A critical review of the developments in building adaptability

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Abstract

Purpose – This paper provides a critical review of developments in the adaptability of buildings. The purpose of this paper is to determine the current "state-of-the-art", describe current thinking and trends in research and practice, and identify issues and gaps that further research can address. It provides a basis for a scientific and practical understanding of the interdependencies across different design criterion. This paper increases the awareness of architects, engineers, clients and users on the importance of adaptability and its role in lowering impacts over the lifecycle of buildings as part of the infrastructure system.

Design/methodology/approach – This paper draws mainly from the literature as its source of evidence. These were identified from established databases and search engines (e.g. Scopus, ISI Web of Knowledge and Google Scholar) using keywords such as adaptability, adaptable, adaptation, and flexibility. Over 80 sources including books, journal papers, conference proceedings, research reports and doctoral theses covering the period 1990 to 2017 were reviewed and categorised. An inductive approach was used to critically review and categorise these publications and develop a framework for analysis.

Findings – The concept of adaptability includes many dimensions which can broadly fall into two categories: changes to buildings and user adaptations to buildings. However, previous research has mostly focussed on the former, with many attempts to identify building attributes that facilitate adaptability, and some considerations for its assessment. Key areas that have not been adequately addressed and which require further research include: user/occupant adaptations, cost, benefits and implications of various adaptability measures, and the development of a standardised assessment methodology that could aid in decision making in the design stage of buildings.

Research limitations/implications – The adaptability strategies considered in this review focussed mainly on building components and systems, and did not include the contribution of intelligent and smart/biological systems. The coverage is further limited in scope due to the period considered (1990-2017) and the exclusion of terms such as "retrofit" and "refurbishment" from the review. However, the findings provide a solid basis for further research in the areas identified above. It identifies research issues and gaps in knowledge between the defined needs and current state-of-the-art on adaptive building for both research and practice.

Originality/value – This paper is a review of research into a highly topical subject, given the acknowledged need to adapt buildings over their lifecycle to environmental, economic or social changes. It provides further insights on the dimensions of adaptability and identifies areas for further research that will contribute to the development of robust tools for the assessment of building adaptability, which will enhance the decision-making process of building design and the development of a more sustainable built environment.

Keywords Strategy, Resilience, Built environment, Flexibility, Buildings, Adaptability

Paper type Conceptual paper

1. Introduction

Buildings as part of the infrastructure system have to cope with many changes over their lifespan. These include: the need to accommodate the changing needs of owners and users; respond to market conditions, legislative requirements and the challenges from climate change and other environmental factors such as flooding or heat risks; and improve technical and functional performance (Mansfield, 2009; Kelly *et al.*, 2011; Schmidt, Eguchi and Austin, 2010; Beadle *et al.*, 2008; Thompson *et al.*, 2015; Manewa *et al.*, 2016). Constraints such as land availability are also drivers for adaptability, because in some countries, e.g. Italy (ISPRA, 2014) adaptability is strictly connected with the issue of land availability where demolishing and re-building new buildings is not a feasible alternative.

These changes require that buildings are adaptable to prolong their useful life. Resource and legislative constraints such as the availability of land and finance, and zoning laws suggest that the construction of new buildings is unlikely to meet demand. The reality that the vast majority of today's buildings will still exist in 2050 and beyond (Harvey, 2013; Sandberg *et al.*, 2016) and the significant investment made in refurbishment in the UK and other EU countries such as Italy and the UK (ANCE, 2014; ONS, 2015) further highlights the importance of adaptability.

The adaptation of buildings is linked to climate change strategies. Mitigation aims to reduce the causes of climate change and adaptation aims to manage the consequences and reduce the damages likely to be caused by a changing climate. Amongst others, Reckien *et al.* (2015) and Heidrich, Reckien, Olazabal, Foley, Salvia, de Gregorio Hurtado, Orru, Flacke, Geneletti, Pietrapertosa, Hamann, Tiwary, Feliu and Dawson (2016) have shown the pitfalls of the interactions between adaptation and mitigation, and potential synergies and trade-offs that change depending on the context and locality. Mitigation and adaptation efforts increase the complexity of the interactions, particularly at the nexus across water, energy, land use, and biodiversity (Villarroel Walker *et al.*, 2017).

Adaptable buildings are also an emerging but strong and practical solution to address the problem of building redundancy (Kronenburg, 2007; Gibb and Austin, 2017; Douglas, 2006). However, the critical challenge to building stakeholders, who have different interests and influence over the project, is the inability to prepare for unforeseeable futures, mainly because of the difficulty in predicting future uncertainties, risks and the costs of change (Ellingham and Fawcett, 2006; Phillips *et al.*, 2017). Therefore, the measure of how easy it is to modify a building during the course of its life becomes essential (Webster, 2007).

The purpose of this paper is to identify trends in research and development, and the evolution of current thinking and practice in building adaptability. It identifies research issues and gaps in knowledge that might exist between the defined needs and current state-of-the-art on adaptable building research and practice. The key questions considered include: the meaning, requirements, enablers and inhibitors for realising building adaptability; the underlying theories, models and strategies for adapting buildings, and how these have evolved over time. Following a description of the research methodology adopted, the findings in relation to the research questions are presented and discussed. The paper concludes with recommendations on the way forward.

2. Research methodology

Since the key focus of the paper is to discover the current state-of-the-art and identify research gaps, it is therefore exploratory in nature and broadly reflects an interpretivist approach to research (Wing *et al.*, 1998). It however relies solely on secondary sources of evidence similar to other "state-of-the-art" reviews (Volk *et al.*, 2014; Xue *et al.*, 2012) that are conducted from time to time to critically summarise and reflect on the body of knowledge in a particular discipline, at a particular point in time.

Being interpretivist in nature, the strategy has been to discover and make sense of existing knowledge. However, the search for such knowledge was guided by the research questions mentioned above and pragmatic considerations to manage the scope of the study. These included: discipline boundary, period of coverage, relevant keywords and so on. Thus, the study is not a pure form of Grounded Theory research both in the sense that the aim is not necessarily to develop theory, and also that research questions were defined to frame its scope (Hunter and Kelly, 2008).

First, with a focus on buildings, built environment sources were considered, although literature from other disciplines and sources (e.g. dictionaries) were also consulted in developing an understanding of the concept of building adaptability. Second, keywords such as adaptability, adaptable, adaptation, and flexibility were used in the search from established databases and search engines such as Scopus, ISI Web of Knowledge and Google Scholar (related keywords such as retrofit or refurbish were not included in the search mainly to manage the scope of the research). Nevertheless additional literature sources were identified through the reference lists of some papers to track and/or verify the original sources. Third, although an inclusive approach (i.e. to consider all aspects of adaptability) was adopted, the coverage of publications was restricted to the period from 1990 to 2017. This was mainly to manage the scope, but also to reflect the growing interest in the subject during that period (Duffy, 1990; Brand, 1994).

Data analysis involved the categorisation of sources of evidence and developing a framework for analysis. The bibliographic sources used in this publication synthesise and categorises information from 9 books, 33 journal papers, 27 conference proceedings, 2 websites and 11 reports (including one PhD thesis). Figure 1 shows the temporal distribution of sources, with the peak in 2006 due to the Adaptables conference (Scheublin and Pronk, 2006), which was held in Eindhoven University of Technology in The Netherlands.

The strategy adopted was to first develop an operational definition and requirements for building adaptability given the different perspectives and perceptions of the concept (Pinder *et al.*, 2017). This provided the framework for analysing various sources in line with the research questions posed at the beginning. A database of adaptability indicators of building components and systems was also developed as part of the analysis and categorisation of adaptability strategies. This was designed to assist with the identification of trends and the current state-of-the-art and a platform for further research into the subject. It is acknowledged that the methodology adopted in this paper is limited in that it does not lend itself to the discovery of new knowledge from primary sources of data. However, its validity rests on the fact that it reflects similar approaches to state-of-the-art reviews (e.g. Volk *et al.*, 2014; Xue *et al.*, 2012). Furthermore the analysis of the sources considered offers scope for new insights into previous research into building adaptability, which in itself is a contribution of knowledge in the field, given the dynamic and ever-changing nature of knowledge (Knight and Turnbull, 2008).

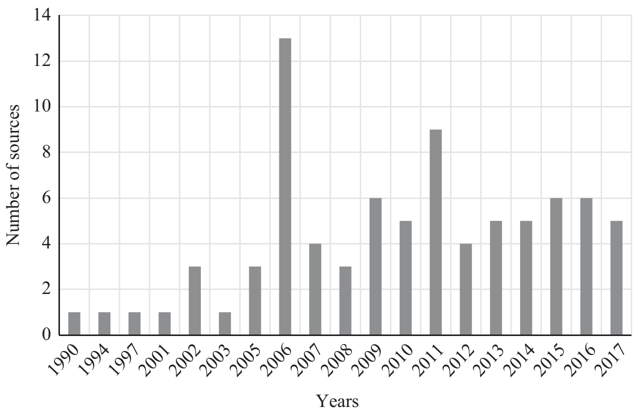


Figure 1.
Temporal distribution of the sources

3. Research findings

3.1 Meaning and dimensions of building adaptability

Adaptability can be defined as the "ability to change (or be changed) to fit changed circumstances" (TheFreeDictionary, 2017); and "the quality or state of being adaptable", that is, being "able to adjust to new conditions or situations, or to changes in one's environment". In biology and business it is the "ability of an entity or organism [organisation] to alter itself or its responses to the changed circumstances or environment" (BusinessDictionary, 2017). In ecology and education, it is the "ability to learn flexibly in a variety of ways, contexts, and circumstances […]" (Fazey *et al.*, 2007, p. 375). Other definitions from various authors are: "ease of change of [a] building['s] spatial organisation within the same use [and] […] for new use; ease of change of technology and services; ease of use for people with different physical abilities" (Langford *et al.*, 2002, p. 148); "a measure of how easy it is to modify a building during the course of its life" (Webster, 2007, p. 1); and "the capacity of a building to accommodate effectively the evolving demands of its context, thus maximizing value through life" (Schmidt, Eguchi, Austin, and Gibb, 2010, p. 235). Brand (1994) refers to adaptability as changes that are "not only […] possible in the building, but the structures (people and organisational) that make this possible". Sinclair *et al.* (2012) define the adaptive capacity of a building as the ability "[…] to cope with future changes with minimum demolition, cost and waste and with maximum robustness, mutability and efficiency" (p. 40), and which leads to building agility and resilience.

The above definitions suggest that adaptability either refers to the inherent properties in a building that gives it the ability to change, or the relative ease with which it can be changed through some external intervention. Change to a building is always in response to some stimuli, e.g., changing environment, owner/user needs, etc. as described in the introduction above; and is affected by the physical features of the building as well as people and organisational structures that interact with the building. Reference to "ease of change" or "measure of" in various definitions also suggest that there is a degree to the adaptiveness of buildings. The definitions therefore raise a number of questions. First, is our focus on inherent characteristics (embedded within building materials and components) or imposed changes to a building? The equipping of buildings with inherent capabilities to change has been the focus of intelligent/smart systems research in buildings over the years (Clements-Croome, 2013; Wang, 2010; Weng and Agarwal, 2012) and, more recently, the use of biological agents to alter the properties of building components (Ramirez-Figuero *et al.*, 2016). But they also relate to pre-configured adaptive capacity that is built in at the design stage (Beadle *et al.*, 2008). Imposed changes are made by human agency through some means of adaptation, and generally relate to re-configured changes in use (Beadle *et al.*, 2008). The degree to which re-configuration is possible depends on what has been pre-configured into the building. Consideration should therefore be given to both inherent characteristics and imposed changes. However this review does not include the smart/biological systems aspects of pre-configuration.

Second, what kind of change to a building constitutes an adaptation? Definitions of adaptation by Gosling *et al.* (2013) and Bullen (2007) indicate that this involves major works that result in improvement and conversion of a building, to adjust, reuse, upgrade or extend the useful life of a building to suit new conditions. This suggests that routine maintenance or repairs to maintain the existing state of a building is not adaptation; or that adaptability is not the same as flexibility, which has more to do with relatively quick changes to meet changing functional needs or range of states of spaces (Arge, 2005; Saleh *et al.*, 2009), but can be part of the overall adaptive capacity of a building (Arge, 2005; Sinclair *et al.*, 2012). This further suggests that there can be different aspects of adaptability encompassing a range of "major" changes to a building, depending on the purpose of that change.

For example, Langford *et al.* (2002) mentions different changes for same use or different use; others make reference to adaptive reuse – change of a disused building for a different purpose, e.g., disused factory into a residential building (Bullen, 2007; Bullen and Love, 2011; Langston, 2012). Additional dimensions identified by various researchers are summarised in Table I (Arge, 2005; Kelly *et al.*, 2011; Schmidt, Eguchi and Austin, 2010; Pinder *et al.*, 2011; Fuster *et al.*, 2009).

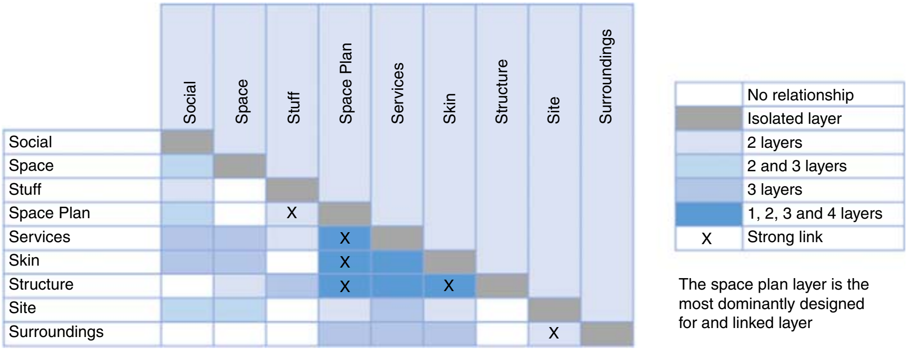
The dimensions of adaptability in Table I suggest that the different degrees of "adaptability" can fall into two main categories (as indicated by the first two are): user-driven changes that do not affect the fabric of the building and which relate more to how users adapt to a building; and changes/adaptations to the fabric of the building, which become necessary when user actions are no longer adequate to address their needs (the latter 4).

3.2 Underlying theories and models

Building adaptability research over the years has resulted in various models and concepts that underpin the understanding and development of adaptive capacity in buildings. One of the key conceptualisations is that buildings consist of layers, which have different rates of change. An early categorisation by Duffy (1990) identified the following building layers: shell (structure), services (heating, plumbing, etc.), scenery (fittings) and set (e.g. furniture), with each requiring change in approximately 50yrs, 15yrs, 5-7yrs, and daily, respectively. This concept was further developed by Brand (1994) into six layers: site, structure, skin, services, space plan, and stuff. More recently, Schmidt and Austin (2016) have added three further layers (social, space, and surroundings) to Brand's list (Gibb and Austin, 2017; Schmidt and Austin, 2016) (Figure 2). The importance of building layers is that the interdependencies between layers can be a key enabler for further adaptations in buildings. For example, Schmidt and Austin (2016) observe that "keeping as many elements as

Table I.
Dimensions of adaptability

Adaptability dimension	Meaning	Examples
Adjustable/ generality	Change of tasks by users on a daily/monthly basis	Having a multi-purpose room, or a room ready to be used for multiple tasks with no/few adjustments. Possibility to divide spaces with movable walls
Versatile (flexible)	Changes of space and location of services, furniture and equipment by users on a daily/monthly basis	The possibility of moving furniture, equipment and even services where they need to be used. This and the previous are partially overlapping and related to frequent changes of the building
Refit-able	Change of performance	Having the possibility of easily improving the performance of one or more components, without the need for replacing the entire system. E.g. installing a more efficient burner in a heat generator. This characteristic is very useful during retrofit and refurbishment
Convertible	Change of function – space, services	The possibility of changing the function of a building (or of a zone/space) without much effort and modification. E.g. from an office to a residential unit or vice versa. This change is less frequent than the first two but nevertheless very important
Scalable/ Elastic	Change of size of the building	Being able to increase/decrease surfaces and volumes of the building without big effort and using modular components. This is relevant e.g. for factories with expansion plans
Movable	Change of location of fabric	Being able to move the entire building or a part of it without demolishing it, but dismantling and/or reusing it



Source: Schmidt and Austin (2016, p. 57)

possible outside the structural layer [creates] an immutable infrastructure around which change can occur" (p. 57).

The concept of building layers is similar to the idea of "levels of intervention", which is part of the Open Building concept first developed by John Habraken. Open Building is a design approach that includes a number of related ideas such as: "distinct levels of intervention in the built environment" e.g. "support/base building" and "infill/fit-out", importance of users and participants in the design process, "the idea that the built environment is in constant transformation and change must be recognised and understood", and that it is "the product of an ongoing, never ending, design process in which environment transforms part by part" (www.habraken.com in Kendall, 2015, pp. 1-2). Similar terms that are used to describe "Open Building" in various parts of the world include: "skeleton-infill" "Long-Life Housing", "Raw Space Housing" and "Free Plan Apartments" (Kendall, 2015, p. 2). Thus, Open Building embodies the concept of designing for change and its principles can therefore inform the development of strategies for building adaptability.

Other attempts to develop theoretical models of adaptability include the work by Gosling *et al.* (2013), who adopt a systems approach to understand the contribution of adaptability to the sustainable construction agenda. One of the key approaches in their paper is to use reliability theory and failure analysis (specifically the Bathtub Curve) to model building performance and failure, and develop a Building Adaptation System (BAS). The underlying assumption of the BAS is that change (the need for adaptation) is fuelled by a failure of a component or system. Such failure can be assessed using variables such as Building Performance, User Fitness (UF) (i.e. difference between user expectations and building performance), and Technical Fitness (TF) (difference between technical specifications and building performance). Both UF and TF drive the need for some kind of adaptation, which will be designed to address gaps in building performance. While the BAS is theoretical, the authors see its potential application in the development of simulation tools that can measure and quantify the cost of adaptability, as a decision-making process at various levels of building design and management (Gosling *et al.*, 2013).

Beyond the development of concepts, other research studies have sought to develop tools and methodologies to assess the adaptability of buildings. An earlier attempt in this regard was by Langford *et al.* (2002) who developed an adaptability assessment tool based on criteria such as: low, medium and high adaptability, depending on how easy it is to make changes – from minor to complete change of use. The assessment features, based on spaces, structure, services and features for users with different physical abilities, include: access and possibilities for expansion of the site, interior layout and design, location and space requirements for HVAC systems, and so on.

Other assessment tools include that proposed by Osman *et al.* (2011), Geraedts and Prins (2015, 2016), and the Adaptive Reuse Potential (ARP) and AdaptSTAR models (Conejos *et al.*, 2014; Langston *et al.*, 2008). The ARP model is an integrated model for assessing the ARP (expressed as a percentage) of existing buildings. Its underlying hypothesis is that building obsolescence is an appropriate method to reduce expected physical life and calculate its useful life. The model requires an estimation of the current age and expected physical life of a building, and of its physical, economic, functional, technological, social and legal obsolescence. Useful life is discounted physical life, with the "discount rate" being equal to the sum of the obsolescence factors per annum. Reuse potential decreases as the building age approaches its effective physical life. The ARP has been used (and validated) mostly by retrospectively applying it to adaptive reuse projects and by a multi-criteria decision tool (Langston, 2012). Its principles have been extended into the AdaptSTAR rating tool, which is "a weighted checklist of design strategies that lead to future successful adaptive reuse of buildings" (Conejos *et al.*, 2014, p. 98). Thus both the ARP and AdaptSTAR tools seek to assess the adaptive reuse of buildings at the in-use and design stages, respectively.

In terms of climate change the recent IPCC report (IPCC, 2014) provided an assessment of a wide variety of approaches for reducing and managing risks and building resilience. The report proposes strategies and approaches to adapt to a changing climate by, for example, decreasing vulnerability or exposure and/or increasing resilience or adaptive capacity of communities, infrastructures and buildings. Indeed they argue that adaptation is place- and context-specific, that cannot be addressed with one approach for reducing risks across all settings; to reduce risks effectively, whole adaptation strategies need to be introduced that consider the dynamics of vulnerability and exposure and their linkages with socioeconomic processes, sustainable development, and climate change. Quantitative modelling and hazard resistance within lifecycle assessment of strategies to produce resilient and sustainable building are proposed (Phillips *et al.*, 2017). Such developments require planning and implementation across all levels, from individuals to governments (Harvey *et al.*, 2014). Thus local government and business is increasingly recognised as being critical to stimulate and progress adaptation given their roles in scaling up adaptation of communities, households, and civil society and in managing risk information and finance (Sandberg *et al.*, 2016; IPCC, 2014).

3.3 Adaptability strategies

Adaptability strategies are usually defined in relation to the adaptability characteristics in buildings. The review undertaken for this research identified 27 publications that considered the adaptability features of various building characteristics. A total of 172 univocal characteristics were identified, several of which are cited in one or more publications. Table II shows the characteristics that were cited in two or more publications (to simplify the table). The other characteristics not listed in Table II are reported in (Gijsbers, 2006; Ham and Wouters, 2006; Eguchi *et al.*, 2011; Hwang *et al.*, 2006; Saari and Raveala, 2006; Talamo *et al.*, 2006; Verweij and Poelman, 2006).

The 38 characteristics listed in Table II have been summarised to reduce duplicates (initially there were 48). Nevertheless, the duplicates identified in this research are counted, in order to highlight the most cited characteristics. Figure 3 shows that only two characteristics have been cited four times: accessible floor and modularisation; six characteristics have been cited three times; nineteen characteristics have been cited twice; the remaining 145 have been cited only once.

Figure 3 has been compiled without semantic elaboration of the characteristics: they have been reported as found in the references. It is necessary to highlight this because most of them are connected or similar, for instance: "layers dismountable" and "layers disassemblable" are the same; "kit of parts" and "standardisation" are strongly connected.

Adaptable characteristic	Beadle *et al.* (2008)	Blok and van Herwijnen (2006)	Conejos *et al.* (2014)	Davison *et al.* (2006)	Fukao (2006)	Fuster *et al.* (2009)	Geraedts (2006)	Grinnell *et al.* (2011)	Kelly *et al.* (2011)	Manewa *et al.* (2009)	Nakib (2010)	Pinder *et al.* (2011)	Scheublin (2006)	Schmidt, Eguchi, Austin, and Gibb (2010)	Slaughter (2001)	Webb *et al.* (1997)	Webster (2007)	Remaining sources
Accessible floor	•					•					•		•					•
Accessible services						•	•											
Buffer zones/ plenums											•							•
Cable/ducts strategic location											•							•
Ceiling space	•									•	•							•
Central cores											•							•
Cladding reconfigurable				•		•												
Coordinated grid (s)				•	•	•												
Double façade											•							•
Drawings											•			•				•
Extendable										•				•				
Fire protection	•		•	•														
Flexible comp. separated from inflexible ones											•							•
Foundation robustness											•							•
Furniture not fixed									•	•								
Insulation and acoustic			•				•											
kit of parts/ standardisation								•		•						•		
Layer building systems															•		•	
Layers designed to allow alternatives for lower layers											•							•

(continued)

Table II.
Most cited adaptability characteristics (in alphabetical order)

Table II.

Adaptable characteristic	Beadle *et al.* (2008)	Blok and van Herwijnen (2006)	Conejos *et al.* (2014)	Davison *et al.* (2006)	Fukao (2006)	Fuster *et al.* (2009)	Geraedts (2006)	Grinnell *et al.* (2011)	Kelly *et al.* (2011)	Manewa *et al.* (2009)	Nakib (2010)	Pinder *et al.* (2011)	Scheublin (2006)	Schmidt, Eguchi, Austin, and Gibb (2010)	Slaughter (2001)	Webb *et al.* (1997)	Webster (2007)	Remaining sources
Layers dismountable		•				•				•								
Less details											•							•
Loose-fit approach				•				•										
Materials availability						•				•				•				
Minimise number of columns											•							•
Modular installation system											•					•		•
Moveable columns											•							•
Multi-functionality								•				•		•				
No male-female connections											•							•
Optimise space utilisation											•							•
Over-capacity/-design		•								•	•			•	•			•
Over-measure energy											•							•
Pluggable connections											•							•
Prefabrication										•	•				•			•
Re-usability of components						•				•								
Redundancy								•						•				
Skin independent from str											•							•
Structural separations											•							•
Variety of plan depth	•			•														

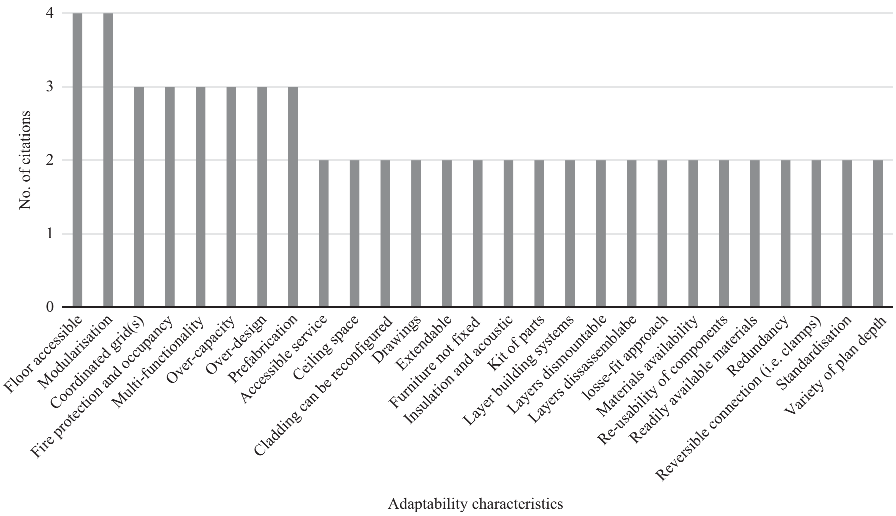


Figure 3.
Most cited adaptability characteristics

4. Discussions

This paper sought to address various questions about the concept of adaptability in buildings, namely: the meaning, requirements, enablers and inhibitors for realising adaptability; the underlying theories, models and strategies and their evolution over time; and to discuss the research trends and gaps that can be identified from the literature reviewed.

4.1 Meaning, enablers and inhibitors of adaptability

Adaptability is clearly about change, or rather the capacity of a building to change or be (easily) changed to accommodate the changing demands placed on it – whether by its users or other external factors (e.g. climate change) and/or stakeholders. But the review above has identified a number of interrelated issues. First is the agency of change: whether it is inherent in the properties of the materials, systems and components in the building or the adaptations made to the building. Either way, it would appear that such ability needs to be pre-configured at the time the building is designed and built. However, Gosling *et al.* (2013) also raise the question of whether such "ability to change" can be retrospectively added into a building, similar to the retrofitting of buildings for energy conservation. Second, is the fact that there are different kinds or degrees of changes that are desired in buildings (Table I): from the day-to-day actions of users, to a change of location of a building. But this does not just involve changes to the building fabric, but also how users can change to adapt to buildings. The BAS developed by Gosling *et al.* (2013) suggests that change to the fabric only becomes necessary when user adaptations are no longer possible. What is becoming apparent is that the concept of adaptability is much more than the changes that can be made on the fabric of the building, but that user actions and inherent capabilities (through intelligent systems and biological agents) also need to be considered. Indeed, the more recent publication by Pinder *et al.* (2017) on the different perspectives of adaptability by different stakeholders, also suggest that other stakeholders and external factors also need to be considered. The addition of "surroundings, social and space" to the list of building layers (Figure 2) by Schmidt and Austin (2016) further underscores the relevance of human/social factors beyond the immediate site of a building, in considering its adaptive capacity.

Enablers for adaptability can be building/technology-related (i.e. pre-configured features that facilitate building change) or may depend on non-building factors which can include:

owners'/clients' motivation and commitment; favourable financial/economic incentives and market conditions; and supportive legislative framework (whether in positively encouraging it or restricting new development which necessitate building adaptation) (Bullen and Love, 2011). However, these categories of factors can also inhibit the adaptation of buildings. For example, a building configuration that restricts the changes possible; legislation that restricts the changes possible on historic buildings; or the lack of finance to carry out much needed adaptations even though there may not be restrictions in other areas. Thus, enablers and inhibitors are strongly interconnected, and considerations for adaptability should therefore will be context-specific (Phillips *et al.*, 2017; Pinder *et al.*, 2017).

4.2 Theories, models and strategies for adaptability

The underlying theories and models reviewed above reflect current and evolving understanding of building adaptability. They essentially suggest disaggregation (e.g. as in building layers) to develop understanding, and integration in the development of adaptation models and strategies (e.g. the ARP model). These approaches are obviously interrelated but can also appear to be contradictory. The issue of disaggregation can appear to be at odds with current industry efforts at pursing integration and development of integrated solutions to buildings. But it is necessary to understand how different layers and components interact before true integrated solutions can be developed. Thus, an understanding of interdependencies between different components and systems is the key to developing viable adaptable solutions (Schmidt III and Austin, 2016). On the other hand, the concept of layers can also be misleading, since there can be many sub-categories within each layer. For example, the "services" layer involves a variety of services from water pipes, drainage systems, heating systems, electrical cabling to IT equipment. The rate of change for each of these is different and may well have different requirements for integrating with other building layers.

With regards to adaptation strategies, much of the research to date appears to have focussed on changes to the building fabric. A categorisation of identified building adaptability characteristics (after Table I), which is presented in Figure 4 suggests that a good proportion of adaptability features are in convertibility and adjustability, with the least strategies in movability (Gibb and Austin, 2017). It is important to note however, that each adaptability characteristic can be connected to one or more features. For instance having spaces larger than the minimum is good for convertibility, versatility and scalability. It is also worth noting that while adjustability is related to user actions, the characteristics identified in the literature relate to building features that will make it easy for users to make changes, not necessarily how users actually make those changes.

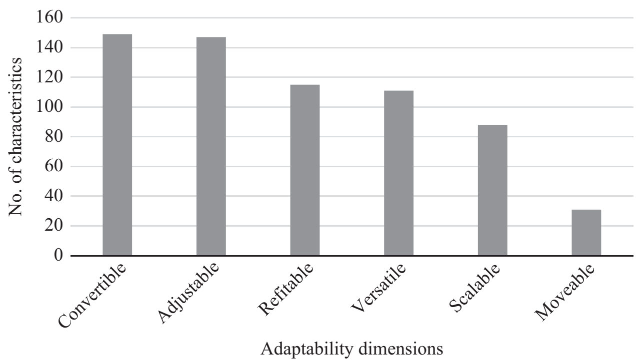


Figure 4.
Number of adaptability characteristics against adaptability dimensions

A key question from the list of characteristics in Table II is: how do they help in delivering more adaptable buildings? The answer to this question is not unequivocal and requires further reasoning. First of all, not all buildings and projects are the same, as they could differ from location, function, extension, etc. and these characteristics influence intrinsically the overall adaptability level. For instance, a building located in a city centre will probably be less adaptable, e.g., no room for space addition; than the same building in the countryside. From this reasoning it can be understood that not all the characteristics listed in Table II can be applied to all buildings with good results. For example, structural modularity, which allows the addition of more units of space (horizontally or vertically), in a city centre where buildings have a fixed maximum height and gross surface, is not a relevant characteristic. Therefore the designer, no matter if it is a new construction or a refurbishment, has to analyse the building and context, to understand if (and where) there is scope for room for more adaptable solutions.

Second, some characteristics are conflicting, e.g. using a suspended ceiling and/or a raised floor greatly helps with maintenance and modification of services during building operation, but reduces the internal usable height, which is another relevant characteristic. Basically the client has to decide in advance which aspect of adaptability they want to achieve, because, despite the presence of relevant case studies, there is no building that can be considered adaptable in all its aspects.

Eventually, some strategies can be used to achieve one or more adaptable aspects. For instance factories and office buildings can be strongly scalable, with modular structures and services, capable of accommodating additional spaces both in terms of additional stories or increase in gross floor area. Office buildings are usually designed to be adjustable, by using movable infill, shared spaces, surfaces larger than minimum, etc. Existing residential buildings can be converted into tertiary buildings (or vice versa) thanks to their space organisation and higher usable height. In general, there is no fixed strategy, but a set of characteristics that allow the fulfilment of a client's needs and deliver a more adaptable building (according to a limited number of features).

What this suggests is that various strategies in themselves do not necessarily lead to adaptable buildings, given the complexity of the interactions of different elements in buildings Roders *et al.* (2013). What appears to be vital is the interrelationships between different strategies within the given context of a particular project, and their early consideration as part of the design criteria for buildings.

4.3 Trends and future research issues

The distribution of the sources used in this research (Figure 1) shows a growing number of publications in this field since 1990. This might be indicative of a growing interest in building adaptability, probably because it was seen as a possible solution to enhance the energy and environmental performance of buildings. The early 1990s was a period when the UK (and other western countries) was coming out of an economic recession, and although the emphasis then was on how to improve the construction process (e.g. the Latham (1994) report), the issue of adaptability (change of use of buildings) was also being recognised as important to reinvigorating the property market (Kincaid, 2002). The Earth Summit that was held in Rio de Janeiro in 1992 and the first IPCC report on climate change also highlighted the issue ofsustainable development, and may have contributed to interest in building adaptation as a way to conserve resources and respond to climate change issues. In fact, the research by (Langford *et al.*, 2002), which commenced in the late 1990s considered the subject of adaptability alongside the durability and energy conservation of buildings. But it is possible that the Open Building movement is a key influence on the development of building adaptability.

However, it would appear that the approach towards adaptability has changed over the years: previously there was more focus on functional aspects of buildings (e.g. buildings/

spaces convertibility), while now, adaptability is seen more as an architectural tectonics and systems integration problem. This might be due to two important changes in the stakeholders, more than in the buildings: now design is targeted to achieve minimum requirements – e.g. in most projects, over-capable spaces and over-designed buildings cannot be built within current budget, time and regulatory constraints; and systems complexity has increased a lot in recent years as have their capabilities. These two can lead to increasing difficulty in changing spaces/building functions (if not planned/designed) and in systems which are, on the one hand, more capable to accommodate increasing users' demand, but on the other hand, more difficult and expensive to be replaced. Design, in its broad sense, is no longer only focussed on technologies and performance, but it is user-centred and focussed on aggregating functions and spaces, providing smart solutions for working, studying and teaching. This new concept of design involves adaptability, as a means to delivering building spaces able to host multiple functions and activities.

While the review has demonstrated good progress towards an understanding of adaptability and the associated strategies, there are still gaps. One such area is in understanding the uncertainties and the capital costs of comparable adaptation measures. This is especially the case for those adaptation measures that are needed to cope with extreme events related to climate change, e.g., flooding, and heat waves (Heidrich, Rybski, Gudipudi, Floater, Costa and Dawson, 2016). The measures may not yield benefits until many years down the line and the uncertainty and high capital costs are regularly identified as major barriers to releasing funds for adaptation investment. Local government and businesses are recognised as critical to progress adaptation as they can play an important and vital role in scaling up the adaptation of communities, households, and civil society and in managing risk, information and financing (IPCC, 2014).

This literature review has revealed the great importance of a building's characteristics at different levels, from products to entire spaces), but also the importance of soft aspects (Schmidt and Austin, 2016) and of user involvement in adaptability. There is a need to expand the scope of research, as users can be seen as the drivers of change, as they are the ones that can express their needs to designers. Therefore, an understanding of user actions and those of various stakeholders in the adaptation process is required. Some work on stakeholder involvement is available, but more needs to be done, especially because they need to be integrated in the design process. To involve users and clients, there is a strong need to demonstrate to them the savings and benefits of an adaptable design, as has been done for acoustic and energy performance, and as is currently being done for environmental sustainability.

Regarding components and products, there is a need for a better understanding of the relationship within layers. Despite the fact that there are relevant works in this area (e.g. Langford *et al.*, 2002; the ARP and AdaptSTAR models), the usefulness of having a viable tool that is based on an understanding of the interdependencies between components and layers is clear. In essence, more than a tool to rate the adaptability, there is the need for strategies, tools and procedures to guide and enhance the design for adaptability (Phillips *et al.*, 2017).

The key strategies to achieve adaptable buildings can be extracted from the list of adaptable characteristics (Table II). On top of this there is the possibility of accessing systems embedded in the floor and in modularisation/coordination. Other important features are for example: over-design/over-capacity (which also includes the over-design of the fire protection system) and prefabrication. Important strategies are: systems' accessibility, possibility to reconfigure spaces (e.g. free standing furniture, loose-fit approach, and redundancy) and layers not connected/made of materials readily available. Inherent capabilities that can be pre-configured through the use of intelligent/smart systems and biological agents (whilst not considered in this paper) have potential for the future, although research in this area (especially in intelligent buildings) has been going on for quite some time. However, research in this area was not badged under the concept of adaptability, but has direct relevance in the adaptation of buildings (Agha, 2016). It could be argued that its relevance is more in the skin, space and stuff layers (Rodden and Benford, 2003; Wang, 2010), but the use of biological agents and other systems can also have an impact in the structural layers as well (Ramirez-Figuero *et al.*, 2016).

Adaptability is strictly connected to the knowledge of a building and its parts, which starts from the documents and the as-built drawings. Dealing with real estate means facing the issue of missing building documentation (Song *et al.*, 2002). Therefore adaptability analysis can be helped by Building Condition Assessment (understood in its broad definition, including also documents due diligence) and Building Information Modelling (BIM) processes, very useful for information and documents management (Becerik-Gerber *et al.*, 2012).

5. Conclusions

This paper provides a wide perspective on building adaptability, aiming to inform future exploitation of the design for adaptability by considering and presenting parts of the research reported from 1990 up to 2017. The perspectives and discussion presented here clarify the meaning of adaptability, which can be categorised into two broad areas: changes to buildings and user adaptations to buildings. The former is related to the characteristics that a building (and its components, spaces and surroundings) can have to allow and to enhance adaptable alternatives; the latter is related to the changes or adjustments that users have to make to adapt to their buildings.

The development of the concept of adaptability has been studied in this paper: it might have had its roots in the open building movement, and has developed from purely focussing on building elements but also looking at user aspects as well. An example of this is the development of the concept of building layers, from Duffy (1990) to Brand (1994) and Schmidt and Austin (2016) i.e. increasing layers that include "soft" aspects as well as hard aspect of adaptability of buildings. The concept of adaptability cannot simply be summarised by having multi-purpose rooms or movable walls, it is a larger concept that involves (from its conception) the study of the building and its surroundings, aiming to define the adaptability potential, to deliver a project able to last longer, to reduce impacts (economic and environmental) and to eventually enhance the quality of life of the users.

A great effort has been paid to the analysis of the characteristics related to the building, its components, its spaces/zones and its surroundings; these characteristics have also been classified according to the six main adaptability dimensions in order to understand where the major effort of researchers in this field is devoted. The result is a collection of 172 characteristics, gathered from 27 references, which can be used as the basis for exploiting and better understanding and guiding the design for adaptability.

Defining adaptability can be based on two pillars: first the possibility of changing the use/technology/services and second the capacity of a building and its parts to accommodate the evolving demand from its context. From this, it is possible to extract two important considerations: buildings and their parts should be both able to accommodate changes (with being modified) and able to be modified/upgraded (in case they are no longer able to accommodate changes). Considering what is stated above, adaptability can be seen as an innate characteristic of a building; but there is still the need to measure the adaptable potential of a building. Although, a necessary requirement is an external stimuli, e.g. changing environment, owner/user needs, etc. the ability to answer needs can be seen as the degree of adaptability of buildings.

Adaptability, to be better comprehended by users, owners and investors must be assessed in an objective and precise way, maybe in combination with new technologies and processes, such as BIM and Automated Compliance Checking, to speed up the assessment process. This assessment should not only be related to adaptability, as a standalone topic, but in connection with cost-benefit analysis and the overall performance of the building over its lifecycle. Circular economy and material reuse (Geldermans, 2016) are strictly connected with adaptability, and so this connection must be exploited to achieve a better adaptability level. Within adaptability assessment, tools exist to understand interrelationships among components, but there is a need to develop methods to calculate and compare adaptability potential (Phillips *et al.*, 2017). Future research may also consider intelligent systems (e.g. to control and modify layers – adaptive façades and shading are actual examples) and biological agents (e.g. that modify materials properties) will play an important role in enhancing the adaptability potential of a building and, more importantly, users' satisfaction over time.

A limitation of this study is that topics relating to the retrofit and refurbishment of buildings, which have a bearing on adaptability, were not considered. However, it does highlight important gaps in the research, such as the need for further study of the connections among products and components, as well as the characteristics influencing the adaptable potential of a building. In addition there is an urgent need to develop tools and procedures to guide and enhance the design for adaptability and not only to rate the adaptability level. In addition more understanding of user actions and stakeholder views in the adaptation process is required. Some work on stakeholders' (and especially clients') involvement is available, but more needs to be done. Finally, this paper can be seen as the basis for future research that aims to highlight adaptability as a key design criterion, making architects, engineers, clients and users aware of its importance and its role in lowering impacts over the lifecycle of buildings as well as infrastructure.

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