3.5[1]	***1.40***[3]	***1.60***[3]	-	-	N/A[‡]	355[5]
BS5950: Optimal compliance	3.7-3.9[†]	3.5[1]	***1.40***[3]	***1.60***[3]	-	-	1.0	355[5]
Eurocode: Omitting reduction / combination factors (ξ, ψ)	3.7-3.9[†]	3.3[2]	1.35[4]	1.50[4]	-	-	1.0	355[5]
Eurocode: Omitting imposed load reduction factors (α_a, α_n)	3.7-3.9[†]	3.3[2]	1.35[4]	1.50[4]	0.925[4]	0.7[4]	1.0	355[5]
Eurocode: Targeting UR=0.8	3.7-3.9[†]	3.3[2]	1.35[4]	1.50[4]	0.925[4]	0.7[4]	***0.80***[7, 8]	355[5]
Eurocode: Using over-specified imposed loads	3.7-3.9[†]	***4.63***[6]	1.35[4]	1.50[4]	0.925[4]	0.7[4]	1.0	355[5]
Eurocode: Optimal compliance	3.7-3.9[†]	3.3[2]	1.35[4]	1.50[4]	0.925[4]	0.7[4]	1.0	355[5]

*An additional imposed load of 0.6kN/m^2 (British Standards Institution, 2008) is assumed to act at the roof level.

[†] Comprising: steel self-weight (0.5kN/m^2/storey below 7 storeys, 0.7kN/m^2/storey 7 storeys and above) (The Steel Construction Institute, 2008); lightweight composite slab (2.5kN/m^2) (The Steel Construction Institute, 2008); services, floor coverings and suspended ceilings (0.7kN/m^2) (The Steel Construction Institute, 2008).

[‡] Target UR not applicable to the permissible stress approach employed in BS449.

[1] Comprising 2.5kN/m^2 plus 1.0 kN/m^2 for moveable partitions (British Standards Institution, 1996)

[2] Comprising 2.5kN/m^2 plus 0.8 kN/m^2 for moveable partitions (British Standards Institution, 2002)

[3] British Standards Institution, 2001

[4] British Standards Institution, 2011

[5] British Standards Institution, 2005

[6] Orr and Drewniok, 2018

[7] Orr, 2018

[8] Orr *et al.*, 2019

Table 2 – Parameters employed in each design approach.

Appraisal Approach	**Permanent floor load (kN/m^2)**	**Imposed floor load (kN/m^2)[†]**	**Partial factor for permanent loads**	**Partial factor for imposed loads**	**Permanent load reduction factor**	**Imposed load combination factor**	**Target UR**	**Material strength (MPa)**
Eurocode: Optimal compliance	3.7-3.9[†]	3.3[1]	1.35	1.50[2]	0.925[2]	0.7[2]	1.0	355[3]
Eurocode: Using experienced imposed loads	3.7-3.9[†]	***0.63***[4]	1.35[2]	1.50[2]	0.925[2]	0.7[2]	1.0	355[3]
Eurocode: Using residential imposed loads	3.7-3.9[†]	***2.0***[1]	1.35[2]	1.50[2]	0.925[2]	0.7[2]	1.0	355[3]
Eurocode: With average material strength	3.7-3.9[†]	3.3[1]	1.35[2]	1.50[2]	0.925[2]	0.7[2]	1.0	***402***[6]
Eurocode: With reduced partial factor for permanent loads (γ).	3.7-3.9[†]	3.3[1]	***1.10***[5]	1.50[2]	- [‡]	- [‡]	1.0	355[3]

[*] An additional imposed load of 0.6kN/m^2 (British Standards Institution, 2008) is assumed to act at the roof level.

[†] Comprising: steel self-weight (0.5kN/m^2/storey below 7 storeys, 0.7kN/m^2/storey 7 storeys and above) (The Steel Construction Institute, 2008); lightweight composite slab (2.5kN/m^2) (The Steel Construction Institute, 2008); services, floor coverings and suspended ceilings (0.7kN/m^2) (The Steel Construction Institute, 2008).

[‡] No load reduction/combination factors applied due to their omission when deriving reduced partial (Kala, 2007) .

[1] Comprising 2.5kN/m^2 plus 0.8 kN/m^2 for moveable partitions (British Standards Institution, 2002)

[2] British Standards Institution, 2011

[3] British Standards Institution, 2005

[4] Drewniok and Orr, 2018

[5] Kala, 2007

[6] Melcher *et al.*, 2004

Table 3 – Parameters employed in each appraisal approach.

2.2 Hypothetical frame configurations

The 11,252 considered office configurations are obtained from a parameterised, simply constructed, steel frame of varying storey height (h), bay width (b) and storey number (n) (Figure 2). This assumes a bisymmetric structural grid; eliminating the need to consider nominal end moments, dictating that minor axis member buckling capacity is critical in all instances and resulting in a one-dimensional problem. Lateral and seismic forces are not considered, assuming sufficient capacity within, or localised strengthening/replacement of, roof-level structures, lateral bracing systems, splices, baseplates and foundations.

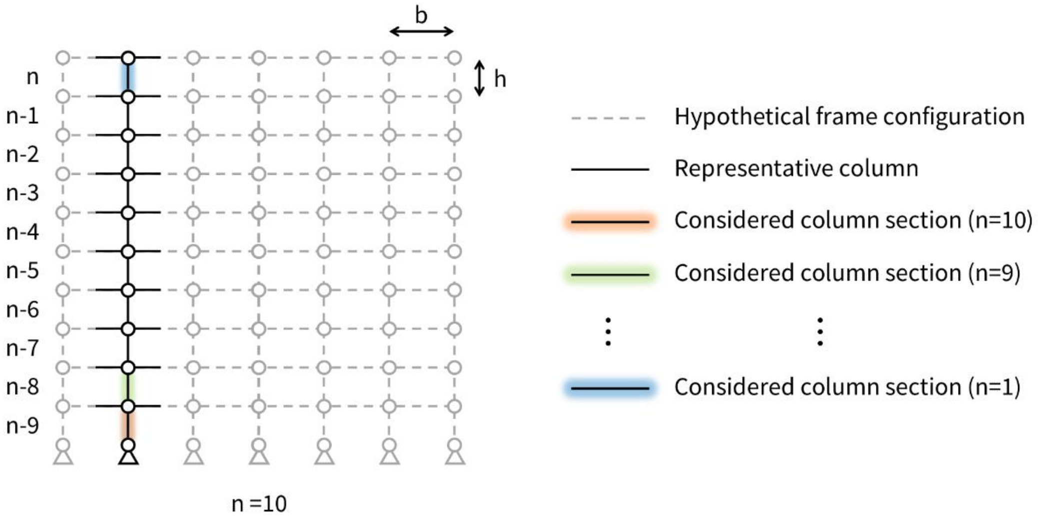

Figure 2 – Indicative simply constructed, braced steel frame of storey height (h), bay width (b) and storey number (n=10).

To model a pragmatic-yet-broad range of likely real-world cases, frame parameters are varied uniformly between upper and lower limits typical across the UK building stock. Storey heights are taken as 2-8m (in 0.25m increments), bay widths as 4-15m (in 0.25m increments) and storey number as 1-10. To ensure that the consideration of such a broad range of parameters does not unduly influence results, analysis of a narrower subset of more common frame configurations is provided as supplementary information. A consistent bay width within each configuration means that all internal columns are identical and may be modelled by a single representative member (Figure 2). As shown in Figure 2, only the ground floor portion of this is required to be explicitly analysed for each configuration, with upper floors being considered implicitly when assessing configurations of fewer storey number.

2.3 Utilisation and reserve capacity

Although following the general workflow in Figure 1 and detailed below, column utilisations and reserve capacities are calculated using alternate processes for scenarios comprising non-standard design (scenarios 1-6) and appraisal (scenarios 8-11) approaches (Figure 3). This is because of the need to repeat the design of each frame configuration for scenarios employing a non-standard design approach (scenarios 1-6), but not when designing to optimal Eurocode compliance (scenarios 7-11). In all cases, and throughout both the initial design and reappraisal process, column effective lengths are taken as equal to storey height.

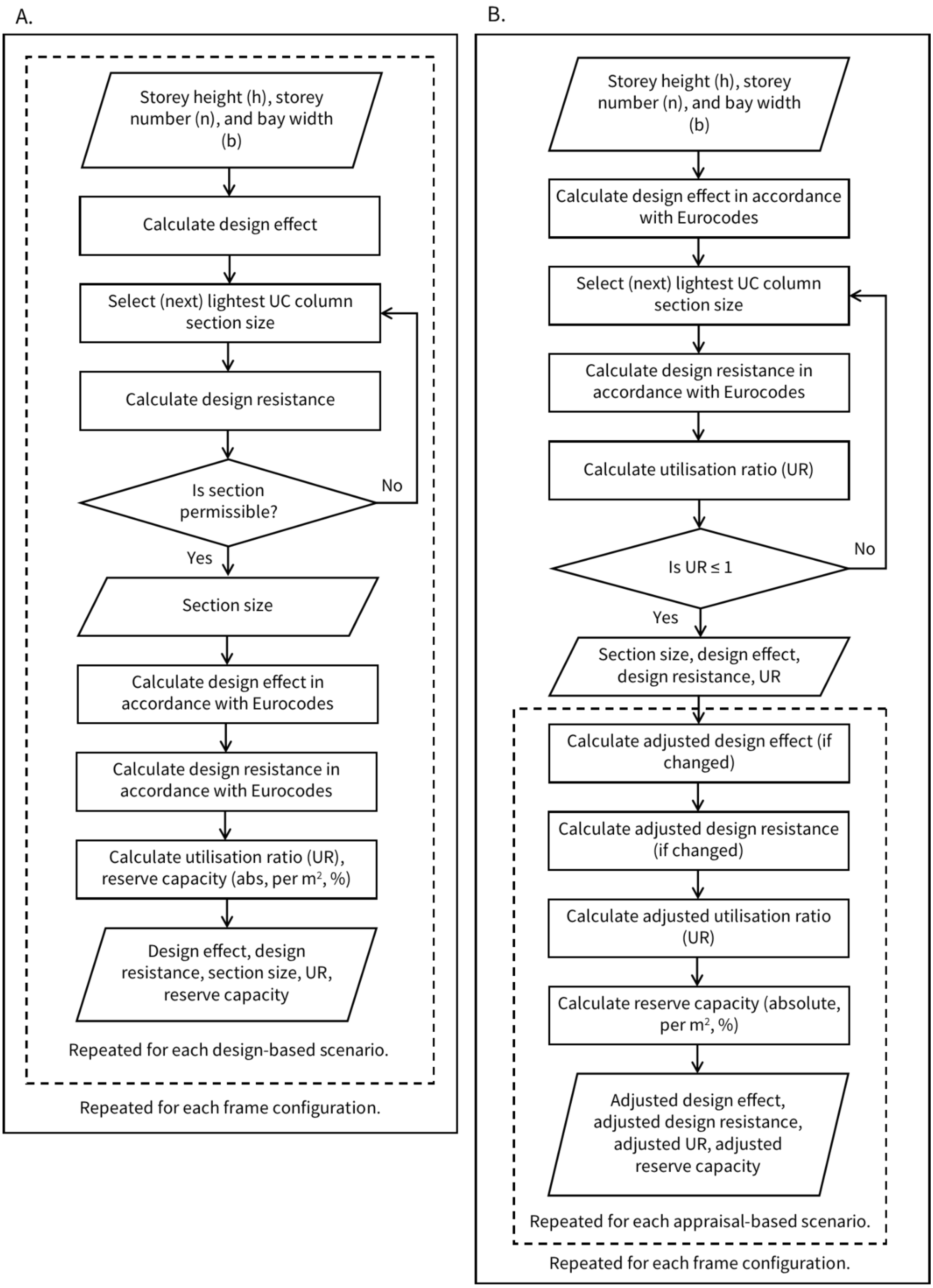

Figure 3 – Detailed assessment workflows for underutilisation scenarios employing a.) non-standard (scenarios 1-6) and b.) standard (scenarios 7-11) design approaches.

As shown in Figure 3, for each of the 123,772 discreet underutilisation scenario and frame configuration combinations, the axial load within the representative column is first calculated in accordance with the relevant design approach (Table 1). The column is initially assumed to be of the lightest catalogue UC section within the Steel Building Design Data 'Blue-book' (The Steel Construction Institute *et al.*, 2015) and its minor-axis buckling resistance calculated using the relevant design approach (Table 1). Next, ULS design compliance is checked using an associated UR (Section 1.1), except in scenario 1 (representing design to BS449) where the permissible stress approach is used. If this section size does not satisfy the buckling resistance requirements of the current frame configuration and design approach combination (i.e. UR >1), the next lightest section is selected, the resistance recalculated, and the compliance check repeated. This iterative process continues until the optimal (i.e. lightest-yet-permissible) section has been identified.

Next, assuming it is of this optimal section size, the representative column is reassessed in accordance with the relevant appraisal approach (Table 1) to calculate an adjusted design effect and/or resistance. Using the appropriate combination of the original and adjusted design effect and resistance (Table 1) a second UR is calculated, indicating the utilisation of the representative column under the current scenario. Associated reserve capacity is also calculated in absolute (kN) and area-averaged (kN/m^2) terms, as well as a percentage of the column's original Eurocode design effect.

2.4 Potential for vertical extension

To contextualise identified reserve capacities in terms of resultant extension potential, a set of four typologies are considered. These represent hypothetical extensions designed for office or residential use and employing a traditional hot-rolled steel frame (i.e. matching the existing building) or a lightweight cold-formed alternative.

Permanent loads for hot-rolled steel extensions are taken as 3.7kN/m^2 (as in Table 2 and Table 3), whilst the lightweight alternative assumes values of 1kN/m^2 for cold formed steel framing (including flooring) (Lawson *et al.*, 2004) and 0.25kN/m^2 for accompanying services (The Steel Construction Institute, 2008). Similarly, whereas imposed loads due to moveable partitions remain at 0.8kN/m^2 per storey for the hot-rolled framing case, a reduced value of 0.5kN/m^2 (British Standards Institution, 2002) is used in the lightweight alternative. 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 respectively (British Standards Institution, 2002).

Combination (ψ) and reduction factors (ξ, α_A and α_n), are omitted when calculating design actions for the four extension typologies, resulting in a single per-storey load for each. Extension potential is thus calculated simply by dividing reserve capacities by these values.

3 Results & Discussion

3.1 Utilisation

URs vary between 0.11 and 1.00 across the 123,772 considered frame configuration and underutilisation scenario combinations. Minimum URs for each scenario vary between just 0.11 (scenarios 10 and 11) and 0.12 (scenarios 1-9), with maximum URs ranging between 0.80 (scenario 5) and 1.00 (scenario 7). Consistently low minimum URs across each scenario result from the consideration of a small number of particularly non-onerous and unlikely frame configurations (i.e. combinations of low bay width, storey height and storey number), for which even the lightest sections are significantly under capacity. Similarly, maximum URs for each scenario represent those for just a small number of particularly favourable frame configuration and design load combinations. To mitigate the influence of these extreme UR values upper and lower bounds indicated by whiskers in Figure 4, are defined at 1.5 times the interquartile range (IQR) from the median. The results of analysis of a narrower subset of more common frame configurations are also provided as supplementary information, verifying that the consideration of such a broad range of parameters has not unduly influenced the findings presented herein.

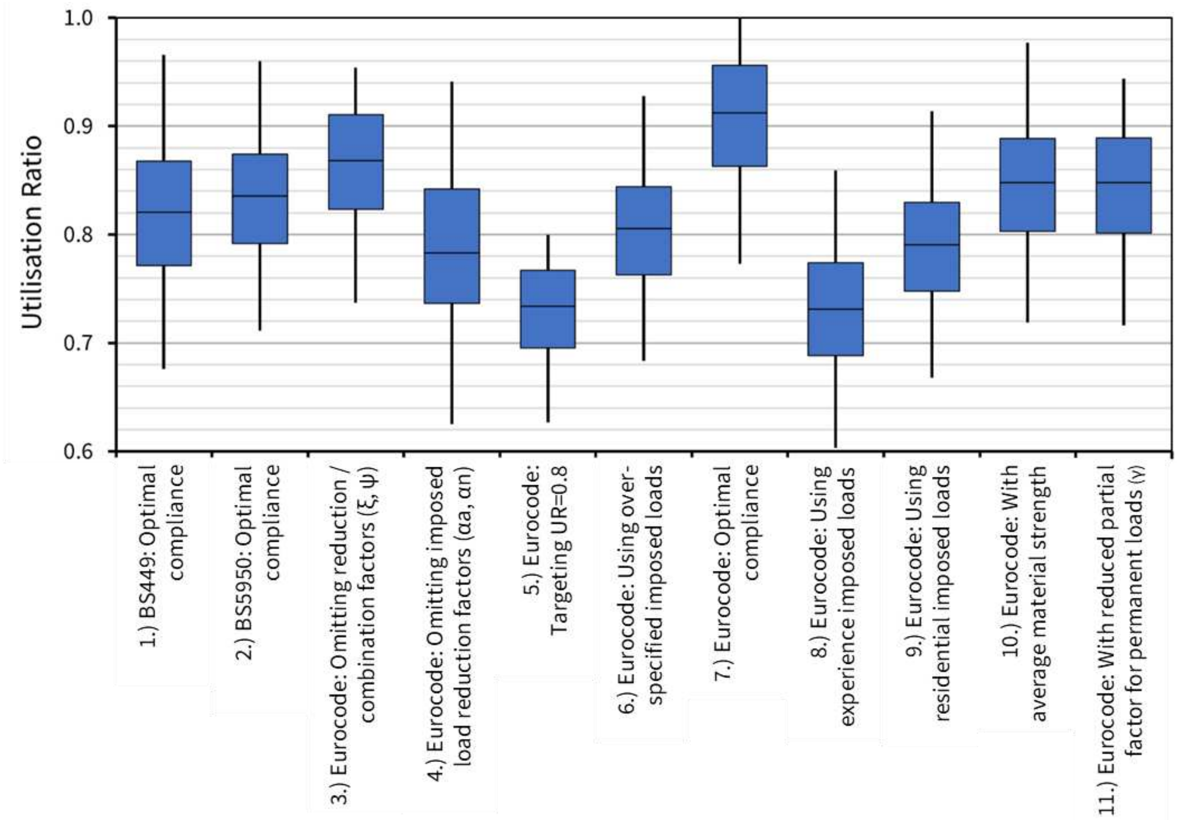

Figure 4 – Distribution of utilisation ratios for the 11,252 frame configurations considered under each of the 11 underutilisation scenarios. To mitigate the effect of a small number of unlikely extreme values, whiskers indicate upper and lower bounds 1.5 times the interquartile range from the median.

Figure 4 reveals the median UR for columns designed *and* appraised to optimal Eurocode compliance (scenario 7) to be just 0.91. This is in general agreement with the previously reported value of 0.90 (Moynihan and Allwood, 2014), suggesting use of catalogue sections to introduce an average of ~10% underutilisation where columns are otherwise optimally designed using current codes of practice. Quartile values of 0.81 and 0.96 indicate at least some underutilisation in the majority of cases, varying between ~5% and ~20% for more or less favourable configurations.

Median utilisation in columns designed using superseded codes is lower than for Eurocodes, with values of 0.82 and 0.84 being obtained for BS449 and BS5950 respectively (scenarios 1 and 2) (Figure 4). This is indicative of increases in efficiency between successive British Standards and Eurocodes (Beal, 2011), resulting from the switch between permissible stress (British Standards Institution, 1969) and limit state (British Standards Institution, 2001), reduction of permanent and imposed load factors (British Standards Institution, 2011), and the introduction of additional factors for the reduction and combination of loads (ξ, ψ, α_a, α_n) (British Standards Institution, 2011).

Eurocode designs omitting permanent load reduction (ξ) and variable action combination (ψ) factors (scenario 3) (i.e. using equation 1) result in a median UR of 0.87 (Figure 4). The associated value when omitting reduction factors for imposed loads acting over large areas (α_a) and multiple storeys (α_n) (scenario 4) is just 0.78. This shows how the conservative application of Eurocodes can result in greater underutilisation than the use of superseded codes in *some* cases. The same is true for the defensive application of Eurocodes, with the targeting of URs = 0.8 (Dunant *et al.*, 2018; Orr, 2018; Orr *et al.*, 2019) (scenario 5) giving a median value of just 0.73 (Figure 4).

When reappraised using the Eurocode recommended value of 3.3kN/m^2 (British Standards Institution, 2002), designs generated assuming imposed loads of 4.63kN/m^2 (Orr and Drewniok, 2018) (scenario 6) are revealed to have a median utilisation of 0.81 (Figure 4). Further underutilisation is seen where optimal Eurocode designs are reappraised using average-experienced imposed loads (0.63kN/m^2 (Drewniok and Orr, 2018), scenario 8) or those recommended for residential use (2.0kN/m^2 (British Standards Institution, 2002), scenario 9), giving median UR's of 0.73 and 0.79 respectively. This reiterates the often-significant contribution of design conservativity to underutilisation within existing buildings and suggests opportunity to identify further underutilisation through reappraisal using modified design values. Such a possibility is also posed by scenarios 10 and 11, which both result in median URs of 0.85 (Figure 4).

3.2 Reserve capacity

For ease of comparison, Figure 5 reports reserve capacities for the 123,772 considered frame configuration and underutilisation scenario combinations as a percentage of their original optimal Eurocode design effect. Whiskers again represent upper and lower bounds at 1.5 times the interquartile range from the median, in order to mitigate the influence of a small number of particularly non-onerous and favourable frame configurations.

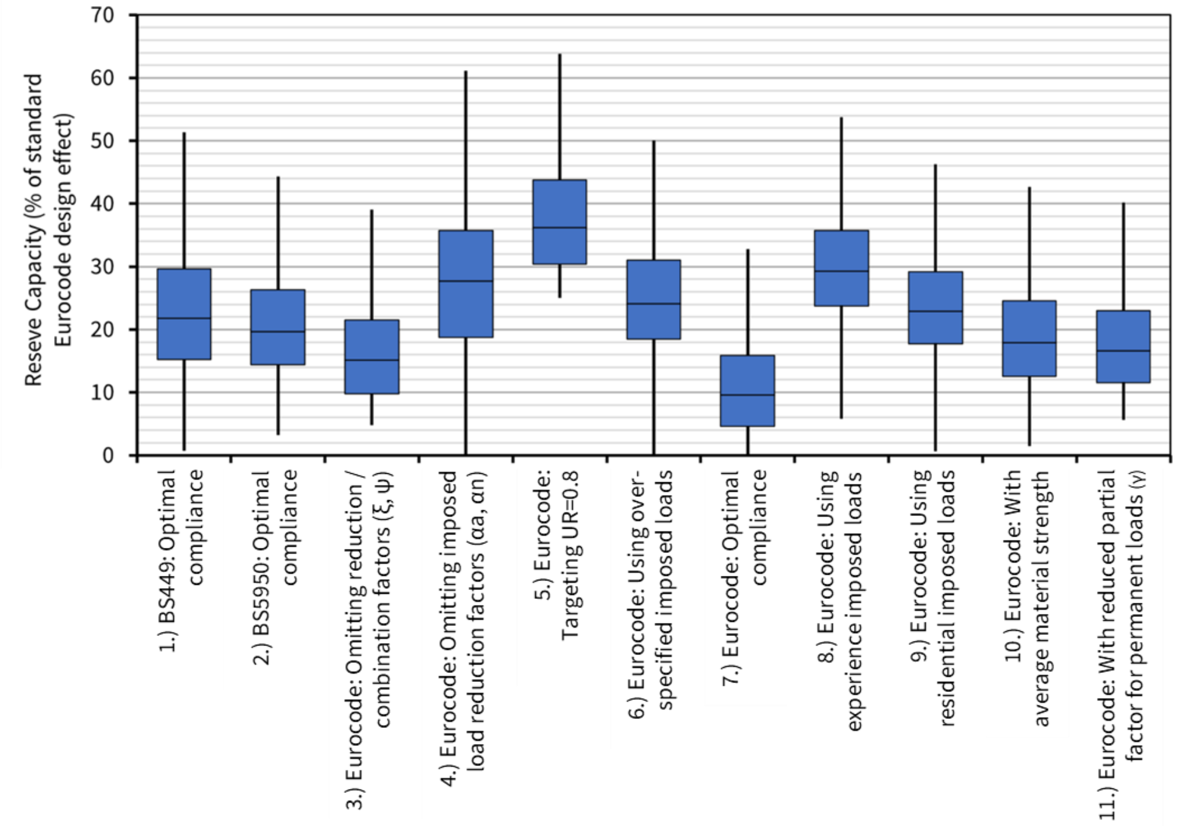

Figure 5 – Distribution of reserve capacities for the 11,252 frame configurations considered under each of the 11 underutilisation scenarios. To mitigate the effect of a small number of unlikely extreme values, whiskers indicate upper and lower bounds 1.5 times the interquartile range from the median.

Figure 5 reveals an average of 10% reserve capacity in buildings designed to optimal Eurocode compliance (scenario 7). Although matching the rule of thumb reportedly used in practice (Gillott *et al.*, 2022b), upper and lower bounds of 0% and 33% (Figure 5) suggest this to be either unsafe or conservative in some cases. On average, more than double the reserve capacity is identified in buildings designed to superseded codes of practice, with median values of 22% and 20% being obtained for BS449 (scenario 1) and BS5950 (scenario 2). Alongside quartile values of 15%-30% and 14%-26% (Figure 5), this suggests the possibility of adopting an increased rule of thumb value for British Standard-designed buildings.

Eurocode designs omitting permanent load reduction (ξ) and variable action combination (ψ) factors (scenario 3) have a median reserve capacity of 15% (Figure 5). The corresponding value for omission of factors for imposed loads acting over large areas (α_a) and multiple storeys (α_n) (scenario 4) is almost twice this (28%, Figure 5), revealing reserve capacity in Eurocode-designed columns to vary greatly depending upon how conservatively these are applied. Associated bounds of 3-39% (scenario 3) and 0-61% (scenario 4) indicate similar disparity across different frame configurations, with the greater range for scenario 4 (Figure 5) resulting from the variation of α_a and α_n factors with bay width (b) and storey number (n) (Beal, 2011). Because of the unknown frequency with which different reduction and combination factors have been omitted over time, the prevalence of associated reserve capacity within the building stock is unclear.

As suggested in previous work (Dunant *et al.*, 2018; Orr, 2018; Orr *et al.*, 2019), the defensive targeting of URs = 0.8 (scenario 5) is perhaps more common, and is revealed to result in a median reserve capacity of 36% (Figure 5). This suggests reserve column capacities of ~1/3 to be widespread across the existing building stock, with potential for this to increase through omission reduction and/or combination factors on a case-by-case basis. As is also common within office building design (Orr and Drewniok, 2018), the over-specification of imposed loads is shown to resulting in a median reserve capacity of 24% (Figure 5) when reappraised to optimal Eurocode compliance (scenario 6).

Even in buildings designed assuming Eurocode-recommended loads, additional reserve capacity may be identified through reappraisal using average-experienced values (Drewniok and Orr, 2018) or those for alternate uses. This results in median reserve capacities of 29% (scenario 8) and 23% (scenario 9) (Figure 5), with the latter value for appraisal using residential loads indicating scope to unlock significant reserve capacity as part of a building's change of use. In real-world cases, the effect of a building's original design using over-specified imposed loads may be compounded with that of its reappraisal using those experienced in reality or representing a less onerous use. This introduces potential for greater amounts of reserve capacity than suggested in Figure 5 within portions of the UK building stock.

Reappraisal using tested material strengths (Melcher *et al.*, 2004) (scenario 10) and modified design codes (Kala, 2007) (scenario 11), results in median reserve capacities of 18% and 17% (Figure 5). Although potentially requiring a more involved on-site investigation and design reappraisal process, this represents potential to identify small amounts of additional reserve capacity in specific members to supplement to that from other sources.

3.3 Extension potential

Figure 6 shows the proportion of the 11,252 considered frame configurations to which different numbers of storeys may be added under the 11 considered scenarios. These are reported for extensions of both office and residential use, employing a standard hot-rolled steel frame (S) and a lightweight cold-formed steel alternative (L). Across all scenarios and extension typologies, between 9% and 89% of considered frame configurations may be extended without strengthening

(Figure 6). Residential extensions and/or those using a lightweight frame exhibit the greatest potential for extension (Figure 6) as a result of their lower associated loads.

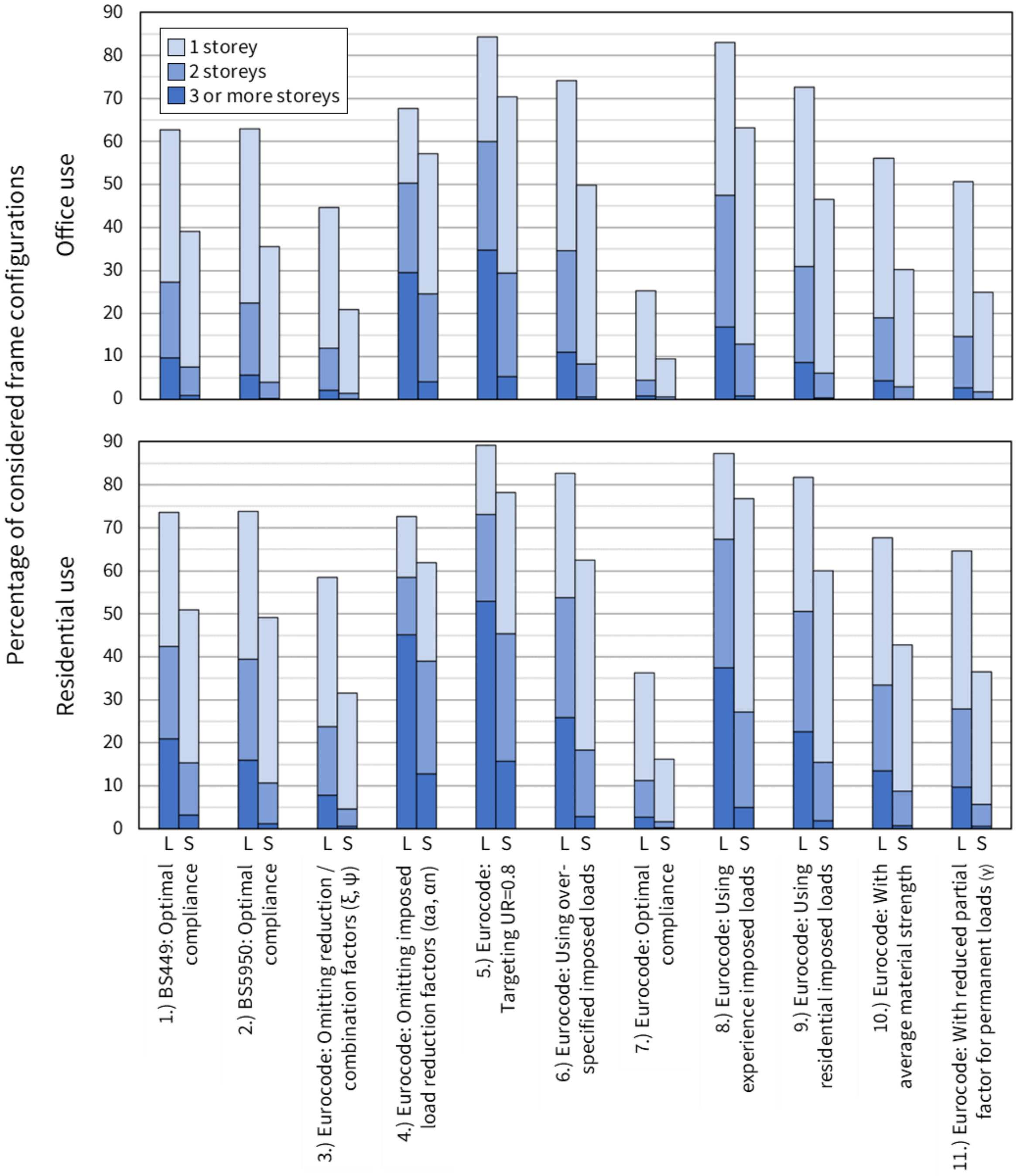

Figure 6 – Percentage of considered frame configurations within each underutilisation scenario extendible by different numbers of storeys when using a lightweight (L) or standard (S) steel frame for office or residential use.

Depending upon the extension's use and structural material, between 9% (standard office) and 36% (lightweight residential) of optimal Eurocode-designed configurations (scenario 7) are extendible by at least one storey (Figure 6). This reveals the use of catalogue sections to frequently facilitate extension without the need for strengthening, even in buildings that have been designed efficiently using current codes of practice.

For superseded design codes the potential for extension increases to between 36% and 74%, representing BS5950-designed buildings (scenario 2) employing a standard office extension and BS449-designed buildings (scenario 1) employing a lightweight residential extension (Figure 6). As well as a greater number, British Standard-designed buildings can also typically be extended by a greater degree. This is exemplified by three or more storeys being able to be added in up to 21% of BS449-designed configurations (scenario 1) without the need for strengthening (Figure 6).

In Eurocode designs, the omission of permanent load reduction (ξ) and variable action combination (ψ) factors (scenario 3) or reduction factors for imposed loads acting over large areas (α_a) and multiple storeys (α_n) (scenario 4) facilitates extension in 21-74% of cases (Figure 6). This suggests that a greater number of Eurocode-designed buildings than are indicated by scenario 7 (9-36%) may be extended in reality. The prevalence of this increased potential within the building stock is unclear, however, because of the unknown frequency with which different factors have been omitted over time.

In contrast, the defensive targeting of URs = 0.8 (scenario 5) *is* thought to be commonplace (Dunant *et al.*, 2018; Orr, 2018; Orr *et al.*, 2019), and facilitates extension without strengthening in 70-89% of cases (Figure 6). The overspecification of imposed loads in office buildings (scenario 6) is known to be a similarly common practice (Orr and Drewniok, 2018), with 50-74% of associated cases being extendible without the need for strengthening (Figure 6). Together, these values suggest an enhanced potential for extension (Figure 6) to be likely within a large number of existing buildings (Dunant *et al.*, 2018; Orr, 2018; Orr *et al.*, 2019; Orr and Drewniok, 2018).

Reappraisal using reduced imposed loads (scenarios 8 and 9) also reveals an increased potential for extension, with 47-87% of considered cases being extendible by at least one storey (Figure 6). Particularly pertinent here is reappraisal using residential imposed loads (scenario 9), for which 60% and 82% of cases may be extended when assuming residential extensions employing standard and lightweight framing respectively (Figure 6). This represents the extension potential unlocked through office to residential conversion, indicating the majority of steel framed office buildings to be extendible without strengthening as part of this hybrid reuse approach. Multiple storeys are also likely to be addable, with a lightweight steel frame enabling extension by three or more storeys in 23% of cases (Figure 6).

3.4 Limitations and future work

This study considers only vertical load transfer through columns in braced, steel-framed offices, assuming sufficient capacity within, or localised strengthening/replacement of, roof-level structures, lateral bracing systems, splices, baseplates and foundations. Fatigue, corrosion and aging are also neglected, with structural degradation and the assessment of reserve capacity within additional elements thus being recommended as part of future work. A broader understanding of reserve capacity and extension potential across different building types could also be obtained through future consideration of moment (i.e. un-braced) frames and those with non-bisymmetric grids, as well as buildings of different use and structural material.

As discussed in Section 2.1, in order to better understand their relative contribution to reserve capacity, each of the 11 considered scenarios have been developed such that they model a single underutilisation source. In reality these are not mutually exclusive, suggesting greater representation of real-world structures to potentially be obtained by future assessment of likely combined scenarios. To better understand applicability to real-world structures, additional work mapping the considered scenarios to the UK's existing building stock is also recommended. In the case of superseded design codes (scenarios 1 and 2) and adjusted imposed loads (scenarios 6, 8 and

9) this may be achieved based upon a buildings age and/or use. For scenarios pertaining to conservative (scenarios 3 and 4) or defensive (scenario 5) practices, however, this would require the collection of additional data to understand their relative prevalence in buildings of different use, age and material.

4 Conclusion

Following growing impetus for adaptive reuse (Architects' Journal, 2019; Gosling *et al.*, 2013; Rockow *et al.*, 2021; Sundling, 2019; The Greater London Authority, 2021), and associated potential for increased loads, this study assesses the impact of different known sources of underutilisation on reserve capacity and vertical extension potential in steel-framed columns. In doing so, 11 underutilisation scenarios have been developed and applied in the design and reappraisal of 11,252 hypothetical frame configurations, totalling 123,772 combinations overall. Identified reserve capacities are contextualised in terms of associated potential for extension assuming both office and residential use and hot-rolled and lightweight steel framing.

Consistent with industry rules of thumb (Gillott *et al.*, 2022b), a median reserve capacity of 10% is identified in buildings designed to optimal Eurocode compliance. This suggests extension without strengthening to be possible in 9-36% of cases, indicating ability to extend even buildings that have been designed efficiently using current codes of practice. British Standard-designed buildings have an increased median reserve capacity of around 20%, enabling extension in up to 74% of cases and suggesting the possibility of adopting enhanced rules of thumb for buildings from different periods.

Employing Eurocodes in a conservative or defensive manner (i.e. sub-optimally) increases median reserve capacity to between 15 and 36%. Although known to be prevalent (Dunant *et al.*, 2018; Orr, 2018; Orr *et al.*, 2019), the proportion of existing buildings to which different conservative and/or defensive approaches apply is not currently understood. This necessitates collection of further practice-based data to identify the proportion of the existing building stock in which different reserve capacities are likely to be present.

Reappraising a building using reduced imposed loads (e.g. for a less-onerous use) reveals median reserve capacities of 23-29%. This represents the ability to extend without strengthening in 60-82% of office to residential conversions, depending upon the grade of structural steel used. Such large potential is particularly pertinent in the UK, considering the existence of office to residential permitted development rights (The Town and Country Planning (General Permitted Development etc.) (England) (Amendment) Order 2021, n.d.) and growing housing demand.

Overall, this work reveals sufficient reserve capacity to facilitate extension in a broad range of scenarios, including where a buildings has been designed efficiently using Eurocodes. Increased reserve capacity and extension potential is identified in buildings designed using superseded codes of practice or applying Eurocodes in a conservative or defensive manner. This is similarly true when reappraising buildings using adjusted design values, with a significant extension potential being unlocked through a building's conversion from office to residential use.

As well as the modelled scenarios, reserve capacity and extension potential vary greatly across the frame configurations and extension typologies considered. This variability is consistent with previous work (Gillott *et al.*, 2022b; Pattison, 2021), but does not preclude the adoption of a suite of enhanced rules of thumb value for different buildings archetypes. These may be assigned using a building's age, use and/or additional practice-based data, and should be mapped onto the UK's building stock as part of future work.

Acknowledgements

This project was funded by EPSRC under the studentship project number 2280211. For the purpose of open access, the author has applied a Creative Commons Attribution (CC BY) licence to any Author Accepted Manuscript version arising.

References

Architects' Journal. (2019), "RetroFirst – A campaign by The Architects' Journal", available at: https://www.architectsjournal.co.uk/news/retrofirst (accessed 12 October 2021).

Astle, P., Bajars, K., Brookes, S., Cartwright, B., Coates, H., Croft, A., Densley Tingley, D., *et al.* (2023), *Circular Economy and Reuse: Guidance for Designers*, The Institution of Structural Engineers, London.

Beal, A.N. (2011), "A history of the safety factors", *Structural Engineer*.

Bocken, N.M.P., Pauw, I. de, Bakker, C. and Grinten, B. van der. (2016), "Product design and business model strategies for a circular economy", *Journal of Industrial and Production Engineering*, Taylor & Francis, Vol. 33 No. 5, pp. 308–320, doi: 10.1080/21681015.2016.1172124.

British Constructional Steelwork Association. (2021), *BCSA Annual Review 2020/21*, London.

British Standards Institution. (1969), *BS 449-2:1969: The Use of Structural Steel in Building — Part 2: Metric Units*.

British Standards Institution. (1996), *BS 6399-1:1996: Loading for Buildings — Part 1: Code of Practice for Dead and Imposed Loads*.

British Standards Institution. (2001), *BS 5950-1:2000: Structural Use of Steelwork in Building — Part 1: Code of Practice for Design — Rolled and Welded Sections*.

British Standards Institution. (2002), *BS EN 1991-1-1: 2002 — Eurocode 1: Actions on Structures — Part 1-1: General Actions — Densities, Self-Weight, Imposed Loads for Buildings*.

British Standards Institution. (2005), "BS EN 1993-1-1:2005 - Eurocode 3: Design of steel structures - Part 1-1: General rules and rules for buildings", doi: 10.1201/b18121-13.

British Standards Institution. (2008), *NA to BS EN 1991-1-1:2002 — UK National Annex to Eurocode 1: Actions on Structures — Part 1-1: General Actions — Densities, Self-Weight, Imposed Loads for Buildings*.

British Standards Institution. (2011), *BS EN 1990:2002+A1: Eurocode 0 - Basis of Strcutural Design*.

Drewniok, M. and Orr, J. (2018), *MEICON: Minimising Energy in Construction Origin of 100 Psf Report*, Cambridge.

Drewniok, M.P., Campbell, J. and Orr, J. (2020), "The Lightest Beam Method – A methodology to find ultimate steel savings and reduce embodied carbon in steel framed buildings", *Structures*, Elsevier Ltd, Vol. 27, pp. 687–701, doi: 10.1016/j.istruc.2020.06.015.

Dunant, C.F., Drewniok, M.P., Eleftheriadis, S., Cullen, J.M. and Allwood, J.M. (2018), "Regularity and optimisation practice in steel structural frames in real design cases", *Resources, Conservation* *and Recycling*, Elsevier, Vol. 134, pp. 294–302, doi: 10.1016/J.RESCONREC.2018.01.009.

Gibbons, C. (1995), “Economic steelwork design”, *Structural Engineer*, Vol. 73 No. 15, pp. 250–253.

Gibson, T., Hunter, I., Henderson, R., Gedge, G., Gibbons, C., Swift, R., Brown, D., *et al.* (1995), *Design for Manufacture Guidelines (P150)*, Ascot.

Gillott, C., Davison, B. and Densley Tingley, D. (2022a), “The Potential of Vertical Extensions: A Case Study Analysis”, *Central Europe Towards Sustainable Building 2022*, IOP Conference Series: Earth and Environmental Science, Prague.

Gillott, C., Davison, B. and Densley Tingley, D. (2022b), “Drivers, barriers and enablers: construction sector views on vertical extensions”, *Building Research & Information*, Vol. 50 No. 8, pp. 909–923, doi: 10.1080/09613218.2022.2087173.

Gillott, C., Mihkelson, W., Lanau, M., Cheshire, D. and Densley Tingley, D. (2023), “Developing Regenerate: a circular economy engagement tool for the assessment of new and existing buildings”, *Journal of Industrial Ecology*, doi: 10.1111/jiec.13377.

Gosling, J., Sassi, P., Naim, M. and Lark, R. (2013), “Adaptable buildings: A systems approach”, *Sustainable Cities and Society*, Vol. 7, pp. 44–51, doi: 10.1016/j.scs.2012.11.002.

Kala, Z. (2007), “Influence of partial safety factors on design reliability of steel structures - probability and fuzzy probability assessments”, *Journal of Civil Engineering and Management*, Vol. 13 No. 4, pp. 291–296, doi: 10.1080/13923730.2007.9636449.

Lawson, R.M., Ogden, R.G. and Rackham, J.W. (2004), *Steel in Multi-Storey Residential Buildings*, Ascot.

Mathworks. (2021), “MATLAB”, available at: https://www.mathworks.com/products/matlab.html (accessed 7 February 2022).

Mei, X., Hawkins, W., Darby, A. and Ibell, T. (2024), “Realising the reserve capacity in existing reinforced concrete columns”, *Structures*, Elsevier, Vol. 63, p. 106360, doi: 10.1016/J.ISTRUC.2024.106360.

Melcher, J., Kala, Z., Holický, M., Fajkus, M. and Rozlívka, L. (2004), “Design characteristics of structural steels based on statistical analysis of metallurgical products”, *Journal of Constructional Steel Research*, Elsevier, Vol. 60, pp. 795–808, doi: 10.1016/S0143-974X(03)00144-5.

Moynihan, M.C. and Allwood, J.M. (2014), “Utilization of structural steel in buildings”, *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*, Vol. 470, doi: 10.1098/rspa.2014.0170.

Orr, J. (2018), *MEICON: Minimising Energy in Construction Survey of Structural Engineering Practice Report*, Cambridge.

Orr, J. (2019), *MEICON: Minimising Energy in Construction Design Uncertainty Report*, Cambri.

Orr, J. and Drewniok, M.M.P. (2018), “Rentable floor loading according to data from Letting Agencies”, MEICON, available at: https://www.meicon.net/letting-floor-data (accessed 12

December 2022).

Orr, J., Drewniok, M.P., Walker, I., Ibell, T., Copping, A. and Emmitt, S. (2019), “Minimising energy in construction: Practitioners’ views on material efficiency”, *Resources, Conservation and Recycling*, Elsevier B.V., Vol. 140, pp. 125–136, doi: 10.1016/j.resconrec.2018.09.015.

Pattison, J. (2021), “Vertical extensions: technical challenges and carbon impact”, *The Structural Engineer*, Vol. 99 No. 5, pp. 12–15.

RICS. (2017), *Whole Life Carbon Assessment for the Built Environment*, London.

Rockow, Z.R., Ross, B.E. and Becker, A.K. (2021), “Comparison of Building Adaptation Projects and Design for Adaptability Strategies”, *Journal of Architectural Engineering*, Vol. 27 No. 3, doi: 10.1061/(asce)ae.1943-5568.0000481.

Sundling, R. (2019), “A development process for extending buildings vertically – based on a case study of four extended buildings”, *Construction Innovation*, Emerald Group Publishing Ltd., Vol. 19 No. 3, pp. 367–385, doi: 10.1108/CI-05-2018-0040.

The Greater London Authority. (2021), *The London Plan*, London.

The Steel Construction Institute. (2008), *Best Practice in Steel Construction: Commercial Buildings*, Steel Construction Institute.

The Steel Construction Institute, Tata Steel and The British Constructional Steelwork Association. (2015), *Steel Building Design: Design Data*, The Steel Construction Institute and The British Constructional Steelwork Association Limited, Ascot and London.

The Town and Country Planning (General Permitted Development etc.) (England) (Amendment) Order 2021. (n.d.). *SI 2021/428*.

UK Green Building Council. (2021), *Net Zero Whole Life Carbon Roadmap: A Pathway for the UK Built Environment*, London.

United Nations Environment Programme. (2022), *2022 Global Status Report for Buildings and Construction: Towards a Zero-emission, Efficient and Resilient Buildings and Construction Sector*, Nairobi.