Article:

Watt, H. orcid.org/0000-0003-1822-5913, Davison, B. orcid.org/0000-0002-6191-7301, Hodgson, P. et al. (2 more authors) (2023) What should an adaptable building look like? Resources, Conservation & Recycling Advances, 18. 200158. ISSN 2667-3789

https://doi.org/10.1016/j.rcradv.2023.200158

Resources, Conservation & Recycling Advances 18 (2023) 200158

Contents lists available at ScienceDirect

Resources, Conservation & Recycling Advances

journal homepage: www.sciencedirect.com/journal/Resources-Conservation-and-Recycling-Advances

What should an adaptable building look like?

Harry Watt [a,*], Buick Davison [a], Peter Hodgson [b], Chris Kitching [c], Danielle Densley Tingley [a]

[a] Department of Civil and Structural Engineering, The University of Sheffield, Sheffield, S10 2TN, United Kingdom
[b] Tata Steel UK Limited, London, SW1X 7HS, United Kingdom
[c] Mott MacDonald Group Limited, Croydon, CR0 2EE, United Kingdom

ARTICLE INFO

Keywords:
Adaptability
Resilience
Optimisation
Lean design
Embodied carbon
Circular economy

ABSTRACT

Current building design practices largely focus on operational efficiency and initial material optimisation in the pursuit of sustainable construction. These short-term carbon savings are potentially detrimental to the long-term futureproofing of a building. As such, the suggestion to design buildings for adaptability has gained traction in recent years. An adaptable building is one that could be easily modified to suit its changing requirements, allowing it to avoid premature demolition and reconstruction, and the associated carbon emissions. This paper explores what is meant by adaptability in the built environment, suggestions for design strategies and the benefits and drawbacks of each. The paper expressly emphasises the importance of balancing the needs of the present day, through upfront carbon reductions, with the consequences in the long-term, through accelerated building obsolescence, demolition and rebuild. The paper concludes with the recommendation that further research is needed into the true benefits of adaptability design strategies, factoring in the uncertainty of future predictions and the time-value of carbon.

1. Introduction

As the world has become increasingly focused on combating the climate crisis, the construction sector has strived to produce optimised, energy-efficient buildings. Whilst these efforts have succeeded in reducing operational emissions and started to reduce structural embodied carbon, through decreased material usage (IStructE, 2021), they are potentially short-sighted, focusing only on the immediate upfront carbon. This focus may, in fact, result in higher carbon emissions over the whole lifecycle of the building; for example, if a building is too finely optimised, it may be unable to accommodate changes to its use or environment, leading to early obsolescence and demolition. The carbon implications of demolition and rebuild will likely outweigh the over-investments of material required at initial construction in order to avoid this fate. Therefore, we need a whole-life approach to consider the balance of long-term adaptability benefits with those of short-term optimisation.

Whilst adaptability is not a new concept in the built environment, with its origins in Habraken's (1961) theory of 'support' structures, it is yet to become a staple priority in the minds of clients, architects and engineers (Melton, 2020). Presently, there are numerous barriers between current design practices and a future in which buildings are designed for a whole-life, circular economy (CE). Ultimately, we need to shake the current psyche that "buildings are built with yesterday's technology and today's ideas for tomorrow's people" (de Ridder and Vrijhoef, 2008), and instead we should be looking forward (Brand, 1994), taking calculated risks to design for an uncertain future with the best strategies we currently have at our disposal (Fawcett, 2011).

To work toward this aim, this paper reviews the barriers and enablers to the adoption of design for adaptability (DfA) and discusses strategies within literature. Although similar work has been carried out by others (Askar et al., 2021; Heidrich et al., 2017; Pinder et al., 2017; Schmidt III et al., 2010; Slaughter, 2001), only a few discuss the impact of DfA on the often-times contradictory approach of designing for minimum upfront material usage (IStructE, 2022; Kelly et al., 2011; Rockow et al., 2021), referred to as 'lean design' (LD) (Cook and Arnold, 2020). This paper, therefore, works to emphasise the importance of balancing the needs of the future, through adaptability, with the upfront carbon and financial costs in the present. The paper also highlights areas requiring further research before tangible DfA strategies can be implemented in industry in order to achieve long-term carbon reductions.

Abbreviations: DfA, Design for adaptability; LD, Lean design; CE, Circular economy; DfD, Design for deconstruction.

* Corresponding author.
E-mail address: hwatt1@sheffield.ac.uk (H. Watt).

https://doi.org/10.1016/j.rcradv.2023.200158

2. Background

2.1. Defining adaptability

What the exact definition of building adaptability is, is considered a contentious point, with many suggesting that this lack of consensus is a significant blocker to the adoption of DfA practices (Anastasiades et al., 2021; Friedman, 2002; Kanters, 2020; Kelly et al., 2011; Pinder et al., 2017; Schmidt III and Austin, 2016). Whilst some discrepancies within definitions do exist (which will be returned to later in this section), we consider that the principles that underlie the definitions resolve to the same set of core characteristics, being: a building's ability to accommodate changes in use, environment or specification, throughout time, without the need for extensive refurbishment, in order to extend the building's lifespan and, in the authors' view, ultimately to reduce the embodied carbon emissions from demolition and rebuild.

This definition can be broken down into six key components:

1 "the ability to accommodate change": being the basic definition of adaptability in its broadest context,
2 "changes in use, environment or specification": describing the possible and varied sources of change (van Ellen et al., 2021), with:
  a 'use' referring to changes in ultimate limit states (e.g. floor loading), serviceability limit states (e.g. vibration or deflection), space or service requirements, etc.;
  b 'environment' referring to the broader context, or surrounding environment, within which the building exists (e.g. climate change, economy, urbanisation, etc.);
  c and, 'specification' referring to other possible sources of requirement change (e.g. user expectations),
3 "throughout time": introducing the temporal dimension to design and the importance of considering a building as not just a static object used to solve present needs, but one that has to adjust to suit the needs of whatever future it finds itself in (Brand, 1994; Duffy, 1990; Kelly et al., 2011),
4 "without the need for extensive refurbishment": highlighting the desire to simplify, enable and encourage refurbishment, dissuading intrusive structural modifications or early demolition and rebuild,
5 "to extend the building's lifespan": emphasising the benefit of easy refurbishment to reduce the frequency at which we need to demolish and rebuild, and retaining materials at their highest value for as long as possible, aligned with the CE movement (Cheshire, 2021; Ellen MacArthur Foundation, 2023; McDonough and Braungart, 2009),
6 "to reduce the embodied carbon emissions": describing the ultimate goal of adaptability, improving the long-term sustainability of the built environment.

The theorised relationship between a building's level of adaptability and its long-term sustainability can be visualised, as shown in Fig. 1, inspired by a similar visualisation of the relationship between transformation capacity and sustainability, from Andrade & Bragança (2019).

2.2. A building of layers

An important concept central to DfA is to consider a building as a series of layers, rather than as one monolithic unit (Blakstad, 2001; Graham, 2005; Melton, 2020; Rockow et al., 2021; Ross et al., 2016; Russell and Moffatt, 2001; Slaughter, 2001). The concept has its origins in the 'levels' of Habraken (1961). Habraken proposed a future of mass housing consisting of two levels: first, an undefined multi-storey 'support' structure, designed to allow independent dwellings to be constructed in isolation from, yet stacked atop, one another; and, secondly, the dwellings themselves. This separation would allow individual units to be built, modified or demolished without impacting those adjacent to it.

Focusing on an individual building, Duffy (1990) later devised to split a structure, not by its material components, but by its temporal dimensions (i.e. grouping the elements by their typical cycle-times), thus generating the four Ss of a building: shell, services, scenery and set. Brand (1994) then added the final two layers and renamed Duffy's four, to give us the six "shearing layers of change": site, structure, skin, services, space plan and stuff (shown in Table 1). Brand highlighted the importance of allowing independence, or 'shear', between these layers such that components in one layer can be modified or removed without compromising other adjacent elements or layers (Graham, 2005; McFarland et al., 2021b; Ross et al., 2016; Russell and Moffatt, 2001), matching the intent behind the separation between dwellings and supports in Habraken's (1961) levels. Others have since added to or modified the layers proposed by Brand, but the concepts and purposes remain unchanged (Leupen, 2004; Maury, 1999).

2.3. Designing for adaptability

Although a definition can succinctly summarise the meaning of building adaptability, and the concept of building layers gives a framework to build upon, there remains uncertainty around what physical design strategies can actually be used to achieve adaptability (Kanters, 2020). Schmidt III et al. (2010) identifies six strategies, each focused on a different type of change, with an associated timescale and affected building layers (see Table 2). Whilst this breakdown offers greater clarity on different types of change and how these relate to the different building layers, it falls short of providing tangible design strategies, as such these are probably better seen as adaptability 'categories' as opposed to 'strategies'.

Gosling et al. (2013) suggests an alternative breakdown of adaptability, making a distinction between 'design-based' and 'process-based' enablers. Design-based enablers focus on strategies which can be applied to a design to increase its adaptability, whilst process-based enablers refer to management strategies of supply, construction and operation of a building. Within these two categories, Gosling et al. (2013) suggest seven enablers, four of which are design-based and three are process-based (see Table 3).

Looking specifically to the design-based enablers, Ross et al. (2016) suggests an additional seven design strategies. Through a survey of experts, Ross et al. prioritise these 11 strategies, in order of recurrence during the surveys, into the order shown in Table 3. It is highlighted,

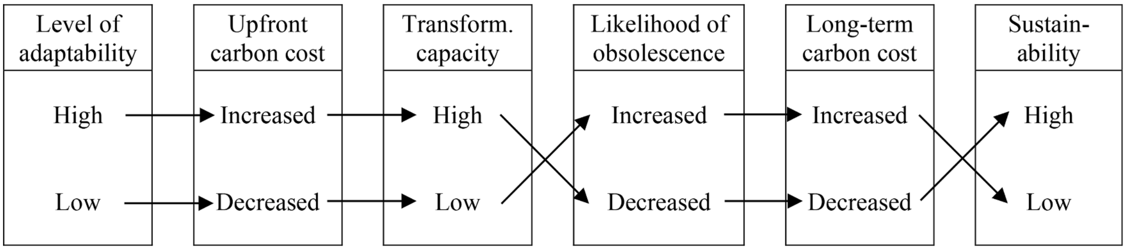
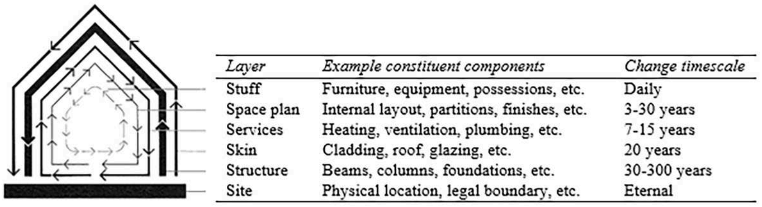


Fig. 1. Relationship between adaptability and sustainability.

Table 1
Building layers, example components and typical timescale of change (Brand, 1994).



Layer	Example constituent components	Change timescale
Stuff	Furniture, equipment, possessions, etc.	Daily
Space plan	Internal layout, partitions, finishes, etc.	3-30 years
Services	Heating, ventilation, plumbing, etc.	7-15 years
Skin	Cladding, roof, glazing, etc.	20 years
Structure	Beams, columns, foundations, etc.	30-300 years
Site	Physical location, legal boundary, etc.	Eternal

Table 2
Adaptability categories, type of change, typical timescale and affected building layers (Schmidt III et al., 2010).

Category	Type of change	Timescale	Building layer					
			Stuff	Space	Service	Skin	Structure	Site
Adjustable	Change of task	Daily/monthly	•					
Versatile	Change of space	Daily/monthly	•	•				
Refitable	Change of performance	Seven yearly		•	•	•		
Convertible	Change of function	15 yearly		•	•	•		
Scalable	Change of size	15 yearly		•	•	•	•	
Movable	Change of location	30 yearly					•	•

Table 3
Lists of design-based and process-based enablers (Gosling et al., 2013; Ross et al., 2016).

	Gosling et al. (2013)	Ross et al. (2016)
Design-based enablers	1. Layering of building elements	1. Accurate information
	2. Indeterminacy	2. Reserve capacity
	3. Interchangeable components	3. Layering of building components and systems
	4. Design for deconstruction	4. Open plan layouts
		5. Simplicity
		6. Access for assessment
		7. Commonality
		8. Appropriate materials
		9. Mechanical connections
		10. Modularity
		11. Design for deconstruction
Process-based enablers	5. Flexibility in planning / project process	
	6. Supply chain integration	
	7. Supply chain flexibility	

however, that some of these strategies potentially overlap (e.g. 'mechanical connections', 'layering' and 'design for deconstruction' (DfD)). Nevertheless, the disaggregation of 'adaptability' into design-based DfA strategies is highly beneficial, and these categorisations will be used to structure the results and discussion later in this paper.

Whilst research into the meaning of adaptability, and the strategies used to achieve it, is the necessary first step toward its eventual implementation, the concept must also be promoted with industry. As such, it is pertinent to review the state of DfA within industry guidance. The British Standards Institution (BSI, 2020) recognise the importance of the approach and suggest three principles of adaptability:

- 'versatility': the ability to accommodate minor system changes,
- 'convertibility': the ability to accommodate substantial changes,
- and, 'expandability': the ability to accommodate addition of new space, features, capabilities and capacities.

Comparing the BSI (2020) principles with the strategies proposed by Schmidt III et al. (2010), we can see evidence of this lack of consensus on definition, as suggested within literature (Anastasiades et al., 2021; Friedman, 2002; Kanters, 2020; Kelly et al., 2011; Pinder et al., 2017; Schmidt III and Austin, 2016). However, with some interpretation, we can consider BSI (2020) as referring to:

- changes in the 'stuff' and 'space' layers as "minor system changes",
- "substantial changes" as changes in the 'space', 'services' and 'skin' layers,
- 'expandability' equivalent to 'scalability'.

Thus, the definitions are not dissimilar in intent, albeit different in word choice. Other institutions have also recognised the benefits, or at least existence, of DfA (BSI, 2020; CIBSE, 2014; GLA, 2022; IStructE, 2021; Steel Alliance, 2010; Sustainability Committee, 2010).

Another common discrepancy is the use of the word 'flexibility' (Schmidt III et al., 2010). Some academics and design guidance use it synonymously with 'adaptability' (Cavalliere et al., 2019), some use it as a subgenre (Schmidt III et al., 2010), and others treat it as a completely different design approach (Blakstad, 2001; GLA, 2022). Using the two words interchangeably can confuse the understanding of DfA, and so should be avoided. Similarly, due to the potential for misunderstanding, 'flexibility' should also be avoided as a subgenre, instead opting for more specific wording, such as 'versatility' from Schmidt III et al. (2010).

A clear definition of adaptability in the context of the built environment is a first step toward the adoption of DfA, and that of Kelly et al. (2011) seems most suitable, succinctly summarising most of the key points discussed in Section 2.1.1: adaptability, therefore, is "a building's ability to accommodate change throughout time, fundamentally extending its life".

3. Method

This review of academic journal papers, industry articles and design guidance, consolidates proposed DfA strategies, extracting their purpose, benefits and drawbacks, and barriers and enablers, cross-referencing them to find analogous, complementary or contradictory recommendations. In addition, this paper includes consideration of the often-overlooked (within adaptability review papers, in any case) counterargument to DfA: the upfront material optimisation of lean design (LD).

4. Results and discussion

The following results and discussion section will follow the breakdown of adaptability enablers suggested by Gosling et al. (2013) and Ross et al. (2016).

4.1. Process-based enablers

Although this paper focuses primarily on the design-based enablers of adaptability, it is appropriate to first discuss the barriers to the approach's process-based enablers.

4.1.1. Flexibility in planning

For the first process-based enabler, Gosling et al. (2013) suggests that, in order for DfA to be successfully implemented in construction projects, it must be considered from the very early design and planning stages, so much so that the planning processes themselves are adaptable. Such a method would allow for late changes to the design, be able to accommodate the unique nature of buildings and mitigate the uncertainty inherent to designing for the future.

Many have raised the concern that the future cannot be predicted and suggest that attempting to do so would be futile (Russell and Moffatt, 2001) or, as the IStructE (2021) put it: "do not imagine you can predict the future". These sentiments risk misunderstanding the purpose of adaptability, for it is not to predict which changes will occur but to design in such a way that a building can adapt in the face of unexpected changes the future (Blakstad, 2001; Brand, 1994; O'Connor, 2004). Although the future is impossible to predict, the best adaptability strategies do not require accurate insights into future building uses, instead they should focus on ensuring future conversion is left unhindered, or even promoted, by decisions made for the benefit of the present-day.

Uncertainty is inherent when contemplating the future. Unfortunately, a high level of uncertainty can limit the persuasive draw of adaptable strategies if it cannot be proven that they will ever be utilised. Fawcett (2011) expresses this concern as a paradox: we want adaptable strategies to allow for an uncertain future, whilst also wanting a certain future to dictate what changes we should accommodate. Therefore, there is a need to further the research currently available on uncertainty quantification and the time-value of carbon, in order to better understand the optimal level of adaptability, so as not to under- nor over-invest in the approach.

The unique nature of building projects also hinders the adoption of DfA (de Ridder and Vrijhoef, 2008; Fawcett, 2011), as designers can find it difficult to apply generic strategies to the variations evident within real-world projects. As such, consideration of DfA at concept stage, and allowing for flexibility within the design process, would accommodate these variations and uncertainties; however, for this to be achieved, the remaining two process-based enablers, integration and flexibility of the supply chain, are necessary (Gosling et al., 2013).

4.1.2. Supply chain integration

In order for adaptability to be considered early on in the design process, as is recommended within the 'flexibility in planning' enabler and by many other researchers (CIBSE, 2014; Giesekam et al., 2016; Hart et al., 2019; Hossain et al., 2020; Melton, 2020), the supply chain for the project must be fully integrated. Currently, clients, contractors, architects and engineers tend to focus only on their own sphere of influence and do not consider the knock-on implications of their decisions on the other disciplines (de Ridder and Vrijhoef, 2008; Gillott et al., 2022; Hossain et al., 2020).

Early design stage consideration of adaptability, or even just a greater awareness of sustainability, from those involved in the conceptual stages of a design project, is often considered one of the greatest opportunities for reducing whole-life carbon (Dunant et al., 2021; Gauch et al., 2022). Many DfA strategies incorporate the design characteristics and philosophies that are often solidified at concept stage. As such, it can be too late to consider DfA only at detailed stage and still achieve meaningful impact (Melton, 2020); we need clients to understand the benefits of DfA and to push for integrated design processes.

Acting as a barrier to this early adoption is the negative perception of adaptability so often held by clients, advisors and developers. It is often considered that DfA will only add extra material, cost and work to a project with no guarantee of a return on this investment (Finch, 2005; Hossain et al., 2020; Kelly et al., 2011; Melton, 2020). Ideally, an integrated design process would allow the initial developers to see a return on their investment, through a greater shared understanding of the value of DfA across the supply chain, although this is still not guaranteed. This is where a standardised method to quantify adaptability would be highly beneficial. Such a method would allow for the valuation of buildings to reflect the adaptability investment put into them and ensure that adaptably-designed buildings retain their inherent monetary value for future owners.

Whilst adaptability quantification methods do exist, it is often recognised that they are only in the very early stages of development (Askar et al., 2022; Kanters, 2020; McFarland et al., 2021a; Rockow et al., 2019). As such, these methods are not yet suitable for large scale deployment, enforcement within building design processes, or for use to determine the financial value-add of DfA strategies. By comparing the construction industry to that of the financial sector (where 'options' and their accurate, standardised quantification underpins the modern financial market), Fawcett (2011) suggests three reasons why the process of quantifying adaptability will be challenging:

1 Financial transactions are repeatable and units are interchangeable; buildings are unique,
2 Stock markets have been tracked and monitored for decades; data on building adaptability is lacking,
3 The financial sector employs a sufficient quantity of "high-powered mathematicians" to synthesise such quantification methodologies; the building industry lacks these numbers and the means to attract them.

What is clear, however, is that for adaptability to be of interest to a developer there needs to be a link between the adaptability and the profitability of a project (Russell and Moffatt, 2001). To this end, the immediate benefits of DfA need to be understood. Slaughter (2001) suggests that, whilst DfA can lead to slight increase in upfront material cost, this can be mitigated by simpler – and, therefore, cheaper – construction and maintenance, with financial savings being achieved within the first renovation cycle of a typical building. Similar sentiments have been made by others (Cavalliere et al., 2019; Ellison and Sayce, 2007; Israelsson and Hansson, 2009; Sustainability Committee, 2010), with Schmidt III & Austin (2016) going as far as to suggest that some DfA strategies may actually require no increase in upfront cost.

Whilst balancing the desires of the client, designers must also adhere to the requirements of building regulations and, unfortunately, these needs are typically of detriment to DfA. Current regulations often focus on operational efficiencies and neglect to consider the knock-on impacts of these proposals (Dunant et al., 2018b; Ellison and Sayce, 2007; Kanters, 2020; Schmidt III et al., 2010). For example, the energy efficiency measures of increased insulation or deployment of renewable technologies can sometimes conflict with those of long-term adaptability, leading to issues such as over-insulation and reduced air quality in future climates or increased maintenance requirements of the specified renewable technologies (CIBSE, 2014). This highlights the ever-present importance of balancing the desires of upfront energy efficiency with the predictions for long-term repercussions.

Alongside the focus on operational efficiencies, regulatory drivers have also been shown to favour new build structures over retrofit, unintentionally incentivising demolition and rebuild instead of DfA and refurbishment (Hossain et al., 2020; Kanters, 2020). An example of this is the case of the tax exemptions applied to new builds, but not renovation projects, in the UK (Gillott et al., 2022; Hart et al., 2019). These governmental biases act as a significant barrier to the shift toward DfA and will, again, limit a designer's ability to convince clients of the financial benefits of doing so.

4.1.3. Supply chain flexibility

Following on from, and enabled by, an integrated supply chain, is the need for flexibility within the design and procurement process. Such flexibility, whilst not an obvious DfA enabler in itself, benefits the concepts of DfD and CE, through creating space for the growth of new reuse stockist industries and prepares designers for the uncertainty inherent to reuse markets (Dunant et al., 2018b; Hossain et al., 2020).

In order for element reuse to become commonplace in the construction sector, the procurement processes most familiar to designers, contractors and suppliers will have to change (Anastasiades et al., 2021). Designers and contractors will have to get accustomed to working with what materials they have access to at the time, rather than being able to specify whichever virgin material they require, and suppliers will have to develop a new industry for used material recertification and stockpiling. Unfortunately, as will be a recurring barrier for many DfA principles, the inertia of the construction industry, and its reluctance to adopt new, potentially risky design processes, will limit the rate of change and emergence of flexible supply chains (Giesekam et al., 2016; Kanters, 2020; Orr et al., 2019).

4.2. Design-based enablers

Whilst the process-based enablers are vital in the implementation of DfA, they do not resolve the uncertainty around what exactly the physical manifestations of adaptability are, and how they ought to be balanced with the desires of minimum upfront carbon and LD. The eleven design-based enablers from Ross et al. (2016) give us a framework around which tangible design strategies can be speculated, as will be discussed within the following subsections.

4.2.1. Accurate information

The first of Ross et al.'s (2016) design-based enablers is 'accurate information'. The retention of accurate information is one of the most frequently recommended strategies within the literature (Anastasiades et al., 2021; BSCA, 2022; Dunant et al., 2018b; Hart et al., 2019; Heinrich and Lang, 2019; McDonough and Braungart, 2009; Russell and Moffatt, 2001). This concept is often referred to as a building's 'material passport' (Orms, 2015). The contents of such a record, however, is often suggested to go beyond a mere register of materials and components, and should include, but be not limited to, details on any building adaptation and demolition plans, records of any and all modifications to the structure throughout its life, and highlight any potentially hazardous materials (Anastasiades et al., 2021; Rockow et al., 2021; Ross et al., 2016). As the majority of DfA strategies are not necessarily intended to be implemented now but instead allow for easier renovation or replacement in the future, it is important that the intentions of the original designer and their envisaged DfA strategies are not lost.

As this concept is still relatively early in development, the exact contents, format and method of storage for such a record is still undecided. An early suggestion from Graham (2003) is to include a physical black box within the building to store this information. More recently, there have been proposals for the information to be stored within the 3D design models (Baker-Brown, 2017; Melton, 2020) or on an online database system (Madaster, 2023). The stakeholders who are responsible for the generation, retention and dispersal of the material passport is also still uncertain. The production of the passport will undoubtably require some level of increased effort from designers and, with increased work, comes increased cost. This cost is unlikely to be significant, yet, if there is no incentive or requirement for clients to fund such a practice, it is unlikely to become widely adopted, except maybe by climate-minded individuals and companies.

A concern that is not simply tackled by the retention of information is the educational focus of the institutions training the next generation of engineers, prioritising the design of new build structures and neglecting to teach the skills necessary for building reappraisal (Gillott et al., 2022; Kanters, 2020; Kelly et al., 2011). A lack of this ability in upcoming engineers would further amplify the drive for demolition and new build, and increase the likelihood that, even if a building were to be designed for adaptability, upcoming engineers may lack the ability to realise and implement the intention of the original designer, as such, the adaptable building may be demolished anyway.

In a similar vein to this, although not often mentioned in literature, is the issue whereby construction companies are finding it difficult, if not impossible, to acquire professional indemnity insurance to undertake building refurbishment projects (CLC, 2021). As such, these companies are either having to pay significantly increased insurance fees or end up losing out on work, as a result of being unable to carry out building adaptation works for which they would no longer be insured. With this being a relatively recent development, neither the construction industry nor academia have yet researched a solution for this. In the meantime, with this uncertainty surrounding insurance and the concern around the limited education on building reappraisal, the development of DfA practices is further discouraged.

4.2.2. Reserve capacity

The over-provision of floor load carrying capacity is often seen as the most obvious DfA strategy (Graham, 2005; Hamida et al., 2022; Melton, 2020; Rockow et al., 2021). The suggestion is that if a structure is overdesigned – that is, designed for a load above and beyond that of its original use requirement – it will be suitable for any alternative use in the future. Unfortunately, the extent to which a building can be adapted is not often as simple as its increased load carrying capacity (Kamara et al., 2020). Simultaneously, whilst not guaranteeing a level of adaptability, blanket overdesign does result in unfavourable excesses of material usage, cost and carbon at construction stage. The idea of blanket overdesign is, therefore, frequently discouraged by researchers and industry guidance alike (BSCA, 2022; IStructE, 2021; Russell and Moffatt, 2001).

What should be explored, however, is the adaptation opportunities that are retained or lost by the specification of a given design load, and what the carbon implications of this decision are, in order to determine when it may be preferable to overdesign floor loading to achieve long-term carbon savings. As usual, there is a trade-off between the adaptability benefits of overdesign and the embodied carbon implications of its specification; McFarland et al. (2021a) showed this, in their suggestion for a DfA quantification method, as a diminishing return on level of adaptability with increasing deployment of certain DfA strategies, such as increasing live load, floor-to-ceiling heights and column spacings.

Whilst uniform overdesign is likely to be wasteful, an argument could be made to providing reserve capacity within selected elements; elements that are either difficult to access or difficult to strengthen in the future. For example, the lateral stability mechanism and foundations for high-rise buildings are often difficult to retroactively strengthen. The stiffness of a bracing system is often governed more by its gross geometry (i.e. length and height of a braced bay) rather than individual component performance (Liang et al., 2000), and foundations can be logistically challenging to access in order to strengthen in the future. This selective overdesign must, as usual, balance the opportunities for long-term carbon savings afforded by it, with the upfront increases in carbon required at construction stage to achieve it. For this balance to be determined, research into the likely increases in loading on any given element would be vital (e.g. how the lateral stability requirements could increase due to changes of use, vertical extension or climate change).

On a spatial, rather than element, basis, another aspect of reserve capacity would be the circulation capacity provided by the structural cores. The requirements for circulation capacity often vary between use typologies (e.g. higher in offices and retail than residential, due to higher peak occupancies). Rinke & Pacquée (2022) identify the 'diversity of circulation' as a key strategy to DfA, whereby having a surplus of vertical access routes, ideally on opposite sides of buildings, allows for future subdivision of the building into smaller units of use if necessary in the future. Whilst additional cores or external staircases can be retrofitted, this work can be costly and disruptive, going against the "without the need for extensive refurbishment" goal of DfA. As such, consideration could be given to the overprovision of circulation capacity in the structural cores for residential first-use buildings.

The overprovision of building services is another commonly suggested route toward adaptability (BRE Global, 2017; Russell and Moffatt, 2001). Whilst this would be an ideal adaptable solution, it would also increase project costs, and there is a risk that it would be wasteful, if the building does not undergo the use change for which the services were provided (Melton, 2020). Therefore, options to improve the adaptability of a building's services without significantly increasing the cost are necessary. A potential solution for this falls within the 'layering' and 'access' enablers, discussed in the following section.

4.2.3. *Layering of building components and systems*

Utilising the concept of building layers from Brand (1994) and others, the next DfA enabler is the concept of separating layers (Blakstad, 2001; BSCA, 2022; Hamida et al., 2022; Rockow et al., 2021; Russell and Moffatt, 2001; Slaughter, 2001; Sustainability Committee, 2010); designing in such a way that every element can be accessed, maintained or replaced without compromising those adjacent to it. This can be achieved through a variety of means, such as the later enablers of 'mechanical connections' and 'access', and links strongly with the final enabler, and complementary design strategy, of DfD.

Similar to how Duffy (1990) differentiated between his layers by considering the temporal dimension, the concept of separating layers is sometimes referred to as 'lifetime compatibility'(Russell and Moffatt, 2001). As there can be great variation in the cycle-rates of connected elements, an adaptable building should be designed in such a way that rapid-cycling, short-lifespan elements can be replaced without affecting the slower-cycling, long-lifespan elements (Graham, 2005).

The benefits of 'layering' are many: it can simplify future modifications, reducing cost and duration of refurbishment works (Cavalliere et al., 2019; Hamida et al., 2022), in turn, reducing void periods between tenancies and increasing client financial returns (Ellison and Sayce, 2007); it can improve the ability to maintain and upgrade faulty building components (BSI, 2022; Melton, 2020; Ross et al., 2016), improving the safety and longevity of the structure; it can decrease the risk of building obsolescence, which could be caused by technological advancements or changes in architectural style, by allowing ready replacement of outdated components (Kelly et al., 2011; O'Connor, 2004); and, ultimately, it can benefit DfD and the CE, allowing for extraction of all building components, undamaged, at end-of-life, either improving the reuse potential of the elements or allowing for improved cradle-to-cradle recycling (Anastasiades et al., 2021; Hamida et al., 2022; McDonough and Braungart, 2009; Russell and Moffatt, 2001).

Problematically, however, similar to the barrier of the construction sector inertia limiting 'supply chain flexibility', the construction industry historically relies on traditional methods which do not consider DfA or DfD (BSI, 2020; Gillott et al., 2022); techniques such as welding steel, casting concrete, bonding polymers and cementing masonry (de Ridder and Vrijhoef, 2008). These methods, and, by extension, the common oversight of designing buildings as static objects (Askar et al., 2021; Brand, 1994), go against the separation of layers approach.

Whilst the concept of separating layers can be seen to offer many long-term environmental benefits, it may preclude some opportunities for upfront carbon savings. An example of this is the preference of non-composite materials to promote 'layering' (Anastasiades et al., 2021; Ross et al., 2016; Sustainability Committee, 2010). Composite, non-separated construction forms and materials are an opportunity to reduce material consumption through greater refinement of the symbiosis between different construction materials (Allwood and Cullen, 2011; Gibbons, 1995). As such, the industry needs solutions that achieve both the benefits of separating layers and the material efficiencies of composite construction.

An example of such a solution is the proposal for composite-acting, yet demountable, floor slabs (Ataei et al., 2016; Pavlović et al., 2014; PCI Committee, 1988; Rehman et al., 2016; Wang et al., 2020). This demountability is achieved through the use of threaded shear studs slotted into recesses within precast concrete units, instead of the welded shear studs and cast-in-situ concrete typically used in composite construction. These threaded shear studs (similar to the use of bolts in other demountable connections) are what will be discussed in the later 'mechanical connections' enabler section. Such a solution achieves the aspirations of both composite construction and separating layers, yet these proposals are still not commonplace within industry. Investigation into the reasons for this reluctance (e.g. construction sector inertia, no guarantee of initial developer return on investment, and increased design and construction complexity), and into the development of other demountable alternatives of composite building systems, should be undertaken.

4.2.4. *Open plan layouts*

What can most often come to mind when considering the adaptation of a building is the versatility (to use one of Schmidt III et al.'s (2010) categories of adaptability) of the space (to use Brand's (1994) associated layer) provided by the building; how many different activities or arrangements can the space provide such that it allows for changes of use or task? The level of openness of a building is primarily determined by a few concept stage design decisions, such as those of the distances between, and number of, internal columns; the height between floors and ceilings; and the frequency and positioning of immovable obstacles, such as bracing or load-bearing walls (McFarland et al., 2021a; Rockow et al., 2021; Sustainability Committee, 2010).

Looking at the distance between the columns, or the grid spacing, longer spans are often seen as preferable for adaptability (BSI, 2020; IStructE, 1999; Melton, 2020; NRC, 1993). This, predictably, comes at a cost to LD; typically, longer spans require more material than shorter spans, even when taking into account the reduced number of vertical elements required for long-span structures (Gauch et al., 2022; IStructE, 2021). In order for the short-term and long-term carbon implications of grid spacing choice to be fully understood, there needs to be the understanding of: which building uses are gained or lost by the specification of a given grid spacing; how this impacts the longevity of a structure; and, how the carbon implications of grid spacing selection varies between use types (e.g. different loading, vibration or deflection requirements) and frame choice (e.g. decisions on both material type and stability mechanism).

The floor-to-floor or floor-to-ceiling heights of a building can also influence its level of openness. This decision is often governed by user perceptions, planning constraints and cost, rather than structural requirements. Melton (2020) suggests a higher floor-to-ceiling height would increase a building's ability to switch between uses and help for natural daylighting and ventilation. The downside to greater floor-to-floor heights is the increase in material and cost requirements of a resulting taller structure, which necessitates more cladding and glazing, and stiffer lateral stability mechanisms. Alternatively, larger floor-to-floor heights may instead result in a reduced number of floors within the building, if planning permission imposes a limitation on the overall height of the building. This would reduce the lettable floor area and, in turn, rental returns on investment for the client. Therefore, once again, the desires of adaptability and greater floor-to-floor heights must be balanced with the requirements of the client and upfront material usage.

With the floor-to-ceiling height requirement being similar across many of the standard building use typologies (Steel Alliance, 2010), it is unlikely to be a critical factor in the decision to retain or demolish an existing building. Nevertheless, the lack of true understanding of floor-to-floor height impact on building adaptability is yet another gap in knowledge requiring research, especially when considering the differing service void requirements for different building uses and the impact this will have on the remaining floor-to-ceiling height after refurbishment (see ‘access’ enabler for further discussion).

A slightly tangential approach from floor-to-floor heights, yet still a route to improved natural ventilation and daylighting, is structural plan depth (Gann and Barlow, 1996; McDonough and Braungart, 2009; McFarland et al., 2021a). Similar to the overprovision of circulation capacity (discussed in Section 4.2.2), opting for a narrower plan depth (i.e. the distance from one side of a building to the other) was found to be of benefit when subdividing buildings, to ensure all units still have access to an external wall for sufficient natural ventilation and daylighting. This is especially problematic with more recently designed offices where a focus on deeper, open plan spaces has been preferable (Gann and Barlow, 1996). This can be achieved in the design of a new building by either designing them as narrow structures in the first instance, or by including design features such as lightwells and internal courtyards (McDonough and Braungart, 2009) or, if that is impractical in first use, designing such that these measures could be readily retrofitted (e.g. by designing capacity for retrofitting additional bracing and floorplate apertures).

The final barrier to the ‘open’ enabler is the positioning of immovable internal walls or bracing. To this end, out of the two commonly used lateral stability mechanisms in multi-storey building design, braced or moment-resisting frames, the latter is often promoted for its adaptability benefits (Rinke and Pacquée, 2022; Sustainability Committee, 2010). Moment-resisting, or continuous, frames are recommended for their inherent lack of obstacles of braced bays or shear walls, which are required in the alternative, braced frame option. The carbon implications of this recommendation must obviously be a consideration at optioneering stage, especially in the design of taller structures where continuous frames can become uneconomical (Liang et al., 2000). Similarly, to avoid unnecessary immovable obstacles, load-bearing internal walls should be avoided, instead opting for lightweight, demountable partitions, mirroring the concepts of ‘layering’ (Kelly et al., 2011; Melton, 2020).

4.2.5. *Simplicity*

A building’s level of adaptability can be influenced by its simplicity. A structure that is simple to understand reduces the uncertainty for future designers interpreting its load transfer mechanisms, and increasing the repetition and predictability of its element placement (BRE Global, 2017; Hamida et al., 2022; McFarland et al., 2021a; Melton, 2020; Rockow et al., 2021). Both of these factors will help reduce the cost of refurbishment and further incentivise building retention and retrofit over demolition and rebuild. There are a few key design strategies to achieve structural simplicity: by specifying a regular, rectangular grid shape; by repeating floor layouts throughout a building; and, by avoiding complex load paths (e.g. extreme cantilevers or transfer structures).

Unlike most other adaptability strategies, the preference for simple structures is aligned with both DfA and LD. It has been repeatedly shown that structures with simple load transfer mechanisms can achieve significant material reductions when compared to examples that opted for more complex structural frames (BSCA, 2022; Carruth et al., 2011; Dunant et al., 2021; IStructE, 2021; Sustainability Committee, 2010). Simple design can also reduce the financial cost of buildings, by reducing design and construction timeframes, and the reduced likelihood of construction errors and their associated costs. A potential drawback of this approach, however, would be the reduced artistic freedoms resulting from a strict specification of a rectangular grid and removing the option for unconventional, creative load paths. How much of limitation these requirements actually impart ought to be investigated, and this would have to outweigh the proven carbon savings achieved by the approach for it to be justifiable.

4.2.6. *Access*

Similar to the ‘layered’ strategy, ensuring sufficient access to all elements and components will improve a building’s adaptability, through improved upgradeability, and longevity, through increased maintainability. For example, due to the great variance in service requirements between use types, or even between consecutive tenants within the same use type, and their historically high cost in refurbishment works (Gann and Barlow, 1996), access to the building services is a commonly highlighted as a critical DfA strategy (BRE Global, 2017; BSI, 2022; Hamida et al., 2022; McFarland et al., 2021a, 2021b; NRC, 1993; Rockow et al., 2021).

Oversizing the vertical service risers and horizontal service voids can improve the accessibility and upgradeability of services, analogous to the principles of ‘reserve capacity’, without the need for dramatically increased upfront costs. It could be argued, however, that oversizing the service risers takes away from the usable floor area of the building, reducing the achievable rental returns. Nevertheless, the decision comes back to balancing the requirements and sacrifices in the short-term with the opportunities and advantages afforded in the long-term.

The choice between dropped ceilings or raised floors for horizontal service passage is not an obvious one from an adaptability perspective. Raised floors allow for greater short-term adaptability by providing the building users the ability to modify the services and cabling as and when required (Brand, 1994; Hamida et al., 2022; Ross et al., 2016). A potential downside to raised flooring is the possibility of misaligned windows in the event of raised floor removal during a future retrofit (Gann and Barlow, 1996), yet this could be countered by a layered approach to the building envelope. What is certain, however, is that a key facilitator for ‘access’ is ensuring a separation of ‘layers’ design approach and utilising ‘mechanical connections’ wherever possible, as not to encapsulate services in such a way that they cannot be readily accessed, inspected, maintained or replaced (McFarland et al., 2021b). Doing so may result in the early redundancy of entire systems that only require the replacement of a minor, yet inaccessible, component.

4.2.7. *Commonality*

Commonality is a strategy complementary to DfD, complimented by ‘simplicity’ and not to be confused with ‘modularity’. Ross et al. (2016) introduce the strategy as “using the same component sizes and construction details throughout a building”, which matches the design approaches of ‘standardisation’ and ‘rationalisation’ (BRE Global, 2017; BSCA, 2022). Rationalisation can have immediate benefits to a construction project, as well as promote DfD and CE (Hamida et al., 2022), but it can also potentially impose some significant increases in upfront embodied carbon.

Rationalisation can reduce the immediate financial costs of a project through increased design simplicity, and reducing design, fabrication and construction costs (Anastasiades et al., 2021; Gibbons, 1995; Moynihan and Allwood, 2014; Needham, 1977). This benefit has become less pronounced in recent years, with the use of computer aided design to automate aspects of the design process, as well as developments in technologies to aid contractors on site, minimising the risk of construction errors (Dunant et al., 2018a; Moynihan and Allwood, 2014).

The benefit of rationalisation on DfD and CE is achieved through the reduction in number of unique construction components going into a building, making it easier to redistribute and reuse those elements in later construction projects (BSI, 2020; Carruth et al., 2011; Dams et al., 2021; Hamida et al., 2022). Whilst this benefit is undeniable, its long-term carbon reduction potential is hard to quantify, and, at the same time, the upfront carbon costs of rationalisation have started to come under scrutiny. Many consider rationalisation as a significant contributor to underutilisation of structural elements and, therefore, a key cause of the inflated carbon emissions of the construction sector (BSCA, 2022; Carruth et al., 2011; IStructE, 2021; Moynihan and

Allwood, 2014). Dunant et al. (2018a), however, argues there is not a significant correlation between rationalisation and underutilisation.

As usual, it can therefore be seen that the benefits of rationalisation, for reduced construction costs and improved DfD and CE, must be balanced with any reductions in structural efficiency, leading to overuse of materials and excessive embodied carbon emissions.

4.2.8. *Appropriate materials*

The decision around structural material specification is a multifaceted one. From a DfA standpoint, the selected materials should be ones that allow for the realisation of the other DfA enablers: non-composite materials play a part in the 'layers' enabler; and, the benefits of 'mechanical connections' is allowed for within some materials (e.g. steel or precast concrete) (Blakstad, 2001; Graham, 2005; Melton, 2020; Sustainability Committee, 2010) whilst prevented in others (e.g. in-situ concrete) (Dams et al., 2021; de Ridder and Vrijhoef, 2008). Similarly, from a LD standpoint, steel frames have been shown to contribute less carbon in their construction than concrete (Gauch et al., 2022) as well as allow for more effective recycling (Moussavi Nadoushani and Akbarnezhad, 2015; Sustainability Committee, 2010); however, these findings are not unanimously agreed upon in either industry or academia (Guggemos and Horvath, 2005; Moussavi Nadoushani and Akbarnezhad, 2015; Sustainability Committee, 2010).

Secondary to the overarching material choice is the specification of material properties. Many suggest that selecting high durability materials will reduce the requirement for repair and maintenance, and increase the design lifespan of building elements, in turn increasing the survivability of a structure and the time for adaptation to take place (Hossain et al., 2020; Kelly et al., 2011; Melton, 2020; Rockow et al., 2021; Russell and Moffatt, 2001; Sustainability Committee, 2010). Selecting higher durability materials for their associated benefits must, of course, be balanced with any resulting increases in financial and carbon cost (McFarland et al., 2021a).

The appropriateness of a material should also consider its toxicity (Rockow et al., 2021; Ross et al., 2016). Toxic materials should be avoided to minimise the occupational hazards associated with construction (Melton, 2020) and facilitate easier deconstruction at end-of-life. In the event that a material currently considered non-toxic is identified to be harmful, the approaches of 'layers', 'access' and 'mechanical connections' will aid to facilitate in its easy removal.

4.2.9. *Mechanical connections*

The benefits of specifying 'mechanical connections', over welding, chemical bonding or casting of cementitious material, have been mentioned in previous sections; their specification benefits a 'separation of layers' approach, allows for greater 'access' to components and, ultimately, underpins the principles of DfD (BSI, 2020; de Ridder and Vrijhoef, 2008; Hamida et al., 2022; Sustainability Committee, 2010).

To this end, as was highlighted in the previous section, steel frames can more readily utilise 'mechanical connections' between elements and are, therefore, preferable over in-situ concrete structures (Blakstad, 2001; Graham, 2005; Melton, 2020; Sustainability Committee, 2010); concrete structures are often designed to be monolithic and impossible to disassemble (Dams et al., 2021; de Ridder and Vrijhoef, 2008). The continuous frame nature of monolithic concrete construction does provide opportunities for material reduction and carbon savings, however, through the ability to redistribute moments and reduce peak demands on elements (Carruth et al., 2011). Therefore, this decision provides yet another area where the long-term desires of DfA must be balanced with the immediate carbon costs against LD.

Similarly, the preference for composite floor construction to achieve carbon savings has limited the advantage of mechanical connections in steel frames (Allwood et al., 2010) and, as such, the selection of a steel frame alone does not entirely negate the entire issue around DfD; consideration must also be made for demountable solutions that allow for disassembly through the use of 'mechanical connections' (Ataei et al., 2016; Pavlović et al., 2014; PCI Committee, 1988; Rehman et al., 2016; Wang et al., 2020), described previously in Section 4.2.3.

4.2.10. *Modularity*

Following on from the suggestions of 'simplicity' and 'commonality' comes the final piece of the puzzle: 'modularity'. Whilst very similar to 'commonality' (which focuses on rationalisation of structural elements to reduce the number of unique components within the building), 'modularity' instead focuses on utilising common connection details between components (Hamida et al., 2022; Ross et al., 2016). Ross et al. likens this enabler to the standard connection seen with plastic building block toys, where a set of these toys could have high modularity (i.e. any one block could be connected to any other) whilst still being able to maintain a low commonality (i.e. by having a huge variety of block shapes and sizes).

The suggestion for standardised connection details has made its way into design guidance (BSI, 2020); however, these standards does not yet go as far as to recommend precisely what these connections and standard components should be (Anastasiades et al., 2021). Whilst having a common connection system, especially cross-material and cross-layer connections, throughout construction would be highly beneficial for DfD and CE, this would require cross-industry collaboration and consensus, and is, therefore, unlikely to be achieved quickly. Instead, focusing on the smaller product-scale components used in construction, such as services or cladding, may be more achievable. The benefits of a modular cladding system, for example, would include easy alteration of insulation levels, changes to external aesthetic or modification of glazing ratios and window openability, all of which could save a structure from early obsolescence (Gann and Barlow, 1996; Mansfield and Pinder, 2008; Melton, 2020).

4.2.11. *Design for deconstruction*

The final, and therefore least-mentioned, DfA enabler, according to Ross et al. (2016), is DfD. Ross et al. caveat this with the understanding that, for the sake of their study, enablers such as 'layers', 'mechanical connections', 'commonality', 'simplicity' and 'modularity' are considered separate to DfD whilst, in reality, they are strategies for both DfA and DfD. As such, DfD is, and should be, considered a separate, but closely associated, design approach to DfA (Askar et al., 2022; Russell and Moffatt, 2001). The distinction between the two could be drawn with DfA focusing on extending the useful lifespan of given structure as a structure, whilst DfD considers the structure as a series of individual components and focuses on maintaining each one of those at its highest level, transcending a singular building lifecycle.

5. Conclusions

This paper has discussed the background and definition of adaptability in the building environment, and reviewed various breakdowns of the approach. The categorisation of DfA enablers from Gosling et al. (2013) and Ross et al. (2016) structured the discussion into process-based and design-based strategies. The discussed process-based barriers to DfA include the inconsistencies in definitions, antagonistic habits of the construction industry, underdeveloped quantification methodologies, counterproductive planning policies and fragmentation of the supply chain.

A review of the proposed design-based DfA strategies highlighted their benefits, enablers, barriers and drawbacks, discussed tangible design methods to achieve them, and suggested a number of avenues within which further research would be beneficial. The following design-based enablers were identified, which must balance the benefits of long-term adaptability with the short-term increases in upfront cost and carbon:

- A separation of layers within a building, through the use of mechanical connections and ensuring access is maintained, allowing

individual elements to be maintained, upgraded, removed or replaced without compromising adjacent elements.
- Balancing the adaptation opportunities of openness provided by the sizing of spatial building characteristics, such as grid spacing and floor-to-ceiling heights, with the potential increase on financial and carbon costs.
- Avoiding deep plan structures, instead opting for narrower floor plates, by including design features such as lightwells or internal courtyards, or designing in such a way for easy retrofit of such measures.
- Avoiding blanket overdesign of element strength or component capacity, and only use selective overdesign if it is proven that this will result in a whole life carbon saving or that future modification would be difficult, on an element-by-element basis.
- Aiding future designers in understanding the original adaptability proposals through retention of key building documentation in a material passport (e.g. information such as an element capacity register, adaptation and deconstruction strategies, maintenance schedules and modification records).

It is important to recognise that buildings are unique and a strategy that may be ideal in one instance may not be suitable for another. Whilst some adaptability strategies might be suitable for all buildings, regardless of the use type, location or form, other strategies may require case-by-case evaluation of applicability and relevance.

Alongside the need to develop an understanding of tangible DfA strategies, the need for further development of adaptability quantification tools was highlighted. An ideal quantification methodology would rely on quantitative data exported from design software and minimise the requirement for subjective user input. Such a tool would allow different concept designs to be compared for their level of adaptability, allow the quantification of the value-add of DfA such that the initial developer could see return for their investment, and allow a balancing process to occur between LD and DfA.

The long-term benefits of DfA must be contrast against the lost opportunities for immediate short-term carbon savings, which could be achieved through LD. Whilst some DfA strategies are aligned with those of LD, most contradict the desires of immediate carbon reduction, by necessitating an increased upfront investment of carbon to achieve long-term savings. It is, therefore, necessary determine the long-term carbon saving capabilities of each DfA strategy. Such a study must account for the uncertainty around future prediction, must understand the realistic increases in capacity for change, and must quantify the carbon saved. This balance of short- versus long-term strategies is often mentioned within literature but rarely studied in great depth, leaving a sizeable gap in knowledge that must be answered before the construction industry is able to make meaningful, informed, long-term reductions in its embodied carbon emissions.

CRediT authorship contribution statement

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

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.

Data availability

No data was used for the research described in the article.

Acknowledgements

The authors acknowledge this research has been undertaken at The University of Sheffield, with financial support from EPSRC (Project Reference 2733613), Tata Steel UK Limited and Mott MacDonald Group Limited.

References

Allwood, J., Cullen, J., 2011. Sustainable Materials – with Both Eyes Open, 1st ed. UIT Cambridge Ltd., Cambridge.

Allwood, J., Cullen, J., Cooper, D., Milford, R., Patel, A., Carruth, M., McBrien, M., 2010. Conserving Our Metal Energy, 1st ed. University of Cambridge, Cambridge.

Anastasiades, K., Goffin, J., Rinke, M., Buyle, M., Audenaert, A., Blom, J., 2021. Standardisation: an essential enabler for the circular reuse of construction components? A trajectory for a cleaner European construction industry. J. Clean. Prod. 298 https://doi.org/10.1016/j.jclepro.2021.126864.

Andrade, J., Bragança, L., 2019. Assessing buildings' adaptability at early design stages. In: IOP Conference Series: Earth and Environmental Science. IOP Publishing, Brussels. https://doi.org/10.1088/1755-1315/225/1/012012.

Askar, R., Bragança, L., Gervásio, H., 2022. Design for Adaptability (DfA) – Frameworks and assessment models for enhanced circularity in buildings. Appl. Syst. Innovation 5. https://doi.org/10.3390/asi5010024.

Askar, R., Bragança, L., Gervásio, H., 2021. Adaptability of buildings: a critical review on the concept evolution. Appl. Sci. 11 https://doi.org/10.3390/app11104483.

Ataei, A., Bradford, M., Liu, X., 2016. Experimental study of composite beams having a precast geopolymer concrete slab and deconstructable bolted shear connectors. Eng. Struct. 114, 1–13. https://doi.org/10.1016/J.ENGSTRUCT.2015.10.041.

Baker-Brown, D., 2017. The *Re*-use Atlas: A designer's Guide Towards a Circular Economy. RIBA Publishing, London.

Blakstad, S., 2001. A Strategic Approach to Adaptability in Office Buildings (Doktor Ingeniør Thesis). Norwegian University of Science and Technology, Trondheim.

Brand, S., 1994. How Buildings Learn: What happens After They're Built, 1st ed. Viking Press, New York.

BRE Global, 2017. BREEAM international non-domestic refurbishment 2015. Technical Manual: SD225 1.4. Building Research Establishment, Watford.

BSCA, 2022. National structural steelwork specification for building construction: annex J – sustainability specification. The British Constructional Steelwork Association Ltd, London.

BSI, 2022. ISO 21931-1 sustainability in buildings and civil engineering works – framework for methods of assessment of the environmental, social and economic performance of construction works as a basis for sustainability assessment – Part 1: buildings. London.

BSI, 2020. ISO 20887 Sustainability in Buildings and Civil Engineering Works – Design for Disassembly and Adaptability – Principles, Requirements and Guidance, 1st ed. British Standards Institution, London. BS ISO 20887:2020.

Carruth, M., Allwood, J., Moynihan, M., 2011. The technical potential for reducing metal requirements through lightweight product design. Resour. Conserv Recycl. 57, 48–60. https://doi.org/10.1016/j.resconrec.2011.09.018.

Cavalliere, C., Dell'Osso, G., Favia, F., Lovicario, M., 2019. BIM-based assessment metrics for the functional flexibility of building designs. Autom. Constr. 107 https://doi.org/10.1016/j.autcon.2019.102925.

Cheshire, D., 2021. The Handbook to Building a Circular Economy, 1st ed. RIBA Publishing, London.

CIBSE, 2014. TM55: Design for Future climate: Case Studies. Chartered Institution of Building Services Engineers, London.

CLC, 2021. Professional Indemnity Insurance Restrictions Harming Industry. Construction Leadership Council, London.

Cook, M., Arnold, W., 2020. A framework for change. The Structural Eng. 98, 8–9.

Dams, B., Maskell, D., Shea, A., Allen, S., Driesser, M., Kretschmann, T., Walker, P., Emmitt, S., 2021. A circular construction evaluation framework to promote designing for disassembly and adaptability. J Clean Prod 316. https://doi.org/10.1016/j.jclepro.2021.128122.

de Ridder, H., Vrijhoef, R., 2008. Developing a strategy for "living buildings": beyond cradle to cradle with living building concept, in: Dainty, A. (Ed.), 24th Annual ARCOM Conference. Association of Researchers in Construction Management, Cardiff, pp. 1165–1174.

Duffy, F., 1990. Measuring building performance. Facilities 8, 17–20. https://doi.org/10.1108/EUM0000000002112.

Dunant, C., Drewniok, M., Eleftheriadis, S., Cullen, J., Allwood, J., 2018a. Regularity and optimisation practice in steel structural frames in real design cases. Resour. Conserv. Recycl. 134, 294–302. https://doi.org/10.1016/j.resconrec.2018.01.009.

Dunant, C., Drewniok, M., Orr, J., Allwood, J., 2021. Good early stage design decisions can halve embodied CO2 and lower structural frames' cost. Structures 33, 343–354. https://doi.org/10.1016/j.istruc.2021.04.033.

Dunant, C., Drewniok, M., Sansom, M., Corbey, S., Cullen, J., Allwood, J., 2018b. Options to make steel reuse profitable: an analysis of cost and risk distribution across the UK construction value chain. J. Clean. Prod. 183, 102–111. https://doi.org/10.1016/j.jclepro.2018.02.141.

Ellen MacArthur Foundation, 2023. How to build a circular economy [WWW Document]. URL https://ellenmacarthurfoundation.org/(accessed 2.20.23).

Ellison, L., Sayce, S., 2007. Assessing sustainability in the existing commercial property stock. Property Manag. 25, 287–304. https://doi.org/10.1108/02637470710753648.

Fawcett, W., 2011. Investing in flexibility: the life cycle options synthesis. Projections 10, 13–29.

Finch, E., 2005. Flexibility as a design aspiration: the facilities management perspective. Ambiente Construído 9, 7–15.

Friedman, A., 2002. The Adaptable House. McGraw-Hill, New York.

Gann, D., Barlow, J., 1996. Flexibility in building use: the technical feasibility of converting redundant offices into flats. Construction Manag. Econ. 14, 55–66. https://doi.org/10.1080/01446199600000007.

Gauch, H., Hawkins, W., Ibell, T., Allwood, J., Dunant, C., 2022. Carbon vs. cost option mapping: a tool for improving early-stage design decisions. Autom. Constr. 136 https://doi.org/10.1016/j.autcon.2022.104178.

Gibbons, C., 1995. Economic steelwork design. The Structural Eng. 73, 250–253.

Giesekam, J., Barrett, J., Taylor, P., 2016. Construction sector views on low carbon building materials. Build. Res. Inf. 44, 423–444. https://doi.org/10.1080/09613218.2016.1086872.

Gillott, C., Davison, B., Densley Tingley, D., 2022. Drivers, barriers and enablers: construction sector views on vertical extensions. Build. Res. Inf. 1–15. https://doi.org/10.1080/09613218.2022.2087173.

GLA, 2022. London Plan Guidance: Circular Economy Statements. London.

Gosling, J., Sassi, P., Naim, M., Lark, R., 2013. Adaptable buildings: a systems approach. Sustain. Cities Soc. 7, 44–51. https://doi.org/10.1016/j.scs.2012.11.002.

Graham, P., 2005. Design for adaptability – An introduction to the principles and basic strategies. Environ. Design Guide GEN 66, 1–9.

Graham, P., 2003. Building Ecology: First principles For a Sustainable Built Environment. Blackwell Science, Oxford.

Guggemos, A., Horvath, A., 2005. Comparison of environmental effects of steel- and concrete-framed buildings. J. Infrastructure Syst. 11, 93–101. https://doi.org/10.1061/ASCE1076-0342200511:293.

Habraken, N., 1961. Supports: An alternative to Mass housing, English language. The Architectural Press, London.

Hamida, M., Jylhä, T., Remøy, H., Gruis, V., 2022. Circular building adaptability and its determinants – a literature review. Int. J. Build. Pathol. Adaptation. https://doi.org/10.1108/IJBPA-11-2021-0150.

Hart, J., Adams, K., Giesekam, J., Densley Tingley, D., Pomponi, F., 2019. Barriers and drivers in a circular economy: the case of the built environment. In: 26th CIRP Life Cycle Engineering Conference. Elsevier, pp. 619–624. https://doi.org/10.1016/J.PROCIR.2018.12.015.

Heidrich, O., Kamara, J., Maltese, S., Re Cecconi, F., Dejaco, M., 2017. A critical review of the developments in building adaptability. Int. J. Build. Pathol. Adaptation 35, 284–303. https://doi.org/10.1108/IJBPA-03-2017-0018.

Heinrich, M., Lang, W., 2019. Materials Passports – Best practice. Technical University of Munich. Technische Universität München, Munich.

Hossain, U., Ng, T., Antwi-Afari, P., Amor, B., 2020. Circular economy and the construction industry: existing trends, challenges and prospective framework for sustainable construction. Renew. Sustain. Energy Rev. 130 https://doi.org/10.1016/J.RSER.2020.109948.

Israelsson, N., Hansson, B., 2009. Factors influencing flexibility in buildings. Structural Survey 27, 138–147. https://doi.org/10.1108/02630800910956461.

IStructE, 2022. How to Calculate Embodied Carbon, 2nd ed. The Institution of Structural Engineers, London.

IStructE, 2021. Design For Zero, 1st ed. The Institution of Structural Engineers, London.

IStructE, 1999. Building For a Sustainable future: Construction Without Depletion. The Institution of Structural Engineers, London.

Kamara, J.M., Heidrich, O., Tafaro, V.E., Maltese, S., Dejaco, M.C., Cecconi, F.R., 2020. Change Factors and the Adaptability of Buildings. Sustainability 12. https://doi.org/10.3390/su12166585.

Kanters, J., 2020. Circular building design: an analysis of barriers and drivers for a circular building sector. Buildings 10. https://doi.org/10.3390/BUILDINGS10040077.

Kelly, G., Schmidt III, R., Dainty, A., Story, V., 2011. Improving the design of adaptable buildings through effective feedback in use, in: 2011 CIB Management and Innovation for a Sustainable Built Environment Conference. Conseil International du Bâtiment, Amsterdam.

Leupen, B., 2004. The frame and the generic space, a new way of looking to flexibility. In: Kendall, S. (Ed.), 10th International Conference of CIB W104 Open Building Implementation. Ball State University, Paris, pp. 1–9.

Liang, Q.Q., Xie, Y.M., Steven, G., 2000. Optimal topology design of bracing systems for multistory steel frames. J. Structural Eng. 126, 823–829.

Madaster, 2023. Material passport [WWW Document]. URL https://madaster.com/material-passport/(accessed 7.25.22).

Mansfield, J., Pinder, J., 2008. Economic" and "functional" obsolescence: their characteristics and impacts on valuation practice. Property Manag. 26, 191–206. https://doi.org/10.1108/02637470810879233.

Maury, C., 1999. Framework to Assess a Facility's Ability to Accommodate Change: Application to Renovated Buildings (Master of Science). Tufts University, Medford.

McDonough, W., Braungart, M., 2009. Cradle to Cradle: Remaking the Way We Make Things. Vintage, London.

McFarland, D., Ross, B., Albright, D., 2021a. Quantifying adaptability of college campus buildings. In: Littlewood, J., Howlett, R., Jain, L. (Eds.), Sustainability in Energy and Buildings 2020. Springer, Singapore, pp. 75–88. https://doi.org/10.1007/978-981-15-8783-2_6.

McFarland, D., Ross, B., Naser, M., Blok, R., Teuffel, P., 2021b. Quantitative evaluation of the relationship between physical parameters and building demolition or adaptation outcomes. Architecture, Structures and Construction. https://doi.org/10.1007/s44150-021-00014-9.

Melton, P., 2020. Buildings That last: Design For adaptability, Deconstruction and reuse, The American Institute of Architects. The American Institute of Architects, Washington.

Moussavi Nadoushani, Z., Akbarnezhad, A., 2015. Effects of structural system on the life cycle carbon footprint of buildings. Energy Build. 102, 337–346. https://doi.org/10.1016/J.ENBUILD.2015.05.044.

Moynihan, M., Allwood, J., 2014. Utilization of structural steel in buildings. Proceed.: Math., Phys. Eng. Sci. 470 (2168) https://doi.org/10.1098/rspa.2014.0170.

Needham, F., 1977. The economics of steelwork design. The Structural Eng. 55, 367–373.

NRC, 1993. Fourth Dimension in Building: Strategies for Minimizing Obsolescence. National Research Council, Washington.

O'Connor, J., 2004. Survey on actual service lives for North American buildings. Woodframe Housing Durability and Disaster Issues. Forintek Canada Corp., Las Vegas.

Orms, 2015. Material passport vision [WWW Document]. URL https://orms.co.uk/insights/material-passport-vision/(accessed 7.25.22).

Orr, J., Drewniok, M., Walker, I., Ibell, T., Copping, A., Emmitt, S., 2019. Minimising energy in construction: practitioners' views on material efficiency. Resour. Conserv. Recycl. 140, 125–136. https://doi.org/10.1016/j.resconrec.2018.09.015.

Pavlović, M., Spremić, M., Marković, Z., Buđevac, D., Veljković, M., 2014. Recent research of shear connection in prefabricated steel-concrete composite beams 1, 75–80. https://doi.org/10.5937/jaes12-5676.

PCI Committee, 1988. Design and Typical Details of Connections For Precast and Prestressed Concrete, 2nd ed. Prestressed Concrete Institute, Chicago.

Pinder, J., Schmidt III, R., Austin, S., Gibb, A., Saker, J., 2017. What is meant by adaptability in buildings? Facilities 35, 2–20. https://doi.org/10.1108/F-07-2015-0053.

Rehman, N., Lam, D., Dai, X., Ashour, A.F., 2016. Experimental study on demountable shear connectors in composite slabs with profiled decking. J. Constr. Steel Res. 179–189. https://doi.org/10.1016/j.jcsr.2016.03.021.

Rinke, M., Pacquée, R., 2022. Structures and change – Tracing adaptability based on structural porosity in converted buildings. Architecture, Structures and Construction 2, 699–710. https://doi.org/10.1007/s44150-022-00054-9.

Rockow, Z., Ross, B., Becker, A., 2021. Comparison of building adaptation projects and design for adaptability strategies. J. Architectural Eng. 27 https://doi.org/10.1061/(ASCE)AE.1943-5568.0000481.

Rockow, Z., Ross, B., Black, A., 2019. Review of methods for evaluating adaptability of buildings. Int. J. Build. Pathol. Adaptation 37, 273–287. https://doi.org/10.1108/IJBPA-01-2018-0013.

Ross, B., Chen, D., Conejos, S., Khademi, A., 2016. Enabling adaptable buildings: results of a preliminary expert survey. Procedia Eng. 145, 420–427. https://doi.org/10.1016/j.proeng.2016.04.009.

Russell, P., Moffatt, S., 2001. Assessing Buildings for Adaptability. Annex 31 Energy-Related Environmental Impact of Buildings. International Energy Agency, Paris.

Schmidt III, R., Austin, S., 2016. Adaptable Architecture: Theory and Practice. Routledge, Abingdon.

Schmidt III, R., Eguchi, T., Austin, S., Gibb, A., 2010. What is the meaning of adaptability in the building industry?, in: 16th International Conference on Open and Sustainable Buildings. Bilbao, Spain, pp. 227–236.

Slaughter, E., 2001. Design strategies to increase building flexibility. Build. Res. Inf. 29, 208–217. https://doi.org/10.1080/09613210010027693.

Steel Alliance, 2010. Steel buildings in Europe. Multi-storey Steel buildings. Part 2: Concept design. Steel Alliance: Centre Technique Industriel de La Construction Métallique & Steel Construction Institute, Arcelor Mittal. Peiner, Träger & Corus.

Sustainability Committee, 2010. Sustainability Guidelines for the Structural Engineer, 1st ed. American Society of Civil Engineers, Reston.

van Ellen, L., Bridgens, B., Burford, N., Heidrich, O., 2021. Rhythmic Buildings- a framework for sustainable adaptable architecture. Build. Environ. 203 https://doi.org/10.1016/J.BUILDENV.2021.108068.

Wang, L., Webster, M., Hajjar, J., 2020. Design for deconstruction using sustainable composite beams with precast concrete planks and clamping connectors. J. Structural Eng. 146 https://doi.org/10.1061/(asce)st.1943-541x.0002659.