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Assessing the upfront carbon cost of structural adaptability

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ABSTRACT

As the need for immediate carbon reductions becomes more evident, the structural engineering industry must decide upon the balance between the need for short-term carbon savings, through optimisation strategies such as lean design, and the implications of long-term structural adaptability (or lack thereof). In order to make informed decisions about this, the carbon costs must be quantified. This paper provides an initial benchmark for the carbon costs of adaptability across four design inputs (imposed load, vibration limit, storey height and grid arrangement) applied to medium-rise steel-framed composite floor building structures. The carbon results are then combined with a proposal for an adaptability scoring method, highlighting optimum areas within each parameter range where the upfront carbon cost might be outweighed by the adaptability benefit it provides. The approach of assessing adaptability benefit per unit of carbon is a novel contribution to both research and design decision-making processes, providing the evidence to balance the desires of the short-term with the consequences in the long-term.

1. Introduction

The built environment accounts for almost 40 % of global annual carbon emissions [1]. Recent improvements in operational efficiencies have increased the proportion, and therefore awareness of, the embodied aspects of construction emissions [2,3]. Embodied emissions include those resulting from the extraction, transport, processing, fabrication, construction, maintenance and end-of-life of the materials used within the structure [4]. These embodied emissions are usually presented in units of $kgCO_2e$, or carbon dioxide equivalents (hereon referred to as embodied carbon (EC) or simply 'carbon'), and often expressed as $kgCO_2e$/tonne of material used or $kgCO_2e/m^2$ of building area. The structural frame is a significant proportion of the total EC of a building [3], and structural engineers have acknowledged their responsibility to reduce the environmental impact of construction [5].

One solution to reduce the embodied emissions of buildings is to align construction with the principles of the circular economy (CE). CE aims to keep materials at their highest value for as long as possible [6], e.g. keeping a building as a building, a beam as a beam, or steel as steel. This can be achieved through the combination of three broad strategies: narrowing, closing, and slowing resource loops [7]. To date, the predominate focus of the structural engineering industry's sustainability efforts has been on the 'narrowing' aspect of CE – minimising the upfront material demands of building structures through optimisation and lean design [3,8].

Recently, there has been an increased awareness of the benefits of 'closing' resource loops, by designing new structures using reused elements, and supporting deconstruction and reuse at end of life with demountable design and record keeping in material passports [9]. The final CE component, 'slowing' resource loops through strategies such as design for adaptability (DfA), has largely gone unnoticed in industry even though the concept has its origins as early as the mid-20th century [10]. The barriers to DfA have been extensively reviewed, including arguments such as limited guidance and data on building adaptation, reluctance and risk avoidance of the construction industry, and uncertainty around future prediction and the economic benefit of the approach [11–14]. Nevertheless, in theory, DfA can achieve carbon savings through avoiding early building obsolescence, demolition and rebuild by accommodating changes in their context, environment or user requirements [15].

Abbreviations: EC, embodied carbon; CE, circular economy; DfA, design for adaptability; LCA, life cycle assessment; UB, universal beams; UC, universal columns; ULS, ultimate limit state; SLS, serviceability limit state.

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Nomenclature

M_{Ed}	flexural action
w	imposed load
L	span
δ	deflection
E	Young's modulus
I	second moment of area
f	natural frequency

1.1. Carbon cost of adaptability

As there has been limited impetus from the construction industry regarding DfA, there is currently a lack of understanding of the carbon implications of the approach; both in terms of potential increases in upfront carbon requirements and long-term carbon savings [11,16]. The few studies that have been done on the carbon cost of adaptability typically focus on a single building use typology, e.g. residential houses [17] or education buildings [18] and, therefore, miss out on the aspects of adaptability relating to changes *between* uses. As such, this paper aims to assess the carbon cost of DfA for a broader range of use typologies through a performance-based approach.

1.2. DfA parameters

To understand the carbon cost of adaptability we must understand which input parameters influence the adaptability potential of a building, and what the relationship is between these parameters and resulting material and embodied carbon (EC) demands. Various categorisations of DfA strategies have been proposed in the literature [14,19–21]. This paper will focus on four design inputs, or 'DfA parameters', namely: load carrying capacity, vibration limit, storey height and average span. Each of these design parameters will have influence over the resulting EC of the structure, both in isolation and in combination with varying grid arrangement.

The load carrying capacity of a structure is prescribed by the imposed load specified in the design brief, which represents the maximum force a building is expected to experience during its normal operation. The imposed load requirement for different building use typologies is codified in the Eurocodes [22,23]. As such, a structure that is not designed to carry (and cannot be strengthened in order to carry) an imposed load for a given use, will not be able to be adapted to that use. For example, residential imposed loading is lower than office loading; therefore, if a structure is designed for residential loading, and cannot be strengthened to support the higher office load, it cannot be converted to an office. As such, the overspecification of imposed load is a common strategy to improve the adaptability potential of a building [20,24].

Control of floor vibration is typically one of the more onerous design requirements of a building structure [3]. The key to vibration design is to ensure the natural frequency of the floor structure does not match the anticipated frequency of the applied loading, e.g. rhythmic loading from walking occupants [25]. If these frequencies are too close, the solution is to modify the structure's natural frequency. One option to do this is to reduce the span of the beams and floors. If that is not an option (e.g. the client brief requires open plan spaces) the common alternative is to stiffen the beams or increase the mass of the floor, both of which generally require an increase in material and associated EC. Developments of alternative, possibly lower-carbon, solutions (such as computer-controlled, active mass dampers) are happening [26], although they are not yet commonplace in industry.

The two remaining DfA parameters – storey height and grid arrangement – relate to the structural layout of the building, with the underlying consideration that a more open space, both horizontally (i.e. between columns) and vertically (i.e. between floors), allows for a greater variety of building uses, thus increasing the adaptability of the structure. The spatial requirements of a building will vary with use type and user expectations. For example, the clear height between the floors and ceilings for residential properties is typically lower (i.e. 2.1–2.4 m [27]) than that of offices (i.e. 2.75–3.0 m [28,29]). The servicing requirements (e.g. air-conditioning, wiring, plumbing, etc.) will also vary and play into the storey height decision, as they will consequently require a greater or lesser amount of service zone height for horizontal passage around a floorplate.

The specification of the structural grid determines the positioning of internal obstacles, such as columns and bracing, and therefore influences the adaptability of the space. The grid arrangement influences the EC of a structure, both by its consequences on element efficiency and quantity (e.g. fewer, but more heavily loaded, columns), as well as by its implications on the carbon costs of the other DfA parameters (e.g. longer-span beams requiring more material at higher vibration limits).

These four design parameters were selected as they were considered some of the most influential design inputs affecting both a structure's adaptability [30] and carbon cost [3], whilst remaining within the sphere of influence of the structural engineer. These parameters are also the ones most universally applicable to all major building use types i.e. all buildings have design requirements of loading, vibration limit and layout, but not all have requirements for, e.g., internal partition demountability or stacking floorplates [18].

1.3. Adaptability quantification

An often-reported barrier to the application of DfA is the lack of methods to quantify the level of adaptability of a structure [11,31,32]. It is easier to discuss benefits and drawbacks in design optioneering with quantitative data [33]. McFarland, Ross and Albright [18] propose a scoring system for the adaptability of college campus buildings by assessing the design against eight design parameters (structural spacing, floor-to-floor height, wall deconstructability, HVAC accessibility, design live load, plan depth, orthogonal walls and stacking floor plates), through a mix of quantitative and qualitative scoring.

Of the eight parameters assessed in McFarland, Ross and Albright [18], three overlap with the design parameters assessed in this paper: design live load (i.e. imposed load), floor-to-floor height (i.e. storey height) and structural spacing (i.e. grid arrangement). All three parameters are assessed using graphical relationships, constructed with linear interpolation between a few specified datapoints. These scoring plots have been recreated in the Supplentary Information. The scoring method has been expanded in this paper to include the fourth DfA parameter (vibration limit) as well as widened in scope to include buildings of all major use types in the UK.

1.4. Research aim

Understanding the role of adaptability within the CE, and a desire to compare DfA against lean design, necessitates the assessment of the carbon costs of DfA as well as the development of an adaptability scoring method. This paper aims to: 1) quantify the material requirements and carbon costs of four DfA parameters; 2) revise and expand the adaptability scoring method proposed in McFarland, Ross and Albright [18]; and, 3) combine 1) and 2) in order to investigate optimum areas of maximum adaptability benefit with minimum impact on EC.

2. Methodology

To determine the material requirements and carbon costs associated with each of the four DfA parameters (grid arrangement, imposed load, vibration limit and storey height), over three thousand unique structural designs were produced parametrically (see Section 2.2 for details). The structural EC of each design was calculated using a life cycle assessment

(LCA) methodology [34]. The material mass and EC results for incremental increases in each assessed DfA parameter were then combined to give steel mass and carbon relationships for each parameter. Finally, the carbon relationships were compared against revised adaptability scoring plots, to give graphical representations of the adaptability payback per carbon investment.

2.1. Adaptability scoring

Instead of the quantified y-axes (zero-to-ten axis) as used by McFarland, Ross and Albright [18], a qualitative high-to-low 'adaptability potential' grading is presented here. A quantified axis implies that, for example, a score of ten is twice as adaptable as a score of five, which is difficult to guarantee due to the subjectivity to the assessment. Nevertheless, the graphical method of representing the DfA relationships is a beneficial way to highlight the indirect proportionality between a design parameter and its adaptability benefit i.e. a unit increase of a DfA parameter, e.g. 3.0–4.0 kN/m^2 imposed load, does not necessarily provide an equal adaptability benefit to another unit increase of that same parameter, e.g. 7.0–8.0 kN/m^2.

Revisions to the relevant adaptability scoring relationships from McFarland, Ross and Albright [18] are proposed in a subsection per DfA parameter below, with the addition of a proposal for a vibration limit scoring profile. Comparisons and verification of the scoring results are presented in the Supplementary Information, Section A.1.

2.1.1. Imposed load scoring

The imposed load values and use typologies from the Eurocodes [22, 23] are listed below in Table 1, alongside the cumulative use count at each load value, used to indicate the level of adaptability provided at that imposed load. The nature of codified structural design practices means that, in order for a building to be used for a specific use (e.g. a department store), it must be designed to at least that value of load carrying capacity (4.0 kN/m^2 in the case of a department store). As such, the number of uses possible at a given value of imposed load was considered a suitable metric to measure imposed load adaptability level. There is no adaptability benefit between load values until the next 'step-up' in possible uses is reached. Furthermore, there is no further adaptability benefit beyond 7.5 kN/m^2 for most typical uses, although this excludes extreme cases such as data centres. The resulting scoring relationship is, therefore, stepped and discontinuous (as shown in the results in Section 3).

It should be noted that this method of imposed load DfA scoring gives equal weighting to each use type, regardless of likelihood of adaptation to that use (e.g. it is much more likely for offices to be converted to residential use, but unlikely for them to change to gyms or dance halls) or prevalence of that use type throughout the building stock (e.g. offices and residential use being much more common than hotels or art galleries). Whilst inclusion of these considerations is a potential further development, the relationship proposed in this paper demonstrates a novel way of considering adaptability scoring as a discontinuous, stepped relationship.

Table 1
Imposed load values and allowed building uses [23].

Imposed load (kN/m^2)	Building use types	
	Description	Cumulative use count
1.5	Residential (e.g. self-contained residences)	1
2.0	Previous, and hospitality and areas with tables (e.g. hotels, cafés and restaurants)	3
2.5	Previous, and offices	4
3.0	Previous, and education (e.g. classrooms)	5
4.0	Previous, and retail, areas with fixed seating (e.g. lecture theatres or waiting rooms), and areas without obstacles (e.g. museums or art galleries)	8
5.0	Previous, and circulation space (e.g. corridors) and areas for crowds or physical activities (e.g. concert halls or gyms)	10
7.5	Previous, and non-industrial storage	11

2.1.2. Grid arrangement scoring

Buildings are typically designed on grids of multiples of 1.5 m [29], hence this was used in defining the step-up points for the grid arrangement scoring plot. The general shape of the adaptability relationship was selected from the authors' professional experience and opinion; whereby, there are limited uses allowed for spans below 6.0 m (although there is a slight increase in adaptability potential between 3.0 and 4.5 m); between 6.0 and 9.0 m, most uses are allowed for (e.g. residential typically 6.0 m, low office at 7.5 m, high office at 9.0 m); and beyond 15.0 m can be considered long-spans – hence the plateauing beyond this point (i.e. few typical building uses need spans greater than this) [35,36].

2.1.3. Storey height scoring

The storey height scoring is based on the summation of typical clear heights, service zones and architectural finish depths, and average structural depths resulting from the grid arrangement and structural form. Clear height requirements are dependent on the building use: residential properties typically have the lowest requirements, with a minimum of 2.1 m and a targeted typical of 2.4 m [27]; office height requirements are typically slightly higher with an approximate minimum of 2.5 m, an average of 2.75 m, and values up to 3.5 m for high-end offices [28,29]. Some exceptional uses require storey heights up to around 6.5 m, e.g. assembly halls or atria [37]. At storey heights in the region of 8.0 m, the opportunity exists for retrofit of additional intermediary floors at a later date [18].

Service zone and architectural finish depths vary depending on building use type and fit-out specification. The design process input factors for this assessment (given in Supplementary Information, Table A.2) use 0.45 m for services and 0.25 m for architectural finishes (based on 0.15 m for raised access flooring and 0.10 m for ceilings, lighting and any deflection tolerances) [35,38].

Combining these values we plot the revised storey height scoring relationship starting with 2.75 m being the minimum zero score (from 2.1 m clear height, 0.25 m services and finishes, and 0.4 m structure for a very narrow grid arrangement); 4.0 m having a low DfA score as it allows for average residential and low office uses; between 4.0–4.5 m, most uses can be satisfactorily accommodated, therefore a good score for 4.5 m; a high score toward 5.5 m, which allows for prestigious uses; then plateauing until approximately 8.5 m storey height, which allows for double height uses or retrofitting of an additional floor. (This relationship is visualised alongside the results in Section 3).

2.1.4. Vibration limit scoring

The scoring relationship for the vibration limit parameter starts from zero at 3.0 Hz, this being the lowest suggested minimum in literature [25]. At 4.0 Hz (the target most commonly quoted as suitable for concept-level design of most common non-residential building uses [39]) a moderate DfA score is given. The DfA scoring rises again at 8.0 Hz, which is the typical vibration limit for residential buildings before increasing in smaller increments at 12.0 Hz and 24.0 Hz, being the recommendations for circulation areas and areas subject to rhythmic activities (e.g. gyms or dance halls), respectively [25].

2.2. Structural design process

For the structural design process used for this assessment, a baseline design of a nominally-pinned, steel-framed, composite-decked, medium-rise, square-plan building was used (see Supplementary Information, Table A.2 for specific design input values). Limiting the assessment solely to steel-framed buildings allows for a focus on the carbon implications of adaptability rather than between material options or construction forms; the carbon implications of such decisions have been extensively researched elsewhere [2,3,40,41]. Further investigations are needed to assess alternative structural materials, applying the adaptability-per-carbon methodology proposed in this paper, making use of the materially-agnostic DfA scoring relationships.

The assessment was also constrained to only the superstructure of the building, omitting the design of the foundations and lateral stability mechanisms. Whilst it is likely that these elements would add to the carbon costs of DfA, this assessment boundary has been implemented to maintain a tighter focus of the paper; suggestions for potential nuances of foundation and bracing inclusion are discussed in the relevant discussion sections below, and quantification of these effects remains a possible direction for future research. Similarly, for the sake of brevity, the assessment looks only at four-storey structures, which are often the structurally efficient number of storeys for steel braced frames [35]. As the assessment excludes foundations and bracing, the effect of varying the numbers of storeys of the building would be minimal in regard to the qualitative conclusions of the paper (although it would change the exact EC quantities).

To assess the EC relationship for each DfA parameter, their input value was incrementally varied, keeping the other design parameters fixed, except for grid arrangement which was simultaneously varied to determine the effect of grid on the carbon cost of each assessed parameter. In order to assess these numerous design combinations, a parametric design tool – *Structural PANDA* – was used [42–44]. The software rapidly undertakes concept-level structural designs based on a range of input parameters, outputting material volumes, approximate costings and carbon values.

2.2.1. Grid arrangement

Grid arrangement is handled in *PANDA* by dividing the inputted building plan dimensions into integer number of equally sized bays, separately in both the x- and y-direction, within specified limits of minimum and maximum span (i.e. 6.0–12.0 m). A building plan dimension of 108 × 108 m was chosen as a multiple of 12 m (the maximum span allowed for in this assessment) that was also sufficiently large to permit a large number of solutions from which the grid arrangement can be selected. Although a building of this size is impractical in reality, as the results of this assessment are presented in area-normalised units of kg/m^2 or kgCO$_2$e/m^2, the actual building plan layout is not significant on the findings. (This would not necessarily be the case if lateral stability or cladding EC were included, so this aspect would need parameterising and reporting in any future assessment that includes these elements.)

For the inputs of 108 × 108 m building plan and 6.0 × 12.0 m span range used for the assessment of the DfA parameters other than grid arrangement, the number of bays in a given direction could be between nine (108 m / max. 12.0 m = 9 No. bays) and 18 (108 m / min. 6.0 m = 18 No. bays), giving ten grid spacing options in the two orthogonal plan dimensions, thus resulting in one hundred unique grid arrangements. (To demonstrate this, Supplementary Information, Fig. A.3 shows four of the most extreme grid arrangement possibilities within these assessment limits.)

To assess the grid arrangement DfA parameter in isolation, the span range was extended to 3.0–15.0 m for a single *PANDA* run, where all other input parameters were kept at their default values (Supplementary Information, Table A.2). To retain a level of design realism, a bay aspect ratio lower limit of 0.5 was used to filter out disproportionately long or narrow grid arrangements. This left 649 unique grid arrangements to design for in the assessment of this DfA parameter.

2.2.2. Imposed load

For the imposed load parameter, the design input was varied from a minimum of 1.0 kN/m^2 (below the lowest load prescribed in the Eurocodes, of 1.5 kN/m^2 for residential loading) to a maximum of 8.0 kN/m^2 (encompassing the maximum typical Eurocode load of 7.5 kN/m^2 for non-industrial storage), in intervals of 1.0 kN/m^2. Therefore, there are nine design iterations to represent the spread of imposed load possibilities. Applied to the one hundred possible grid arrangements, this results in nine hundred unique design options.

2.2.3. Vibration limit

The assessed vibration limits range from 2.0 Hz (below the 3.0–4.0 Hz lower bound that is often taken as the minimum vibration limits in concept design [25]) up to 16.0 Hz (which would cover the requirements of most typical building typologies), in increments of 2.0 Hz. Thus, eight permutations of the one hundred grid arrangements results in a maximum of eight hundred possible designs to assess the material and carbon implications of vibration limit specification; however, only 689 of these were possible within the *PANDA* design limits (discussed further in Section 4.2).

2.2.4. Storey height

Storey height was assessed by varying the clear (i.e. floor-to-ceiling) height input in *PANDA*. The structural depths of the design output beams were summed with the fixed input values for service zone and floor finish depths (0.45 and 0.15 m from Supplementary Information, Table A.2, respectively), and the current value of clear height to calculate the resulting storey height of each design. The clear height was varied between 1.5 and 8.5 m, in increments of 1.0 m, which represents an approximate range of storey heights between 2.75 and 10.0 m (i.e. the average combined service, structure and finish depth is 1.25–1.5 m). The 1.5 m minimum clear height was chosen to be well below the realistic minimum of any use typology. The upper limit of 8.5 m was envisaged to exceed the necessary requirements to retroactively install an additional storey between the existing floors. This parameter range and interval value gives nine possible storey heights, resulting in nine hundred unique structural designs.

2.3. Life cycle assessment

The EC of the material volumes output from the design process were calculated in line with the LCA methodology in IStructE [34]. Whilst the material quantity outputs from *PANDA* included both the steel and concrete material masses, this assessment focused solely on the steel materials (i.e. the beams, columns, connections, rebar and decking), due to design boundaries keeping the decking profile and concrete slab depth (therefore concrete volume) fixed. The exclusion of the concrete carbon makes it easier to differentiate the variations in steel mass and carbon. (See Supplementary Information, Fig. A.5 for total mass plots, including both steel and concrete material masses).

The LCA was restricted to the upfront emissions (i.e. modules A1–5 [4]), therefore excluding emissions during the use and at (and beyond) the end of life of the building. This ensures the focus is on the upfront carbon costs of adaptability; future work will look to assess the long-term consequences of these design decisions. The carbon emission factors and wastage rates used in this LCA were taken from IStructE [45], and have been listed in Supplementary Information, Table A.3.

The module A5a (construction stage) emissions were calculated using an emission rate factor of 7000 kgCO$_2$e/£ 1000,000 [34], and utilising results of the cost approximation method built into *PANDA*. *PANDA* conducts a basic quantity survey calculation, using material cost-rate factors (i.e. cost per unit quantity of material) and an overall multiplication factor on the resulting superstructure cost to give an indicative total project cost. The default input factors provided in *PANDA* were unchanged, and are suggested to be indicative of cost-rates typical to Southern UK in late 2023, shown in Supplementary Information, Table A.4 [43].

As is standard practice, the material and carbon results have been normalised by the internal floor area of the structure, excluding the ground floor, ground bearing slab, which is beyond the assessment scope (i.e. 3 No. storeys × 108 ×108 m = 34,992 m^2).

3. Results

The results of each DfA parameter are presented in four sub-plots, combined in the panel plot shown in Fig. 1. Each parameter is represented by the columns (i)–(iv): (i) imposed load, (ii) vibration limit, (iii) storey height, and (iv) average span. The rows, (a)–(d), represent the results at each stage of the assessment process.

Sub-plot (a) shows the steel mass requirements of each design parameter, and sub-plot (b) shows the associated steel A1–5 EC. For both the mass and carbon sub-plots, the line represents the average value across the different assessed grid arrangement, and the shaded area shows the range of the minimum and maximum values. Sub-plot (c) shows the DfA scoring plots developed from the discussion Section 2.1. Sub-plot (d) combines the DfA score and average carbon values to give 'adaptability per carbon' relationships.

To demonstrate the influence of grid on the carbon of the other design parameters, Fig. 2 plots the carbon versus DfA parameter results for each grid arrangement separately, and highlights five key grid arrangements: 6.0 × 6.0 m, 6.0 × 9.0 m, 9.0 × 9.0 m, 9.0 × 12.0 m and 12.0 × 12.0 m.

4. Discussion

By comparing these carbon relationships for each design parameter, it can be seen that the vibration limit has the largest influence on EC, with grid having a moderate influence, and imposed load and storey height having roughly equivalent carbon costs. Not only does the vibration limit parameter have the strongest influence on EC, but it is also the parameter most sensitive to grid arrangement, especially at higher vibration limits. The results of each DfA parameter are discussed in their own sub-section below.

Whilst the exact EC results are dependent on the LCA factors chosen (average UK factors selected for this assessment, provided in Supplementary Information, Table A.3), the general trends of the different DfA parameters would remain unchanged to varying LCA factor. This independency of the conclusions to the LCA factor results from the fact that the LCA factor does not affect the design process and resulting material masses. This can be evidenced by the minimal differences between the relationships shown in Figs. 1(a & b) (i.e. the mass per parameter and EC per parameter results). This shows that the dominant factor in the results is the change in DfA parameter and the influence this has on material mass, and not the LCA factor used. (Comparison between UK and global LCA factors and the resulting EC values has been included in Supplementary Information, Section A.3.2.)

4.1. Imposed load

Fig. 1(i) presents the results for the imposed load parameter. As imposed load increases, so do the material requirements and carbon emissions, and the relationship appears near-linear. On average, EC increases at a rate of 4.6 $kgCO_2e/m^2$ per unit increase of imposed load. The imposed load increase between 4.0 and 5.0 kN/m^2 is an outlier to this (seen as a section of steeper gradient between these points on Fig. 1 (i-a & b)) with an average EC increase of 8.2 $kgCO_2e/m^2$. This is due to the slab reinforcement requirements changing at and above imposed load values of 5.0 kN/m^2 [46].

The predominantly linear nature of the relationship can be derived from the formulae used in the structural design. The design process checks both the ultimate limit state (ULS) requirements for flexural capacity, and the serviceability limit state (SLS) requirements of deflection and vibration. The ULS and SLS formulae are shown in Eqs. (1) and (2), respectively [39]. It can be seen that imposed load (w) and span (L) are factors in both cases equations. So, as either load or span increase, so do the material requirements and associated carbon. If both increase, the effects are compounded.

$$M_{Ed} = \frac{wL^2}{8} \tag{1}$$

$$\delta = \frac{5wL^4}{384EI} \tag{2}$$

Fig. 2(i) show this influence that grid arrangement, or beam span, has on the rates of material and carbon costs. The effect is moderate, with carbon cost of imposed load generally increasing quicker for larger grid arrangements than for smaller arrangements. Compared back to the average EC increase of 4.6 $kgCO_2e/m^2$ per unit load increase, this rate is lower for the 6.0 × 6.0 m grid arrangement, at 3.1 $kgCO_2e/m^2$ per unit increase, but up at 6.8 $kgCO_2e/m^2$ per unit increase for the 12.0 × 12.0 m arrangement.

Looking specifically at the range of imposed load that most building use types fall within, Table 2 extracts the carbon values for imposed loads of 2.5 kN/m^2 (the lean design option, being the minimum UK codified load requirement for an office [23]), 5.0 kN/m^2 (the loading typically used for office design [47]), and 7.5 kN/m^2 (a load that would provide adaptability through reserve capacity), for both the smallest (6.0 × 6.0 m) and largest (12.0 × 12.0 m) grid arrangements. From these numbers, the influence of grid arrangement on carbon cost of imposed load can again be seen. Going from 2.5 to 7.5 kN/m^2 leads to an EC increase of 18.2 $kgCO_2e/m^2$ for the 6.0 × 6.0 m grid but 34.7 $kgCO_2e/m^2$ for the 12.0 × 12.0 m.

From the adaptability scoring discussion (Section 2.1.1), we can see four uses are allowed for at 2.5 kN/m^2, 10 uses at 5.0 kN/m^2, and 11 uses at 7.5 kN/m^2. Taking the number of uses as a proxy for the level of adaptability, we can start to see the trade-offs presented in Fig. 1(i-d); whilst there is an carbon cost resulting from increasing imposed load from 2.5 to 5.0 kN/m^2, the increase in adaptability potential is significant. The same cannot be said for the increase between 5.0 and 7.5 kN/m^2, where there is a similar carbon cost but only one additional use typology. By this logic, from a purely-adaptability perspective, specifying an imposed load value of 5.0 kN/m^2 gives the best trade-off between adaptability potential and carbon (shown by the peak at 5.0 kN/m^2 in Fig. 1(i-d)), with an average carbon cost increase on the lean design option (i.e. imposed load of 2.5 kN/m^2) of 13.7 $kgCO_2e/m^2$ (however, as always, the guaranteed increase in carbon must be balanced with the uncertain future benefit through adaptability).

4.2. Vibration limit

Fig. 1(ii) shows the material and carbon relationships for the vibration limit parameter. The 'S'-shaped average line suggests the carbon-to-vibration-limit relationship was a sigmoid function, however the results by bay area shown in Fig. 2(ii) indicate that this is not necessarily true, and is merely a result of a single average line not representing the entire story behind the data. Specifically, within the assessment boundaries used by *PANDA* (i.e. limiting the beam selection to only universal column (UC) or universal beam (UB) sections, and fixing the floor slab weight at a constant value), there are no feasible designs for the larger grid arrangements at the higher vibration limits (i.e. no UB or UC sections could be found with sufficient stiffness to provide the desired vibration limit at those larger spans [48]). As a result, no datapoints exist for the larger grid arrangements, and so the larger, more materially-demanding grid arrangements are excluded from the averaging at these higher vibration limits, giving the erroneous impression of carbon efficiencies as vibration limit increases. In reality, it is likely that feasible designs could be found with more detailed assessments, such as using bespoke fabricated sections with capacities or increasing the mass and stiffness of the floorplate. These solutions would likely require more material and associated carbon.

The parabolic relationship shown at lower vibration limits and for smaller bay areas can be derived through combination of Eq. (2) for

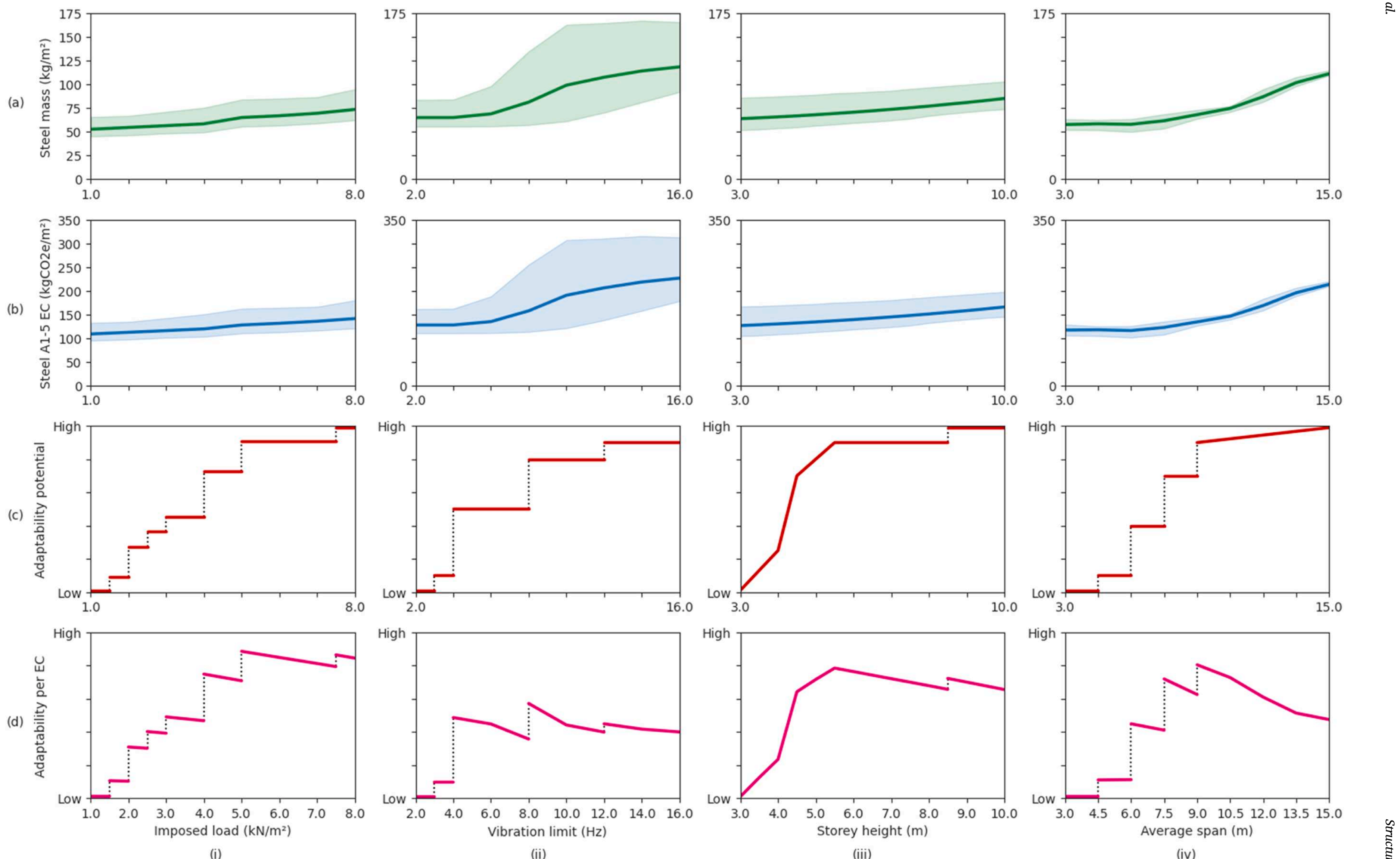

Fig. 1. Panel plot showing results of (a) steel mass, (b) associated A1–5 EC, (c) DfA scoring and (d) DfA per carbon relationships, for design parameters (i) imposed load, (ii) vibration limit, (iii) storey height and (iv) average span.

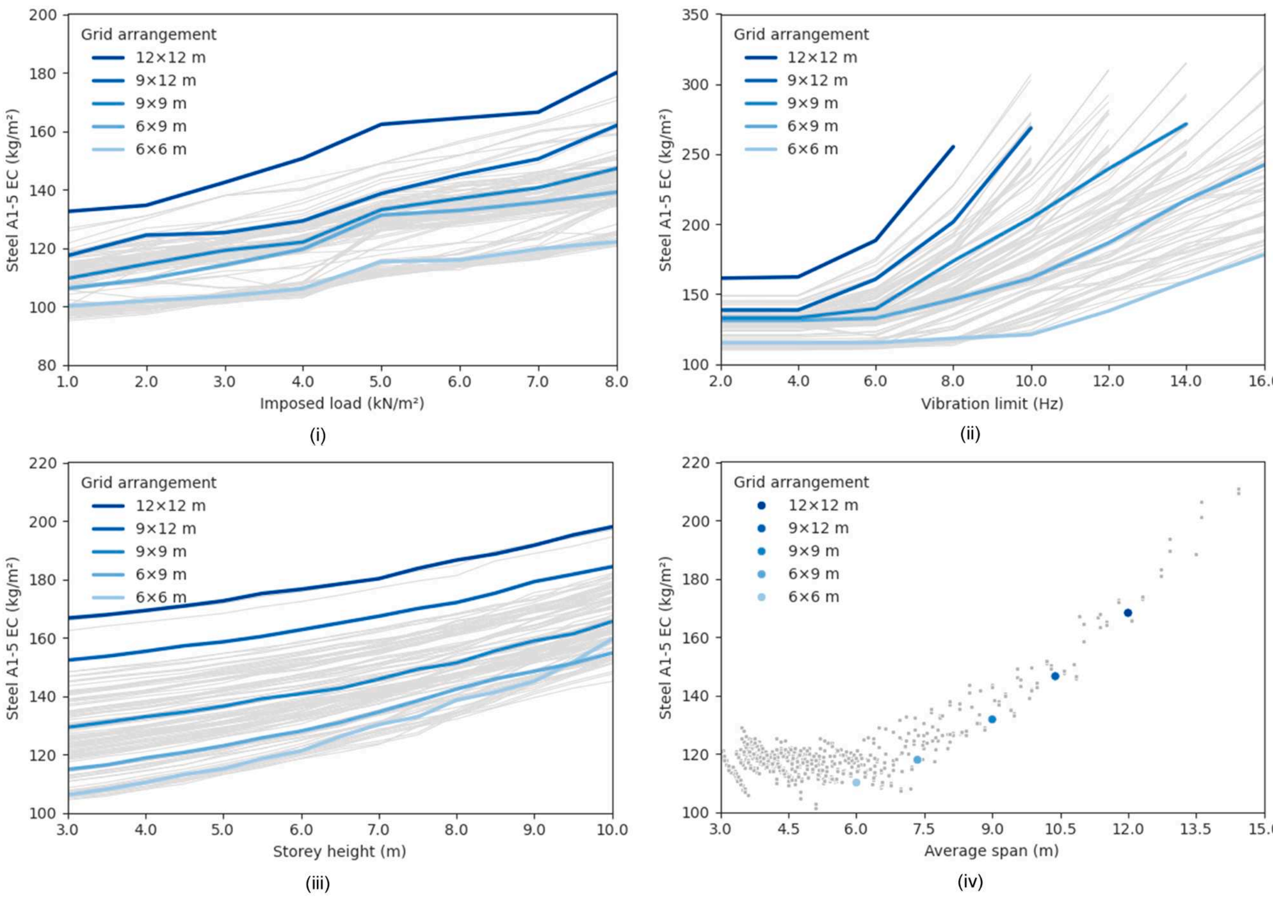

Fig. 2. Panel plot showing steel A1–5 EC against DfA parameter relationships for each grid arrangement, highlighting five key grid arrangements (6.0 × 6.0 m, 6.0 × 9.0 m, 9.0 × 9.0 m, 9.0 × 12.0 m and 12 × 12 m), for (i) imposed load, (ii) vibration limit, (iii) storey height and (iv) average span. Note: varying y-axes ranges.

Table 2
Steel A1-5 EC for imposed loads of 2.5, 5.0 and 7.5 kN/m² for the smallest 6.0 × 6.0 m and largest 12.0 × 12.0 m grid arrangements, and averaged for all grid arrangements.

Imposed load (kN/m²)	Steel A1-5 EC ($kgCO_2e/m^2$)		
	Grid arrangement (m)		Average for all grid arrangements
	6.0 × 6.0	12.0 × 12.0	
2.5	102.7	138.5	114.2
5.0	115.4	162.3	127.9
7.5	120.9	173.2	138.6

Table 3
Steel A1-5 EC for vibration limits of 4.0, 8.0 and 12.0 Hz for the smallest 6.0 × 6.0 m and largest 12.0 × 12.0 m grid arrangements, and aver-aged for all grid arrangements.

Vibration limit (Hz)	Steel A1-5 EC ($kgCO_2e/m^2$)		
	Grid arrangement (m)		Average for all grid arrangements
	6.0 × 6.0	12.0 × 12.0	
4.0	115.4	162.3	127.9
8.0	118.5	255.4	157.7
12.0	138.0	N/A*	206.2*

* No feasible designs for the 12.0 × 12.0 m grid arrangement at vibration limits above 10.0 Hz, thus erroneously lowering the average EC for all grid arrangements

deflection of a simply supported beam, and the equation for natural frequency (f) in Eq. (3) [39].

$$f = \frac{18}{\sqrt{\delta}} \tag{3}$$

Table 3 extracts the data specific to the common ranges of the vibration limit, at values of 4.0, 8.0 and 12.0 Hz. In the 6.0 × 6.0 m grid arrangement data, we can see the non-linear influence vibration limit has on the resulting carbon; for an increase from 4.0 to 8.0 Hz, the carbon cost is 3.1 $kgCO_2e/m^2$, but between 8.0 and 12.0 Hz, the carbon cost is 19.5 $kgCO_2e/m^2$ (i.e. over six times the carbon cost for the same magnitude of vibration limit increase).

Fig. 1(ii-c) shows diminishing returns in the adaptability scoring at higher vibration limits, compounding with their significant carbon costs. Consequently, Fig. 1(ii-d) shows sweet-spots of the adaptability-per-carbon relationship at either 4.0 Hz or 8.0 Hz. Any vibration limits beyond these are either too carbon costly or are of no significant adaptability benefit. As such, the lean versus adaptable design carbon cost for the vibration limit parameter could be taken as the 29.8 $kgCO_2e/m^2$ difference between the 4.0 and 8.0 Hz averages.

4.3. Storey height

Fig. 1(iii) shows the material and carbon implications of storey height specification. As with the other design parameters, the general positive trend of increasing EC with increasing design parameter is visible. Although minor (and therefore hard to discern from Fig. 1(iii-a & b)), the rate of EC increase per unit increase in storey height is non-linear, starting at 3.5 $kgCO_2e/m^2$ for a unit increase between 3.0 and

4.0 m, increasing to 7.7 $kgCO_2e/m^2$ per unit increase between 9.0 and 10.0 m. This results from the fact that, as storey height increases, a greater number of the grid arrangements will have column designs that are governed by buckling rather than axial squashing. As a greater proportion of the column designs become dictated by buckling (which is influenced by storey height, whereas squashing is not), the rate of EC increase becomes more tied with storey height; thus linking the carbon cost of storey height to the influence of grid arrangement.

Fig. 2(iii) shows that for larger grid arrangements, the carbon cost of storey height is reduced rather than increased as was the case for the other parameters. On average, the EC increase per unit increase of storey height is 7.6 $kgCO_2e/m^2$ for the 6.0 × 6.0 m grid arrangement and 4.5 $kgCO_2e/m^2$ for the 12.0 × 12.0 m grid. One simple explanation for this is the fact that there are more columns present in smaller grids and so, as column height increases, there are more columns to lengthen, and so more material and EC increase. There is also a component related to which design case is governing: squashing or buckling. For larger grids, the axial load per column is higher than it is for smaller grids, hence, the chosen column sections for larger grid arrangements will tend to already be heavier; selected for their higher buckling capacity. Therefore, these larger grids have less of an immediate increase in material when increasing storey heights. The columns in small grids, on the other hand, have less reserve buckling capacity, therefore a more immediate, and greater, increase in carbon in order to pass at higher storey heights.

Although the storey height parameter was assessed between limits of 3.0 and 10.0 m, the vast majority of building designs will be below storey heights of 5.5 m (the maximum height of a façade panel is approximately 5.0–6.0 m therefore storey heights above this are often avoided; if a storey height greater than this is specified, special consideration has to be given to providing secondary steelwork to support the cladding). Table 4 extracts the data relating to the storey heights of 3.5, 4.5 and 5.5 m.

Although not as pronounced as for the entire range assessed storey heights, from these datapoints, we can see the inverse relationship of carbon cost to grid arrangement. The overall carbon increase in going from 3.5 to 5.5 m storey height is 10.5 $kgCO_2e/m^2$ for the 6.0 × 6.0 m grid arrangement, but only 7.3 $kgCO_2e/m^2$ for the 12.0 × 12.0 m arrangement. Due to the typically lower starting EC of smaller grids, this effect is emphasised when looking at the carbon cost as a proportion of the initial EC; the 10.5 $kgCO_2e/m^2$ increase for the 6.0 × 6.0 m grid equates to a 10 % increase, whilst the 7.3 $kgCO_2e/m^2$ for the 12.0 × 12.0 m grid is a 4 % increase. More subtly demonstrated in the data is the increasing rate of carbon cost for higher storey heights, irrespective of grid arrangement (i.e. the slight non-linearity of the lines discussed earlier). The carbon cost for a unit increase in storey height between 3.5 and 4.5 m is 3.8 $kgCO_2e/m^2$, whilst the increase between 4.5 and 5.5 m has a carbon cost of 4.6 $kgCO_2e/m^2$.

Looking to the adaptability potential in this range of storey heights, Fig. 1(iii-d) implies there is substantial benefit to be gained, especially in the range of heights between 4.0 and 4.5 m. Due to the relatively small increase in carbon associated with the story height increase, a storey height of 5.5 m would be considered the sweet-spot of adaptability per carbon in this assessment. This results in a carbon investment requirement of 8.4 $kgCO_2e/m^2$ on average for DfA in comparison to a lean design storey height of 3.5 m.

Table 4
Steel A1-5 EC for storey heights of 3.5, 4.5 and 5.5 m for the smallest 6.0 × 6.0 m and largest 12.0 × 12.0 m grid arrangements, and averaged for all grid arrangements.

Storey height (m)	Steel A1-5 EC ($kgCO_2e/m^2$)		
	Grid arrangement		Average for all grid arrangements
	6.0 × 6.0	12.0 × 12.0	
3.5	108.1	167.8	128.4
4.5	113.2	170.9	132.2
5.5	118.6	175.1	136.8

It is important to note that this assessment excluded consideration of elements such as the cladding and lateral stability mechanism, whose respective carbon costs are dependent upon the storey height specified. Further work could build on this paper to include these elements by utilising concept sizing rules-of-thumb for bracing and approximate EC costs for cladding per area of building elevation (see Supplementary Information, Section A.4.2 for example cladding EC calculation and results). Similarly, the assessment does not capture the consequences of varying the number of storeys of the building. This study assesses four-storey structures only; as such, the influence of number of storeys on the EC cost of storey height cannot be quantified, beyond a suggestion that the number of storeys could be seen as a multiplier to the EC cost of the storey height parameter (i.e. more floors, more carbon cost to increase storey height).

Further work should look into the influence of steel yield strength on the EC costs for this parameter, with columns often being considered the ideal application for higher strength steels [49]. Nevertheless, it is anticipated that, although including options for high strength steels would reduce the material mass requirements and resulting EC values slightly, the general trends of the results would not be significantly different from those presented above.

4.4. Grid arrangement

As has been discussed in the respective sections for each of the other DfA parameters, not only does the grid arrangement parameter have its own impact on EC (shown in Fig. 1(iv)), Fig. 2 shows that grid also influences the carbon costs of the other design parameters. As such, it could be argued that the carbon cost attributed to the specification of grid arrangement should not just be limited to the numbers quoted in this section but should also include a certain proportion of the carbon costs associated with the other DfA parameters, if applied in conjunction.

Fig. 1(iv-a & b) shows the increase in material requirements and carbon associated with increasing grid arrangements is greater for larger bay areas than it is for smaller bays. The slight curve to the line on Fig. 1 (iv-a & b) can be attributed to the same discussion as with the imposed load parameter in Section 4.1, where grid arrangement (and resulting beam spans) is a factor in both the ULS and SLS design formulae, to at least of a power of two. As such, regardless of which limit state is governing, if all else remains the same, an increased grid spacing will demand increased material and carbon.

This is not necessarily true at very small grid arrangements (i.e. average spans of 3.0–5.0 m); within this extreme range, where even the smallest UB and UC sections are not fully utilised, EC requirements remain largely unaffected by grid. This effect can be seen in the extracted datapoints presented in Table 5, where there is a carbon *saving*, of 10.6 $kgCO_2e/m^2$, by increasing average span from 3.0 m to 6.0 m. The carbon *cost* of the same 3.0 m average span increase between 6.0 and 9.0 m is 21.6 $kgCO_2e/m^2$, and there is a larger increase of 36.5 $kgCO_2e/m^2$ between 9.0 and 12.0 m. Additionally, the adaptability scoring plot for grid arrangement, given in Fig. 1(iv-c), suggests there is limited adaptability potential provided by spans less than 6.0 m. Combining these results, it is apparent that spans around 6.0 m are a

Table 5
Steel A1-5 EC and average span for the specific grid arrangements.

Grid arrangement (m)	Average span (m)	Steel A1-5 EC ($kgCO_2e/m^2$)
3.0 × 3.0	3.0	120.8
3.0 × 6.0 or 6.0 × 3.0	4.5	110.7
6.0 × 6.0	6.0	110.2
6.0 × 9.0 or 9.0 × 6.0	7.5	122.1
9.0 × 9.0	9.0	131.8
9.0 × 12.0 or 12.0 × 9.0	10.5	146.9
12.0 × 12.0	12.0	168.3

practical minimum for the lean design grid arrangement parameter.

We can also conclude that average spans beyond 9.0 m experience diminishing returns for adaptability-per-carbon, shown in Fig. 1(iv-d). As such, it is suggested that grid arrangements with average spans around 9.0 m would be the most suitable adaptable option, balancing both the benefits to adaptability potential from the longer spans with the increasing carbon costs associated with them. Therefore, taking 9.0 m as the adaptable design option, and 6.0 m for the lean design option, we get a carbon cost of adaptability in this assessment of 21.6 $kgCO_2e/m^2$.

5. Conclusion

The discussion and results presented in this paper demonstrate the complexity of quantifying the carbon cost of structural adaptability, along with the uncertainty relating to the actual adaptability benefit afforded by increases in the DfA strategies. The insights into the resulting carbon of a structure from variations of the four assessed design parameters (imposed load, vibration limit, storey height and grid arrangement) include:

- The vibration limit parameter was shown to have the greatest influence on a structure's EC, with an average carbon cost of 29.8 $kgCO_2e/m^2$ in going from 4.0 to 8.0 Hz and a near-parabolic increase in carbon at high vibration limits and large grid arrangements.
- Grid arrangement closely follows, with an individual cost of 21.6 $kgCO_2e/m^2$ by increasing the average span from 6.0 m to 9.0 m, and also influences the carbon cost of the other DfA parameters.
- Imposed load and storey height have lower impact on carbon, with 13.7 $kgCO_2e/m^2$ associated with increasing imposed load from 2.5 to 5.0 kN/m^2, and a 7.6 $kgCO_2e/m^2$ EC cost for increasing storey height from 3.5 to 5.5 m.

The paper discusses the interactions grid arrangement on the carbon costs of the other DfA parameters; not only does the selection of grid arrangement have its own carbon implications, it also affects the carbon costs of other DfA parameters. For the imposed load and vibration limit parameters, the rate of carbon increase as DfA parameter increases is exaggerated at larger spans (a consequence of beam span (L) being a factor in both ULS and SLS calculations). The grid selection also affects column loading, which has an effect on which of the squashing or buckling checks is critical and, hence, influencing the rate of carbon increase with increasing storey height. Notably, however, the influence of grid arrangement on storey height is in reverse to its influence on the other two DfA parameters; for imposed load and vibration limit, the associated carbon cost increases slower for small grids than it does for large grids, whereas, with storey height, the rate of carbon increase is higher for small grids than for it is large grids. Other than grid arrangement, the other DfA parameters have been assessed in isolation, limiting the investigation of further interactions between parameters (beyond those already discussed for grid arrangement) and a future assessment of these DfA parameter interdependencies would be beneficial.

It is important to note that the carbon costs presented in this paper are only applicable within the design boundaries of the assessment, which principally focuses on the superstructure of four-storey, steel-framed buildings, excluding the carbon costs associated with foundations, bracing and cladding. Further studies into the influence of these other structural elements and material choice are also suggested. For different materials, the carbon results would be different; however, it is likely that the general trends of the relationships and comparisons between the different DfA strategies would remain similar. The adaptability scoring system proposed within this paper is independent of material type and, hence, can be readily applied to these future assessments.

This research provides novel insights into the carbon cost of different adaptability strategies applied to steel-framed structures and shows that, whilst there is often a carbon cost to DfA, it is not always prohibitively high. The findings, when combined with the developed adaptability scoring method, enable structural engineers to identify sweet-spots in the lean design versus adaptability debate, and avoid unnecessary overprovision of adaptability potential within their designs. This provides a novel methodological contribution to the state of the art, simultaneously considering the upfront carbon cost and the long-term benefit afforded by DfA. This methodology could be used by clients and policymakers when deciding upon the brief of building projects when seeking carbon savings in both the short- and long-term.

The discussion of the discontinuous nature of the relationships between adaptability and DfA parameter, i.e. a given increase in a DfA parameter does not necessarily guarantee a benefit to adaptability, is also a novel framing of the problem. This is applied to the adaptability scoring relationships to develop stepped profiles where discreet increases in adaptability occur at specific DfA parameter values. Whilst these plots have been produced by combining the net experience of the authors with proposals and data in literature, further refinement and verification of these would be of methodological benefit.

Combining the carbon and adaptability scoring in a single graphical form gives an insightful representation of adaptability per carbon relationships. As such, the paper concludes by contributing a novel way of thinking that demonstrates the adaptability-potential 'return' on carbon 'investment', highlighting optimum areas of each parameter that balance both the desires of long-term adaptability with those of necessary short-term carbon reductions.

CRediT authorship contribution statement

Harry Watt: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Buick Davison:** Writing – review & editing, Supervision, Methodology. **Peter Hodgson:** Supervision, Funding acquisition, Conceptualization. **Chris Kitching:** Supervision, Funding acquisition. **Danielle Densley Tingley:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used Google Gemini in order to produce Python code for data processing and visualisation. After using this tool/service, the authors reviewed and edited the content as needed and takes full responsibility for the content of the publication.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Harry Watt reports financial support was provided by Tata Steel UK Limited. Harry Watt reports financial support was provided by Mott MacDonald Group Ltd. Harry Watt reports a relationship with Mott MacDonald Group Ltd that includes: employment.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.istruc.2024.108066.

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