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Optimising the Balance Between Flexibility and Structural Mass for Lower Short- and Long-Term Embodied Carbon Emissions in Mass Housing

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Abstract. The building construction industry is one of the largest contributors to global greenhouse gas emissions. One solution to reduce the industry's carbon footprint is to design structures efficiently, thus using less structural mass. However, over-designing is a fundamental aspect of flexibility; a building's capacity to make physical changes in the future – which is key for domestic buildings in particular. It is therefore important to strike a balance between structural efficiency and high flexibility, to limit both short- and long-term embodied carbon emissions. This balance was investigated using a mass housing case study, creating a series of design iterations to explore the trade-off between flexibility and structural mass. An optimum solution illustrated that this case study can be redesigned to have double the flexibility, lower structural mass, and less carbon-intensive materials. Therefore, this research concluded that it is possible to significantly reduce the short-term embodied carbon emissions of this housing design, whilst simultaneously reducing long-term emissions too. Although these findings might be specific to this case study, the duplicate nature of mass housing means that the carbon savings of this one housing design can be multiplied many times across a whole development. Applying this research to other mass housing designs could significantly reduce the embodied carbon of future developments and improve the carbon footprint of the building construction industry.

Keywords: Embodied Carbon, Structural Mass, Flexibility

1.   Introduction
Global greenhouse gas emissions need to be reduced by 70% by 2030, to avoid a temperature increase of more than 1 °C (Khasreen, Banfill and Menzies, 2009). The building construction industry is one of the world's largest carbon emission contributors, generating almost half of the greenhouse gases emitted globally (Khasreen, Banfill and Menzies, 2009). To avoid excessive temperature increases, it is therefore essential that the construction industry reduces these emissions wherever possible.

One route to decreasing the industry's carbon footprint is to design using less structural mass. Designers could potentially reduce their steel consumption by approximately 40%, without compromising safety and services, simply by improving the structural utilisation of buildings (Moynihan and Allwood, 2014). Limiting structural redundancy in this way would lead to material savings, with likely proportional embodied carbon savings.

However, a potential consequence of eliminating structural redundancy is less capacity for a building to adapt to the changing needs and requirements of its users - an essential part of "social, environmental

and economic sustainability" (Till and Schneider, 2005, p.287). Such inflexibility risks premature obsolescence and even wasteful, carbon-intensive demolition.

This dilemma is particularly interesting in the context of housing. In the UK, there is a demand to grow the housing stock by over a quarter of a million annually (Great Britain, Ministry of Housing Communities & Local Government, 2020; Power, 2010). Given the scale of the housing demand, mass housing, a 'dense and repetitive housing solution' (Saglar Onay, Garip & Garip, 2019) is a common way to meet the housing needs. The scale and repetition of mass housing construction therefore reveals significant potential for carbon savings. However, Schneider and Till (2005) and Arge (2005) point out that flexibility is often not in the best interests of housing developer-retailers, who want a quick and high-profit sale. Schneider and Till (2005) explain that 'tight-fit functionalism' is the result of a high-profit design strategy. Given this, housing developers will likely need incentives to adopt a more adaptable and carbon-considerate approach to design.

Given the likely tensions between delivering structurally efficient and flexible buildings, this project investigates the balance between short-term and long-term embodied carbon-saving solutions in mass housing structures. This goal is delivered through three aims, and a series of objectives for each aim, these are as follows:

1) Analyse the flexibility of a housing case study:
   a. Identify the most common flexibility strategies for housing from existing research.
   b. Create scoring criteria to generate a quantitative assessment of flexibility.
2) Analyse the structural mass and associated embodied carbon of a housing case study:
   a. Calculate the utilisation of each structural member.
   b. Calculate the overall structural mass and associated embodied carbon.
   c. Calculate the utilisation and redundancy of the total mass and total embodied carbon.
3) Optimise the balance between flexibility and structural mass, and reduce the structural mass of a case study, without compromising the future structural adaptation potential.
   a. Develop a series of design iterations, demonstrating the different trade-offs between flexibility and structural mass.
   b. Develop an optimum design that balances a low structural mass and a high level of flexibility.

2. Methodology

A case study mass housing design was selected and, in a simplified form, used as the basis for three design iterations.

To assess the flexibility of the designs, a Flexibility Assessment Tool was created, by identifying the most common flexibility criteria in existing research and tabulating them.

The structural members of each design iteration were analysed through loading and utilisation ratio (U/R) calculations. The utilisation ratio is calculated as follows:

U/R   =   governing design stress /design strength

The mass and embodied carbon (EC) of each structural member were also calculated, and the results, along with the utilisation ratios (U/Rs), used to calculate the useful and useless redundancies of each design.

Conclusions drawn from the assessments of each design were used to inform the following iteration. See section 2.2 for the design iteration steps.

2.1. Case study

For the reasons discussed in the Introduction, mass housing offers great potential to improve the social and environmental sustainability of the industry. Due to its duplicate nature, each marginal carbon saving can be multiplied many times, soon adding up across a whole development. A property company shared one of their typical mass housing designs - a 79.4m² detached/semi-detached dwelling. The design received is referred to throughout as the base design.

2.2. Design Iterations

To illustrate the trade-off between structural mass and flexibility, the base design was redesigned with several iterations. The first design iteration prioritises high structural efficiency. The second iteration prioritises high flexibility. The third iteration optimises high structural efficiency with high flexibility.

2.3. Flexibility Assessment

First, the flexibility of each design was assessed using a spreadsheet tool that drew on previous work identified through a literature review. This process involved cataloguing a wide range of flexibility criteria, condensing the list down by removing duplicates strategies not applicable to housing or to the structure. The tool's criteria are composed of the most common flexibility strategies, accompanied by design suggestions and explanations of how to implement them. It was modelled on Heidrich et al. (2017), with adaptability strategies listed on one axis and research papers investigated on the other. Each criterion can be graded from 0-3 (0 = not met at all, 3 = best met), as in the FLEX 4.0 tool (Geraedts, 2016). An explanation for the grade given can be noted in the 'remarks' column, which is useful for future reference and justification. The total of all these grade scores is used to create an overall flexibility score and percentage of flexibility.

FLEXIBILITY ASSESSMENT

Strategy	Strategy Explanation	Assessment Grade Explanation (0 = not at all - 3 = best)
Flexible components separated from inflexible components	Enables changes to take place without the inflexible components interfering with the possibility or difficulty to achieve this change.	0. Placement of inflexible components limits expansion of building in x,y and z directions. Infill cannot be customised/changed without destruction to the Support. 1. Infill can be adapted without impacting the Support structure - customisation is possible. 2. Positioning of inflexible components (bathroom, kitchen and staircase) allow expansion in horizontal and vertical directions (+ level 1). 3. Placement of staircase creates independent nucleus such that ground floor can be bipassed and other floors are accessible from entrance (+ levels 1 and 2).
Layer building systems	Allows various components with different lifespans to be changed/adapted when necessary, without interfering unnecessarily with other components. Layers are site, structure, skin, services, space.	0. Total entanglement of all layers - accessing components with short lifespans is only possible through demolishing integral structural elements, e.g. piping embedded in cast concrete. All layers constructed at once. 1. Entanglement of components but not embedded in structure - all other layers constructed once structure is erected. 2. Disentangled layers. Services have designated runs, however are boxed out/buried behind finishes. 3. Disentangled layers. All services are exposed/accessible through removable panels. All short-lifespan components can be maintained/adapted without impacting long-lifespan components. Designated runs throughout the ceiling/floors that have surplus space for additional services.
Over-designing	Redundancy in the structure equals in-built capacity for additional loading. Allows future structural changes.	0. No useful structural redundancy - maximum utilisation is close to 100% or redundancy is useless. 1. Excess capacity in floor system to anticipate change in internal partition locations. 2. Vertical expansion possible through oversized vertical elements and over-sized attic floor design (anticipate habitation (1.5kN/m²) not just storage). 3. Both grades 1+2.
Large beam spans	Limited vertical load paths. Broadens possibilities for adapting space/changing uses.	0. Very short beam spans used - frequent internal load bearing walls/columns. Very limited options for internal arrangement - tight-fit functionalism. 1. Several awkwardly positioned internal load paths that limits the options for internal arrangement. 2. A few internal load paths that disect the interior space into zones - some freedom as to how to shape/organise these zones. 3. No internal load bearing walls/columns - one large open plan space that can be divided up using partitions. All beams span to external walls.
Open plan attic arrangement	Allows vertical expansion through loft conversion.	0. Fink truss arrangement - no adaptation of loft space possible. 1. Attic truss or cut-roof arrangement but limited floor-ceiling height, not suitable for habitation but can be used for storage. 2. Cut roof arrangement - has sufficient headroom/dimensions for a single room. 3. Cut roof arrangement with large open plan - suitable for partitioning into multiple spaces.
Grid structure / frame	Superstructure consists of regular layout of beam and column elements only.	0. Irregular/inconsistent load path geometry - very limited options for adapting internal space (tight-fit functionalism). Internal and external load-bearing walls limit the opportunity for horizontal expansion (cannot remove walls without structural work). 1. Regular geometry of load path layout - allows some, but little, scope for adapting internal arrangement between load-bearing internal walls. 2. Structural bay layout with load-bearing external walls (including party walls) - neighbouring units cannot be fused, but internal load paths are in column form. 3. Structural bay layout with no load bearing walls (including external walls) - allows for horizontal expansion and fusion of two units. All vertical load paths are columns.

Figure 1. Flexibility Assessment Tool

2.4. Structural Analysis

The structural members of each design were also analysed through a series of loading and U/R calculations. The following design criteria were analysed; bending, axial, combined axial and bending, shear stress and deflection. These loading calculations were done by hand, in accordance to Eurocodes. Only superstructure was considered.

2.4.1. Utilisation Ratio (U/R). From these loading calculations, the governing design criterion (highest U/R) was selected as the U/R for the structural member. The U/R was calculated by dividing the governing design stress by the design strength.

2.4.2. Useful and Useless Redundancy. For design iterations that incorporate additional loading capacity, loading was divided into two types: standard and additional. For example, if the attic went from a light storage space to a habitable room, the variable load would increase from 0.6kN/m² to 1.5kN/m², meaning the standard load was 0.6kN/m² and the additional load was 0.9kN/m². Sections were selected based on the maximum loading the member could experience (standard load plus additional load), meaning that the maximum U/R for this member was based on the sum of both loadings. The standard U/R for this member was based on the standard loading alone, as if the additional loading were not applied yet. The difference between standard U/R and the maximum U/R represents the useful redundancy that would become utilised if the additional loading were applied on top of the standard loading.

2.5. Structural Mass and Embodied Carbon Assessment

Using the calculated U/Rs and the useful and useless redundancies, a series of calculations were created, presenting a dataset of mass-, embodied carbon- and utilisation-related values, described below. Embodied carbon values were sourced from the Inventory of Carbon and Energy (ICE V3.0 database), a free online embodied carbon database for construction materials (Sustainable Energy Research Team (SERT), 2019).

The following embodied carbon (EC) values were used:

Average timber	0.493kgCO2e/kg
OSB timber	0.455kgCO2e/kg
Timber I-beam	0.483kgCO2e/kg
Steel section	1.55kgCO2e/kg

For each structural component, e.g. floor joists, the following values were calculated using member masses, embodied carbon values and utilisation ratios: total structural mass, total utilised mass, total redundant mass, total useful redundant mass, total useless redundant mass, total EC, total utilised EC, total redundant EC, total useful redundant EC and total useless redundant EC.

For designs without additional loading capacity, all redundancy is useless redundancy – there is no useful redundancy.

These values were calculated for each design and were compared along with the flexibility assessment of each design.

3.   Results

3.1.   Evolution of the structural design
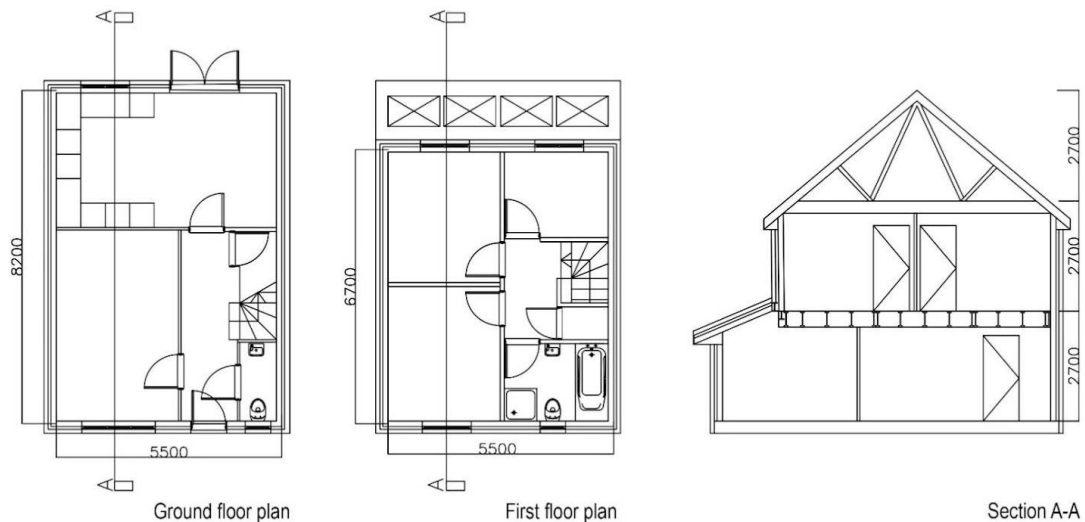
3.1.1. Base Design

Figure 2. Architectural drawings of base design (not to scale)

3.1.2. First Design Iteration: Lowest Mass.
Lateral resistance is provided by two external racking walls – the steel wind frame has been removed, to save embodied carbon. The stepped-out kitchen has been removed as a result. Other than this, the design remains the same. Minimum mass has been prioritised over rationalisation.
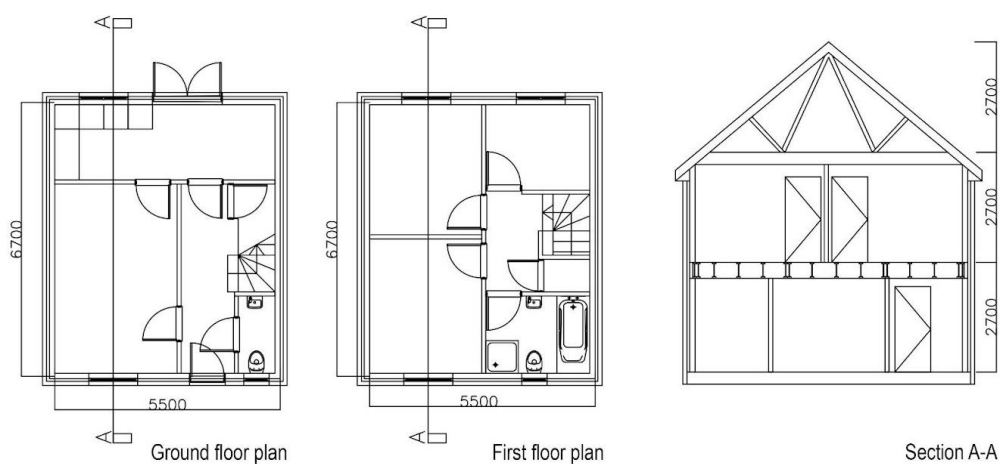
Figure 3. Architectural drawings of first design iteration (not to scale)

3.1.3. Second Design Iteration: Highest Flexibility.
High flexibility was prioritised over low structural mass. The primary aim of this second design iteration was to achieve the highest flexibility score possible for this house. This led to several design changes, using the Flexibility Assessment Tool for guidance. First, the fink truss roof arrangement was replaced by a timber cut-roof arrangement. Second, engineered timber i-joists were used for the attic floor, like the first floor. Third, the timber

stud walls were replaced by a timber frame. Fourth, the timber external racking walls were replaced with steel wind frames. Finally, the overall height of the structure was increased by 1150mm.
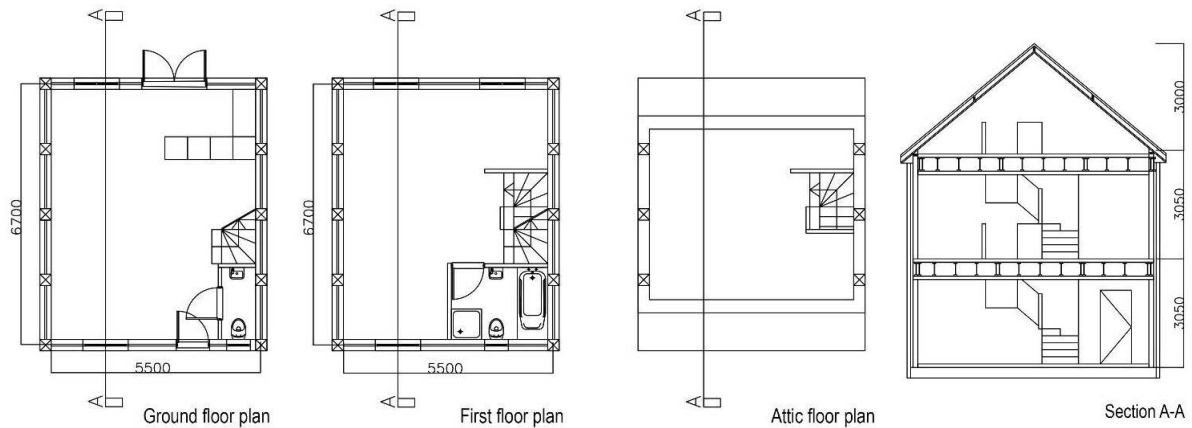
Figure 4. Architectural drawings of second design iteration (not to scale)

3.1.4. Third Design Iteration: Optimised. The aim of the third design iteration was to balance the trade-off between flexibility and structural mass, by considering the outcomes of the two previous designs and balancing how flexibility and structural mass compromise one another. This approach considers both flexibility and global structural factors at the primary design stage.

The construction of this design iteration combines the most successful aspects of previous designs. First, the cut-roof arrangement and the attic floor joist arrangement from the second design iteration has been used. Second, the timber stud walls used in the base design and first iteration have been used, eliminating the need for the roof transfer beams and the steel wind frames. Third, the increased overall height of 1150mm has been used again.
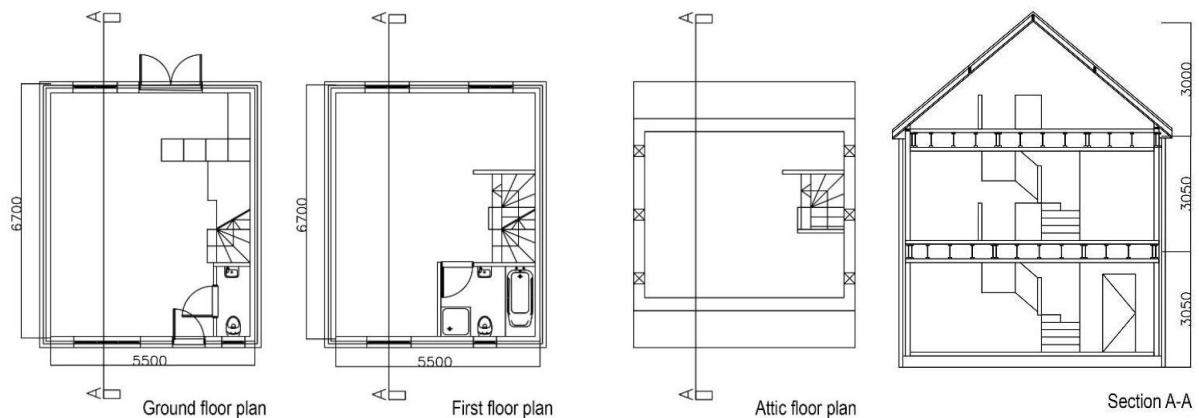
Figure 5. Architectural drawings of third design iteration (not to scale)

3.2. Comparison of Designs

3.2.1. Mass and EC graphs. These graphs illustrate the distribution of mass and embodied carbon between each structural component. They also show the flexibility score of each design, to compare how mass/EC fluctuates with the change in flexibility.
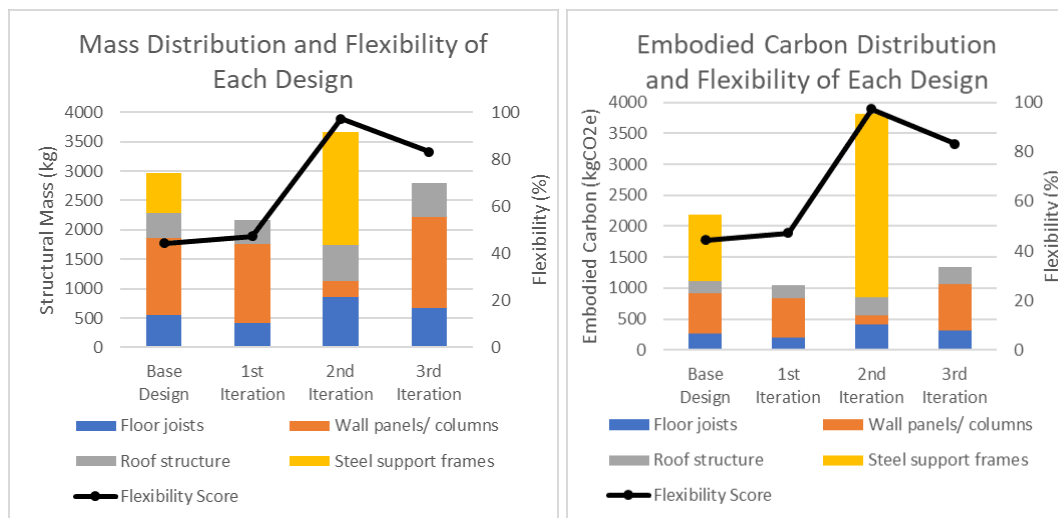
Figure 6. Combined stacked column chart and line graphs, 6a) Distribution of mass between structural components in all 4 designs, 6b) Distribution of embodied carbon between structural components in all 4 designs

The second design iteration (extreme flexibility) has the highest structural mass and associated embodied carbon. This suggests that designing for extreme flexibility significantly increases the short-term embodied carbon emissions. The difference in total embodied carbon between the second and third iterations shows that a relatively small compromise in flexibility can have significant savings.

There is a correlation between total structural mass and flexibility, but the relationship is not directly proportional – it's more complicated. The overall flexibility of the third iteration is almost double that of the base design, as well as being slightly lower in mass and significantly lower in embodied carbon. This demonstrates that it is possible to reduce the structural mass and increase the flexibility of the case study, creating both short- and long-term embodied carbon savings.

3.2.2. Utilisation graphs. These graphs show the same total mass and total embodied carbon of each design but illustrate the distribution of utilisation and redundancy (both useful and useless redundancy).
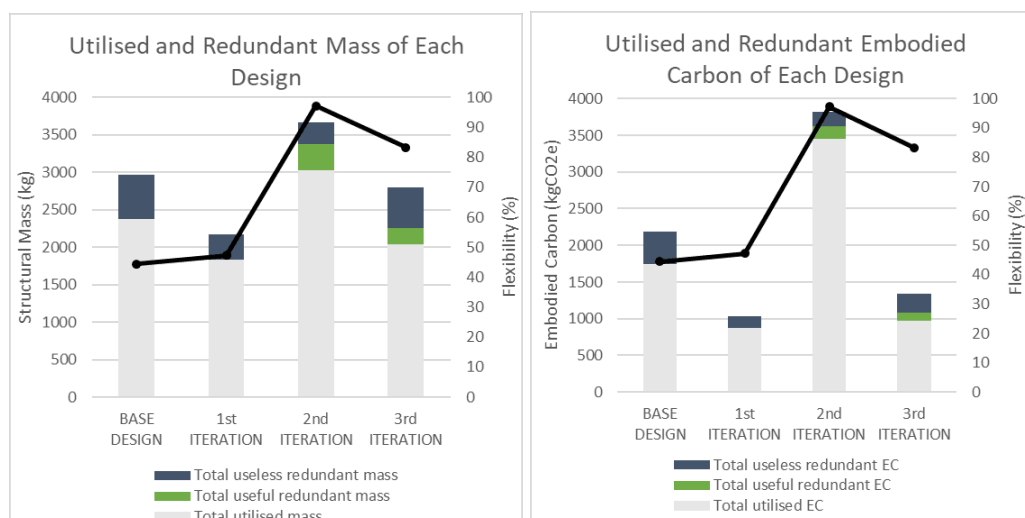

Figure 7. Combined stacked column chart and line graphs, 7a) Distribution of utilised and redundant mass in all 4 designs, 7b) Distribution of utilised and redundant embodied carbon in all 4 designs

The base design has the largest amount of useless redundant mass and embodied carbon, demonstrating that the case study has more wasted embodied carbon than is necessary. However, the proportion of useless redundancy randomly fluctuates between the designs, suggesting that its proportion is design dependent. The second iteration has the largest amount of useful redundant mass and embodied carbon and the highest flexibility score, suggesting that useful redundancy and overall flexibility are related. This reiterates the point made previously that a relatively small reduction in flexibility can have a significant impact on the embodied carbon, including redundancy.

3.2.3. EC per unit usable floor area. This graph illustrates the total embodied carbon of the structure per square metre of usable floor area in each design. The orange line indicates the lower bound of expected embodied carbon of a single-family building in Simonen, Rodriguez and De Wolf's research (2017, Figure 1).
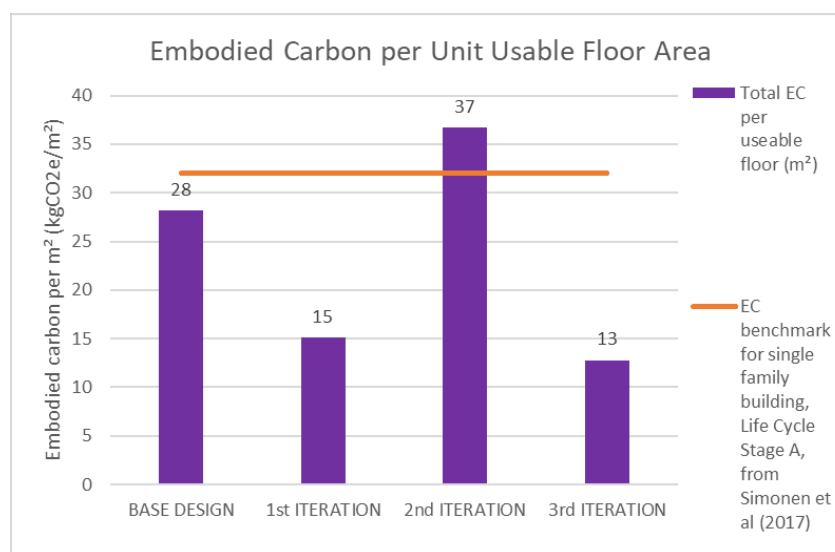
Figure 8. Combined column and line graph showing embodied carbon per unit usable floor area for all 4 designs

The embodied carbon per unit usable floor area (EC/m²) graph tells us that the values of EC/m² from these designs are significantly lower than data collected in previous research. This difference is most likely due to the difference in building layers being assessed – unlike Simonen, Rodriguez and De Wolf's data (2017), the present research was based on superstructure alone. Moreover, the third design iteration has the smallest EC/m², even though it does not have the lowest overall embodied carbon. By utilising the attic space for usable floor area, and increasing the usable floor area by 50%, in addition to having a timber-only structure, this gives the lowest embodied carbon per unit of living space.

4.   Conclusions

4.1.   The Case Study

The assessment of the base design shows that the case study is moderately inflexible. Potential benefits, such as customisation and extending the life of the house, are not being anticipated by the developers. In addition, the research found that the base design has an unnecessary amount of wasted structural mass. The developers seem to have favoured rationalisation, supporting Moynihan and Allwood's theory (2014), that repetition of sections relates to low utilisation. However, the varying levels of useless redundancy in each design iteration indicate that it is difficult to eliminate in-built waste with standardised sections. Therefore, there will most likely always be some wasted embodied carbon in these designs since bespoke sections can significantly increase building costs.

4.2.   The trade-off between flexibility and low structural mass

The results show that the short-term embodied carbon emissions can be reduced by limiting structural mass, rejecting rationalisation, and selecting materials with a lower embodied carbon content. They also show that the long-term embodied carbon emissions can be reduced by potentially extending the building's lifespan through nearly doubling its flexibility. Most importantly, the results show that it is possible to reduce both the short- and long-term embodied carbon emissions of the structure simultaneously, so long as structural efficiency and flexibility are considered simultaneously at the primary design stage. The difference in embodied carbon between the second and third iterations shows that a relatively small compromise in flexibility can have significant savings. This shows that it is not viable to simply limit mass by adjusting local factors, such as section sizes, at the secondary design stage - adjusting global factors, such as the whole structural arrangement, in combination with flexibility strategies at the primary design stage is necessary, to keep embodied carbon content sufficiently low. This research also supports the theory that over-designing is integral to flexibility, as suggested by Densley Tingley *et al.* (2020). 'Over-designing' was identified in 8/11 of the research papers analysed for the Flexibility Strategy Spreadsheet. This suggests that increasing the up-front embodied carbon cost of the case study design can be outweighed by the potential long-term benefits if the in-built flexibility is exploited during the building's life.

4.3.   The importance of materiality

Although the focus of this research was to explore the trade-off between flexibility and low structural mass, it became evident that materiality also has a significant influence on short-term embodied carbon costs. The difference in the range of values in the embodied carbon distribution graphs and the mass distribution graphs demonstrates is large, which suggests that the use of steel is significantly increasing embodied carbon content. This suggests that materiality and structural mass should be considered concurrently in order to achieve low short-term embodied carbon. Minnuno et al. (2021) supports that materiality has an influence on embodied carbon, identifying 'material substitution' as one of five embodied carbon saving strategies. However, the present research has recognised that mass, materiality, and flexibility are interrelated - which appears to be a gap in existing research that has not yet been addressed.

4.4.   Application

The findings of this research are specific to housing, with the Flexibility Assessment tool being developed specifically for this use type. However, there is potential to translate this to other building typologies. This could either involve creating a series of Flexibility Assessments, where each one is specific to a building typology, or could involve the creation of a general flexibility assessment that can be used across building types. From here, the same methodology can be used to investigate the trade-offs between flexibility and low structural mass on a broader range of building uses, and the findings could then be scaled across the built environment.

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