Building and Environment 203 (2021) 108068

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Rhythmic Buildings- a framework for sustainable adaptable architecture

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ARTICLE INFO

Keywords:
Sustainability
Conceptual framework
Systems thinking
Design strategies
Changing over time

ABSTRACT

Adaptable architecture responds to global challenges such as climate change, depleting resources and biodiversity. We argue here that R*hythmic Buildings* incorporate many aspects of adaptation through an integrated approach. Rhythmic buildings react to the various parameters of the sustainability context. This conceptual paper develops a framework for adaptable architecture that includes the sustainability context based on the three pillars of sustainability and incorporates systems thinking. Building on a qualitative literature review the research categorises themes by considering practice examples and illustrates the drivers that motivate the research of adaptable architecture. We present a timeline of adaptability strategies demonstrating how the field has shifted and focussed on specific challenges such as climate change. Our research shows that current practices mainly consider buildings and building components that are responsive to the changing requirements for user comfort and energy reduction. This manuscript proposes a structured framework that considers adaptability and recommends a strategy of Rhythmic Buildings for future adaptable design. The framework uses a systems approach to identify the rhythms of the sustainability context which guides future adaptable concepts as input and output for a balanced design. Finally, we present our vision for Rhythmic Buildings and how this can be taken forward by researcher and practitioner alike.

1. Introduction – global challenges

Global challenges of climate change, and depletion of both resources and biodiversity need to be addressed, especially in the built environment which affects these challenges directly. For example, the carbon emissions from buildings are still growing while they should be cut by almost 8% each year starting 2020 [1] if we want to reach the Paris Agreement [2–4]. These emissions are directly related to the amount and type of energy used during the construction process and the use phase [3]. Although the greatest amount of the energy used in the building sector goes to heating of space (one third of the energy demand for buildings), water, and food, the fastest growing energy demand is space cooling which increased by 33% between 2010 and 2018 [1]. This comes as still many buildings in the UK are not comfortable all year round with possible damaging effects to users health and wellbeing [5].

The IPCC [3] suggests two main approaches to tackle climate change: adaptation and mitigation. The IPCC defines adaptation as “the adjustment in natural or human systems in response to actual or expected stimuli or their effect, which moderates harm or exploit beneficial opportunities” [6] (p. 982) and mitigation as “an anthropogenic intervention to reduce the sources or enhance the sinks of greenhouse gases” [6] (p. 990). Although mitigation addresses most of our long term problems, adaptation strategies are believed to also enhance the built environment’s resilience to said challenges [3,7–10]. It is therefore not surprising that adaptability is often used in design briefs and building design in general [9]. Due to its popularity, adaptation and adaptable architecture are umbrella terms for many different strategies and principles and therefore the term adaptability has been described as a fluid concept [9] heavily influenced by its context [11,12] which can lead to confusion in practice. Hence determining the context which led to the adoption of different strategies could highlight why certain strategies were adopted over others. Furthermore, the context connects adaptability, the built environment and the global challenges.

First, we need to identify what is meant by context and what parameters it spans. In Heidrich et al [12], the context comprises the socioeconomic processes, sustainable development, and climate change. This clarification could be considered a pleonasm as others define

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https://doi.org/10.1016/j.buildenv.2021.108068
Received 8 March 2021; Received in revised form 18 June 2021; Accepted 19 June 2021
Available online 24 June 2021
0360-1323/

List of abbreviations:

CE	Circular Economy
DfD	Design for Disassembly
IPCC	Intergovernmental Panel on Climate Change
MET	Metabolic rate (unit)
PMV	Predicted mean vote
S/I	Skeleton-Infill

sustainable development as the sum of economic, social, and environmental aspects [13]; known as the three pillars of sustainability [14]. While the term sustainability implies an element of thinking about the future, it seems necessary to implicitly add time as an integral dimension of the context as this dimension is often lacking in adaptability definitions [15]. Indeed, Lifschutz [16] (p. 17) wrote "The key to appropriate building design is an understanding of time, a predisposition towards buildings in continuous flux rather than static lumps." Although the context has been identified as critical to understanding and designing an adaptable built environment, it is usually considered sporadically, and the resulting research is often focussed on one or two aspects of sustainability instead of taking an integrated approach [17]. Studying the context and its relationship to historical building strategies might highlight which strategies are needed in the future to address the global challenges [18]. Wang et al. [18] argue that identifying future steps and developing a vision is critical to transition towards a sustainable built environment. Therefore, the aim of this paper is to develop a framework for adaptable architecture that considers the wider sustainability context.

The objectives of this paper are:

- to define important aspects of the context for the framework,
- develop a concise overview of the field of adaptable architecture,
- identify drivers and design strategies in the field, and
- highlight the next steps in the field.

2. Research methods

Following the research objectives, three literature reviews on adaptable architecture [9,12,19] are analysed to provide insights in the field's terminologies, strategies, movements, and dimensions as well as identifying the knowledge gap. Starting from these reviews, journal papers, conference papers, books, and essays were chosen following their relevance to understanding the context of adaptability strategies and dimensions using the search engines Scopus, Google Scholar, and Newcastle University library catalogue. This led to a qualitative literature review of some of the most important works in adaptable architecture. Although we are aware of wider movements and trends which are closely related to adaptable architecture (such as green buildings and structuralism), we choose to focus on adaptability strategies following the definition in Fig. 1. Indeed, the definitions of the related terminology and the hierarchy between these terms are visualised in Fig. 1. A qualitative analysis of adaptable architecture research leads to a thematic organisation to discover patterns and emerging themes, such as the identification of the drivers and ambitions of the various adaptability strategies. The authors visualised these strategies using diagrams following the model from Schmidt and Austin [9] to identify those themes and communicate the findings. Indeed, Schmidt and Austin [9] identify the main trends in architecture and use their diagram to show relationships between strands and design strategies and how they evolved over time. For this research, however, a wider context of influence is identified using the three pillars of sustainability to understand what changes the adaptability strategies respond to. The resulting conceptual framework is assembled using different aspects of research

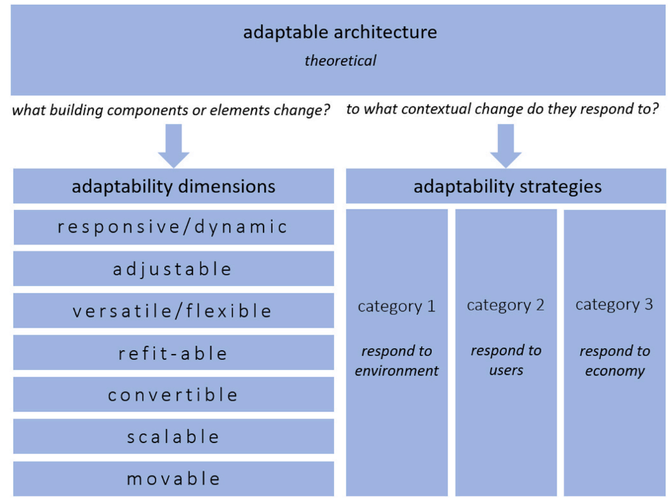

Fig. 1. Hierarchy of terms in adaptable architecture based on the literature analysis.

through design and a new adaptability strategy is proposed to respond to the previously mentioned global challenges.

The term adaptable architecture is used by many different stakeholders, from clients and practices to academics [19], and as such, it spans a wide array of interpretations which is reflected in the large number of definitions found for it [9,12]. It is, therefore, important to define the terms and hierarchy used in this study on adaptable architecture. Olsson and Hansen [20]; found that different researchers, architects, and contractors "either used different terminology or the same terminology with different meanings. Each of the projects tended to develop its own terminology". For this paper, we understand adaptable architecture as "the capacity of a building to accommodate effectively the evolving demands of its context, thus maximising its value through life" which was defined by Schmidt III and Austin [9] (p. 45). This umbrella definition includes all the different strategies and typologies of adaptable architecture, the latter being updated and renamed, dimensions, by Heidrich et al. [12]. The dimensions focus on which different components and elements of the building will change through time. Following Heidrich [12]; adjustable adaptability is specified by change of tasks by the users; versatile and/or flexible adaptability means a change of space and location of the services and furniture; refit-able adaptability is named after a change of performance; while convertible is a change of function (space and/or services); scalable adaptability means the building is changing in size; and finally movable defines a change of fabric location. Responsive architecture has often been cited in adaptable architecture as an aim or means [16], but it is usually used to describe changes or movement in material composition or structure [21,22]. Responsive and/or dynamic is therefore added to the adaptability dimensions as the smallest size scale to describe materials responding to stimuli by changing shape, geometry, and/or movement.

Alongside these dimensions, strategies have been identified how buildings, and specifically the components or elements from the dimensions, can adapt. This relationship between adaptability dimensions and adaptability strategies is depicted in Fig. 1. Contrary to the dimensions, strategies focus on the changes in the context to which buildings should respond, they are elaborated upon further in the text. It is worth noting that the analysed literature often cites other aspects and terminology alongside the adaptability dimensions and strategies such as frequency, span, speed, response time, and scale of change of adaptability [23,24], however, these detailed aspects fall outside of the scope of this study.

3. Adaptable architecture: strategies and dimensions

3.1. Historical development of adaptable architecture

Adaptable architecture has roots in vernacular architecture and is influenced by the fields of climatology[2] and physiology.[3] Indeed, vernacular architecture is seen as some form of adaptable architecture or a precursor to adaptable architecture by many architects [25,26] and researchers [27–30]. In the West, the 1960's and 1970's saw the rise of environmental movements [31] and subsequent architectural movements which incorporated some of the adaptability dimensions and strategies seen in the methods chapter, as a reaction to functionalism and its mass housing [32].

Fig. 2 gives an overview of the historical adaptability strategies identified through the three literature reviews on adaptable architecture by Heidrich et al. [12]; Gosling et al. [19] and Schmidt et al. [9]; and subsequent literature analysis, from the 1930's until 2025 alongside some practical examples of these strategies. This graphic resulted from using both qualitative and thematic methods of identifying different adaptable design strategies in the built environment. The timeline shows vernacular architecture and how it evolved via the different strands and influenced (represented with the dotted arrows) adaptable architecture. Not all vernacular architecture is adaptable and there are plenty of "bad examples" too as argued by Vellinga [33]. However some vernacular strategies are definitely used in adaptable architecture [34] such as the wind catchers of the Borujerdi house in Iran which inspired bioclimatic architecture. The strands identified are inspired by the strand diagram of Schmidt III and Austin [9] (p. 19) and by Jencks *Modernist's evolutionary tree* [35] and focus mainly on adaptability strategies. Bioclimatic design has often been cited as evolving from vernacular architecture [25,27] and is focused on the climatology of the location and the comfort of the users [25,27,36]. Bioclimatic design gave rise to movements and practice examples such as the Earthship movement, which uses natural and repurposed materials as well as heat gains from the sun [37]. Most studies within bioclimatic design focus on thermal comfort and energy performance [25], however, it leaves a gap for other important aspects such as ventilation [29], and daylight [38], as well as socio-economic aspects, and cultural aspects [30,39]. Emerging from bioclimatic architecture, we distinguish two separate strands on Fig. 2. Adaptive comfort which is mainly adopting the responsive, adjustable, and versatile dimensions (much like Passivhaus) while interactive tech is often citing responsive materials or elements [40,41].

Bioinspiration is the fourth strand identified which evolved into the strategies of biomimetics, biomimicry, and regenerative design. Biomimetics is often cited with examples of moving components inspired by the movement of natural systems [41] which might explain why Gamage and Hyde [42] refer to biomimetics as the field of mechanical engineering. Following this statement, Gamage and Hyde [42] describe biomimicry mainly as informing design, following the works of Pawlyn [43] who takes inspiration from biological and natural principles to design adaptable and resilient architecture. Biomimetics and biomimicry both inspired regenerative design which was initially presented by Lyle [44] as a more ecological and human centred approach to design; aiming at shifting interrelations towards a systems thinking [45]. These strategies inspired and sparked discussion of thinking in lifecycles and systems which is very relevant to the current sustainability and circular economy (CE) discussions. Similarly, the Do It Yourself (DIY) and Tiny House bottoms up movements are gaining momentum. Although these strategies span a large spectrum of user-centred solutions, some dimensions are starting to emerge globally [46] such as flexibility, multi-purpose, and versatility.

Open building and the Metabolists of the 1960's have a similar approach to designing flexible buildings using different adaptability dimensions which include adjustable, movable, and convertible elements [47,48]. These strategies split into different strategies or are combined into a multi-disciplinary strategy such as the Skeleton/Infill (S/I) strategy. Two strategies that combine the aspects of systems thinking and S/I, are the Building in Layers and Design for Disassembly (DfD) strategies. Building in Layers is a concept disseminated by Stewart Brand [15] which is further explained in section 3.3. The DfD, Designing with Time, and Circ-Flex design strategies all include designing for multiple lifecycles. Design with Time strategy is conceptual and spans all dimensions [9], while DfD is focussed on the movable dimension of being able to transport and re-assemble the building or elements of the building at a different location. Circ-Flex combines the flexible and infill principles emerging from the S/I system and the principles of design with flows of the circular economy [49].

This ebb and flow of adaptability strategies over time has led to a proliferation of trends which all sit within the umbrella of adaptable architecture. Although some of them have the same roots such as the Passivhaus movements and interactive tech (both emerging from bioclimatic architecture), they implement very different adaptability strategies and/or adaptability dimensions. Also, not all strategies were as widely implemented as passive strategies. For example, the bio-inspiration strand is more experimental and less applied in buildings. This is represented in the timeline by the varying thickness of the bars; the thicker the bar, the more publications and case studies were found for the strategy. This is however just an indicator and not an exact measure.

3.2. Adaptability ambitions and drivers for research and design

The analysis of the history and timeline of adaptable architecture shows that the 20 different strategies have different ambitions. The Architectural Design bi-monthly publication issued an edition on "Loose-Fit" [16] that featured several of the authors of the pioneering historically applied strategies, including Habraken, Minami, Kendall, and Brand. The authors reflect back upon their work, all mentioning the aim of creating responsive systems which react to change in the context [16]. Fig. 2 shows three categories of sustainability context that the strategies respond to.

- Category 1 (in green): strategies ambitions at responding to changes in environmental aspects.
- Category 2 (in yellow): strategies ambitions at responding to changes in societal aspects.
- Category 3 (in blue): strategies ambitions at responding to changes in economic aspects.

Fig. 2 uses the analysis and representation methods developed by Schmidt III and Austin [9] but theirs lack the socio-technical and economic context of the research, even though Heidrich et al. [50] and Wang et al. [18] argue the importance of said context. There is a need for an updated approach to mapping adaptable architecture which includes the wider context to understand the emergence of the different adaptability strategies. In order to unravel why the historical analysis can be divided in the three categories, the drivers behind the research and design of the strategies are identified following the three pillars of sustainability. The reason for this approach is that most research papers in adaptable architecture state that the main driver behind their research is sustainable development which in most cases is related to climate change and specifically energy efficiency and carbon emissions. As the terms sustainability and sustainable development remain ambiguous, the three pillars of sustainability offer a more focussed approach to sustainable development while still being inclusive. Indeed, the three pillars of sustainability (social, economic, and environmental) have

[1] Climatology is the science that deals with climates and their phenomena [98].

[2] Physiology is the part of architectural design that deals with the human needs [76].

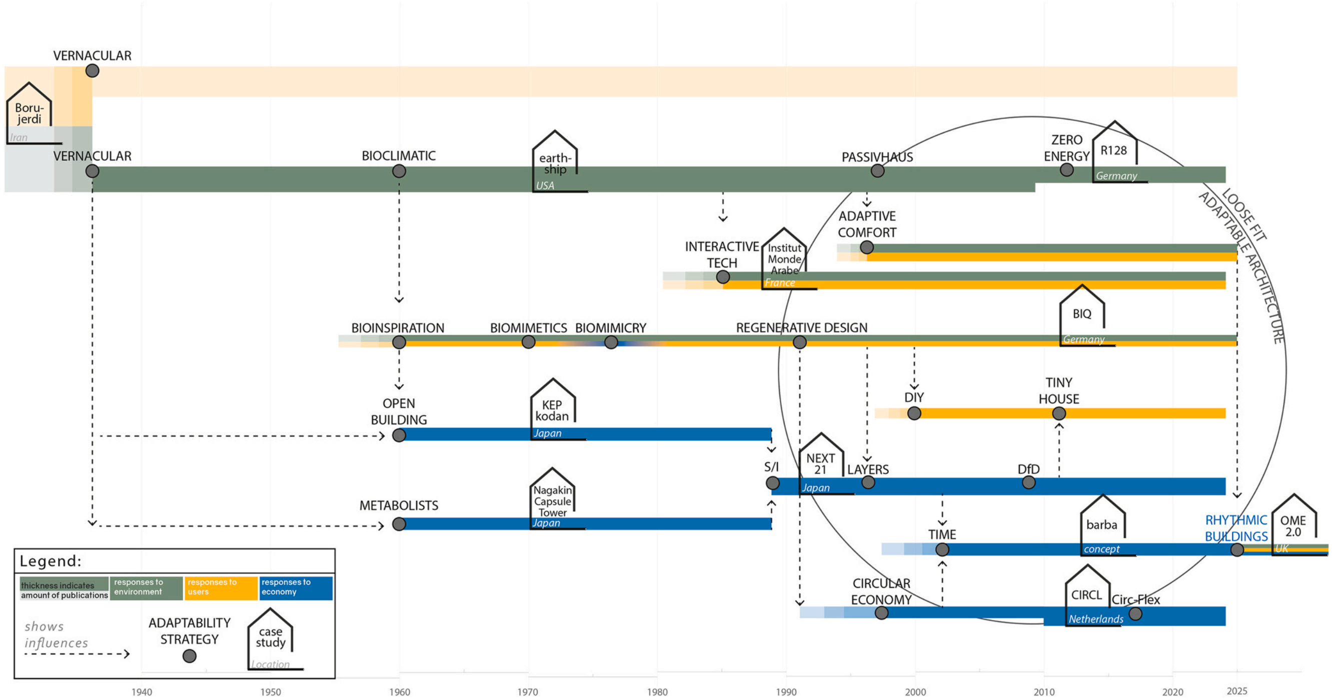

Fig. 2. Historical analysis of adaptable architecture from the 1930's to 2025. Timeline showing the adaptability strategies mapped on different strands (bars) and showing influences (dotted arrows) as well as case studies (house icons) of these strategies.

often been cited in literature as part of a sustainable strategy or development [18,31]. This approach to sustainable development has not a set origin but has emerged from the different environmental movements from the 1960's and different reports written in that time (such as the Brundtland Report calling for economic growth that is socially and environmentally sustainable). This led to the term being used in literature without any theoretical background but as a "common view" at the beginning of the 21st century and is now used widely by authorities such as the UN [31]. For example, the social, economic, and environmental aspects of sustainability were used as a framework to develop the Sustainable Development Goals in 2015 [51].

Therefore, analysing the drivers from the adaptable architecture literature might be the key element to identify how well existing adaptability strategies address the global challenges, and identify opportunities to develop strategies which address all 3 pillars of sustainability. A table presents the key publications for each adaptability strategy including the three literature reviews. Each publication is then analysed to identify to the dimensions the research focusses and to which of the three pillars of sustainability are the main drivers for each publication. Table 1 shows that most of the studies approach two out of the three pillars. For example, Gamage and Hyde [42] and Rasmussen et al. [52] focus on the economic and environmental aspects which Pascale et al [53] have identified as fundamental aspects of a CE. Many studies were found with a focus on social and environmental aspects as adaptive thermal comfort and passive strategies try to optimize buildings to enhance user comfort and reduce energy consumption [54,55]. The reduced energy consumption also leads to economical gain [55] although it isn't the main driver behind the adaptability strategies applied. The strategies are therefore organized on the (stated) main driver behind the research and do not include the "side effects" such as economical gain following the environmental aspect of e.g. reducing energy consumption. Based on Table 1, it can be noted that social aspects are solely focussed on comfort and especially centred around thermal comfort except for the Tiny House strategy which implements all the needs of the user in a novice learning-by-doing process. Adaptability strategies can lead to increased physiological and psychological comfort but also have an impact on other social and cultural aspects [30, 39], by for example increasing community empowerment and interactions within neighbourhoods as seen with the Tiny House movement. Likewise, the environmental aspects discussed in the literature focus on emission capture and energy consumption while the global challenges indicate an urgent need to tackle the depletion of resources and biodiversity.

3.3. Building layers in adaptable architecture

Table 1 shows the relationship between adaptability strategies and the elements or components related to the dimensions, that adapt to change. Interestingly, the biomimicry and regenerative design strategies are not linked to any specific dimension but rather reflect a systems thinking approach [42,45] which is also cited in Metabolist literature [61]. In his book *How buildings learn*, Stewart Brand [15] advocates for a systems thinking as buildings are static and therefore don't adapt well with time as they aren't *designed to adapt* with time but do change anyway according to three drivers: technology, money, and fashion. Brand [15] created an overview on these drivers for change by adding time to building components, which he calls shearing layers of change. Brand was inspired by Frank Duffy [62] who already had this idea that there is no such thing as buildings, but rather layers of building components. These layers were identified as Shell, Services, Scenery, and Set which lasts respectively, 50 years, 15 years, 5–7 years, and change every day [62]. Brand added two layers and renamed them all: Site, Structure, Skin, Services, Space plan, and Stuff. These layers are cited as a novel way of thinking into systems which enables some building elements to adapt without influencing elements from another layer [19]. However, it is clear that the layers correspond to building components. Therefore, there is an overlap with the shearing layers of change and the adaptability dimensions. In order to understand how these relate to each other, the literature from Table 1 is analysed once more against these building layers and the results are visualised in Fig. 3. As most papers highlighted a few different adaptability dimensions, the strategies usually also fit within a few of the Brand layers. For example, Minami [48] studied the effect of loose fit and flexibility strategies within the 1970's built "Tsurumaki-3" housing estate in Tokyo. The study researched how

Table 1
Occurrence of the three pillars of sustainability as main drivers behind the research in the analysed literature of the different adaptability strategies. The adaptability dimensions are also represented to offer insight into the relationship between the dimensions, strategies, and research drivers.

Main drivers for adaptable architecture	Adaptability strategies	Adaptability dimensions	Three pillars of sustainability		
Literature on adaptable architecture			social	environ.	econ.
Schmidt III and Austin, 2016 [9]	multiple	all	x	x	
Heidrich et al., 2017 [12]	multiple	all	x	x	x
Gosling et al. 2013 [19]	–	adjustable, flexible, refit-able	x	x	x
Total:			**3**	**3**	**2**
Literature on specific strategies					
Vellinga, 2015 [33]	Vernacular	all	x		x
Olgyay, 1963 [25]	Bioclimatic	responsive, adjustable, versatile, convertible	x	x	
Du, Bokel and van den Dobbelsteen, 2014 [29]	Adaptive comfort, Bioclimatic	adjustable, flexible	x	x	
Alders, 2016 [55]	Adaptive comfort	adjustable, versatile	x	x	
Roaf, Fuentes and Thomas-Rees, 2013 [28]	Adaptive comfort	adjustable, versatile, refit-able, convertible	x	x	x
Holstov, Bridgens and Farmer, 2015 [56]	Passive	responsive		x	
Holstov, Farmer and Bridgens, 2017 [50]	Passive	responsive	x	x	
Taleghani, Tenpierik, Kurvers, and van den Dobbelsteen, 2013 [57]	Zero energy, Adaptive comfort	not specified (n.s.)	x	x	
Tabadkani et al., 2019 [58]	Adaptive comfort, Interactive tech	responsive/ dynamic	x	x	
Crespi and Persiani, 2019 [23]	Interactive tech, zero energy	responsive/ dynamic		x	
Loonen et al., 2013 [40]	Interactive tech	all dimensions	x	x	x
Kasinalis et al., 2014 [59]	Interactive tech	responsive	x	x	
Watson, 2019 [30]	Bioinspiration	responsive, flexible, movable	x	x	
López et al., 2015 [22]	Biomimetics	responsive		x	
López et al., 2017 [41]	Biomimetics	responsive	x	x	
Gamage and Hyde, 2012 [42]	Biomimicry	n.s. systems thinking		x	x
Cole, 2012 [45]	Regenerative design	n.s. systems thinking	x	x	
Orden van, 2017 [60]	Tiny House	adjustable, versatile	x		
Habraken, 1972 [32]	Open building	adjustable, flexible, refit-able, convertible, scalable	x		
Minami, 2016 [48]	Open building	adjustable, flexible, refit-able	x		x
Schalk, 2014 [61]	Metabolist	adjustability, versatile, refit-able, convertible, scalable also: systems thinking	x		
Rasmussen, Birkved and Birgisdóttir, 2019 [52]	Design for Disassembly (DfD), Circular Economy (CE)	scalable, movable		x	x
Geldermans, Tenpierik and Luscuere, 2019 [49]	Circ-Flex	adjustable, flexible	x	x	
Zarzycki and Decker, 2019 [24]	all	responsive, refit-able, convertible		x	
Total:			**18**	**19**	**6**

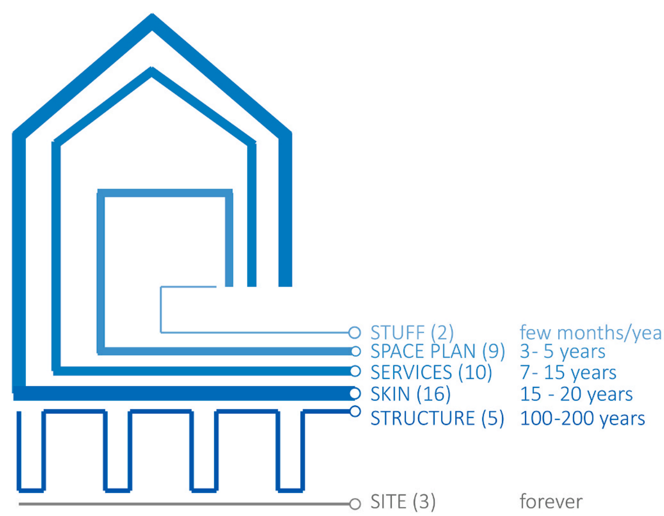

Fig. 3. Occurrence of the adaptation components represented on the shearing layers of Brand [15].

residents adapted the layout of their housing according to their needs using the so-called KEP systems [48], which other studies built upon including other factors such as size and quality [63]. This example has a clear focus on the space plan layer and is therefore marked as such. There are also studies that focus on multiple layers such as the research by Kasinalis et al. [59] which analyses seasonally adaptable façades systems to increase comfort and compare their performance to traditional services. This study was therefore marked as both skin and services. This resulted in the visualisation of the layers of Brand with the relative thickness of the line increasing with the number of documents associated with each layer.

Fig. 3, reveals that most adaptable architecture focusses on the skin layer as well as both the services and space plan layers. Interestingly, research that included services also included skin as a layer, while space plan is either the sole focus of the research or coupled with all the other layers. This makes sense as some adaptability strategies (e.g. Passivhaus, adaptive comfort, interactive tech) use the skin layer to improve indoor comfort and reduce the energy demand. Therefore, dividing the building into components spanning different lifespans but still adapting together seems unproductive. Indeed, systems thinking has evolved in the past years, and the meaning has changed since Brand devised his layers. Now, systems thinking is a methodology often associated with regenerative design and CE, and aims at organising, conceptualizing, and visualising the different facets of a system [64]. It is also used in architectural and urban research and design practices as a multi-disciplinary way of analysing qualitative data. Indeed, the urban climate and built environment in general are sometimes compared to their own ecosystem [45,65,66], especially as cities are the main hubs of consumption and sometimes production [67]. These parameters of ecosystem are strongly linked to the analysis of material and energy flows which are methods used in a CE [65].

Hence, moving from layers of components to systems thinking would enable connections and integration of the layers function to enable them to respond and truly unlock their adaptable potentials such as breathable and active building envelopes in contrast to rigid building skins.

4. Framework for adaptable architecture and Rhythmic Buildings

Based on the previous analysis, the gap in the field of adaptable architecture is identified: there is a lack of specific strategies which address all three pillars of sustainability and incorporate systems thinking. It can be argued that the field has been focussed on specific technological aspects to address environmental issues which has left some areas of the context neglected. This study suggests a framework (see Fig. 4) for adaptable architecture to include the whole sustainability context. The framework is divided into three polygons representing the three sustainability categories emerging from the adaptability strategies in Fig. 2.

The polygons represent the responses (both the active reaction and addressing the parameters) to different contextual aspects following the three pillars of sustainability. The faces of the polygons represent the context of changes and how they relate to each other (which is represented by their proximity to each other and the overlap in categories). This framework presents all the parameters that have been cited in some form in the analysed adaptable architecture literature. Some parameters are more elaborated than others, as they are researched in further depth in the context of the built environment (such as the effects of the temperature cycles on comfort). Each of these parameters are further developed in the next sections. This approach to mapping is inspired by the comfort factors table by Andargie, Touchie, & O'Brien [68]; however, the framework enables the visualisation of the different relations of the parameters, inspired by Schmidt III et al. [69]; and those areas that are more represented in the research by adding the strategies onto the framework following both Fig. 2 and Table 1. It is obvious that the parameters are interrelated and influence each other.

4.1. Responses to the environment

The environment aspect of the context can be divided into four sections following the scale of the environment: climate change (which is at global scale), local climate, urban climate, and micro-climate. According to Oke, Mills, Christen & Voogt [70]; the climate is divided into different scales: macro-, meso-, local-, and micro-scale. The microscale is often referred to in the built environment, especially in bioclimatic design [25,29], however, not all sources associate the same definition/boundaries to it. When Olgyay [25] talks about micro-climates, he explicitly talks about the indoor climate of the building that is achieved through design. A different approach by Du et al. [29] presents the

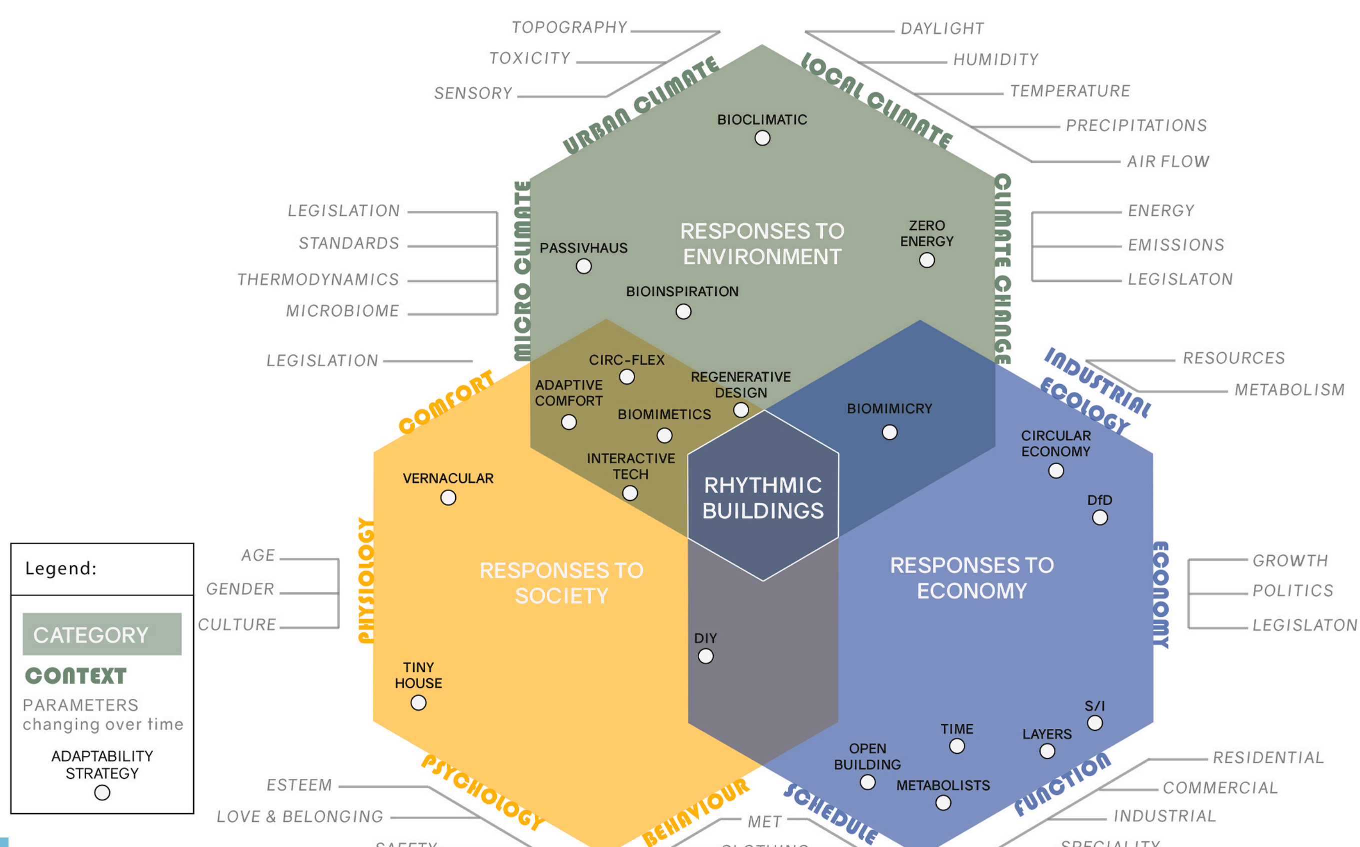

Fig. 4. Framework for adaptable architecture including the wider context.

micro-climate as "involving the indoor space and the spaces around the indoor spaces of a particular building. […] The building micro-climate is mainly defined by spatial and the thermo-physical properties." [29] (p. 216). This approach to climatology and its relation to the building is chosen for the framework and is illustrated in Fig. 5, on top of the added global scale to respond to the global climate challenge.

Climate change in this context addresses the aspect of the environmental global scale that influences adaptable architecture. As explained in the drivers for adaptable architecture, tackling the effects of climate change are critical, and especially the parameters of energy and emissions. Indeed, global targets and legislations are driving adaptability strategies for buildings. This leads to local climate which is emerging from the sun and our relative position to it which translates itself in a planetary rhythm of daily cycles and seasonal cycles [25]. These cycles vary with the location which are involved in the creation of local climates alongside other factors. "The revolution of the globe gives the heartbeat of day and night which regulates the activities of reposes of natural life. The rotation of the earth around the sun sets the rhythm of the seasons, which call to life the dormant vegetation and determines the bounty of harvests. Whether each locale is cool or warm is largely determined by its relative distance from the equator; but the imperative regularity of the sun also sets the pace for the patterns of humidity and wind that sweeps across the earth." [25] (pp. 7–8). Daylight has a significant effect on the circadian rhythm (also called circadian clock), which is the internal rhythm that some species (including humans) possess which regulates the sleep and wake cycles, the level of alertness etc. This circadian rhythm is synchronized using a time cue, or so-called *Zeitgeber* [38]. The primary phenomenon for this to happen is daylight with its different intensity, timing, exposure duration, and spectral composition varying with time and location, but temperature is also cited as a *Zeitgeber* [71]. Solar radiation is directly responsible for the different temperatures and daylight variations at a given location. Thus, both daylight and temperature have an influence on organisms by acting as a *Zeitgeber*, but they are also both factors that influence the micro-climate. The next scale is the urban climate which is identified by aspects that lie between the local climate parameters such as the weather and the micro-climate parameters. The urban climate has a high influence on comfort and wellbeing of dwellers, especially on sensory parameters and toxicity. Toxicity often emerges from the infrastructure and consummation hubs with infamous examples of metropoles showing high toxicity impacting the health of inhabitants. Sensory parameters are less often cited as a contextual parameter, however, they notably influence comfort and wellbeing at a smaller scale [72]. Indeed, some sensory parameters such as noise, smell, and visual comfort, emerging from urban environments stimuli, can cause or relieve stress [73]. These multi-sensory studies also highlight that these sensory stimuli affect the perception of one another as well and are therefore added as one integrated parameter to the framework.

Finally, as Olgyay [25] argued, topography is an important aspect of adaptable architecture and the topography of a place should be taken into the design process. The last environmental scale is the micro-climate which refers to the indoor, semi-indoor, and direct outdoor space surrounding the building following the definition by Du et al. [29]. This environment is strongly regulated by local building legislation. Indeed, there are rules that determine the micro-climates of buildings often citing a desired temperature, air flow, and humidity; the balance of which are sometimes referred to the thermodynamics of the environment. The legislations are linked to the standard of comfort developed over the past years; such as Fanger's PMV (predicted mean vote) that was used for the American ASHRAE55 standard [55]. Lastly, a parameter that has gained more traction over the past years, and even more so since the COVID19 pandemic hit, is the built environment microbiome (which means the microorganisms in a particular environment). The so-called microbial ecology of micro-climates, has an influence on users' health as those microbial communities can either prevent or cause diseases [74].

4.2. Responses to society

The responses towards societal needs of the context can be brought down to the users of the built environment and divided into four sections: physiology, comfort, psychology, and behaviour which all have an effect on the design of habitations and are closely related to each other [75]. Physiology is the part of architectural design that deals with the human needs [76]. Indeed, in his book *The Biology of Human Survival* [75], explains that the limits of human tolerance are low and depend on four variables:

- Physics of the environment,
- Limits of human physiology,
- Length of exposure, and
- Behavioural adaptation.

Although Piantadosi's background is in medicine, his book [75] highlights why we need buildings and what functions they should perform. Indeed, the limits of human physiology is difficult to change (despite fast developments in the field of biotechnology), it mostly does so through *behavioural adaptation*. In biology, these adaptations means: "the extent to which an organism can occupy an environment, use available resources, and multiply." [75] (p. 13). Living organisms therefore try to maintain an active equilibrium with their environment. However, sometimes the conditions are so extreme (physics of the environment) or the length of exposure is so high that the body cannot adapt anymore. *Habitats* allow for surviving and thriving inside it thanks to specific physical boundaries [75]. The limits of human physiology has been linked to socio-demographic characteristics of building occupants [77] such as gender, age, and culture [55]. Comfort is when these physiological needs are met. Comfort is determined by the temperature, humidity, noise, and daylight levels when performing an activity [78]. There have been many studies in determining comfort which in turn led to different standardisation and policies[4] on how to regulate indoor climates to fit this comfort [8,54,78]. There are many studies on *adaptive* thermal comfort [7,8,29,54] as it has now become clear that thermal comfort depends on many factors which are *changing over time*. These factors include all the other contextual aspects of the users (physiology, psychology, behaviour) and of the environment (micro-climate, urban climate, local climate). Indeed, it was shown that the average person does not exist and that people adapt to variations of local climate. For example, people tolerate a wider range of temperature than the PMV based on the seasonal and daily variations in outdoor temperature [79].

Following physiology and comfort is the psychology context. Indeed, many [55,57,80,81] agree that psychological aspects and needs are critical to implement in the design of the built environment and that these aspects are closely related to physiology, comfort and behaviour [39]. However, there are no particular parameters cited for psychology alone, hence, Maslow's hierarchy of needs is used as guideline for design as it has been cited by the IPCC [2] as a notion worth considering for sustainable development and equity. The psychological aspects are found in the middle section of Maslow's pyramid and are divided into three parameters (in order of importance): safety, love and belonging, and esteem. As seen in physiology, behaviour is part of our adaptation strategies and it influences comfort, therefore it is the last societal aspect of the framework. There are two types of behavioural influence in the built environment. The first is behavioural adaptation, which is how the body adapts to extreme climates which is explained in the physiology part. The second type is how our conscious behaviour influences comfort. These behaviours can be classified by users' activities (including modifying the micro-climate such as opening windows) and how intense an activity is. The latter is known as the metabolic rate of our bodies (MET). Both the metabolic rate-which can be associated with activities

[3] such as the previously mentionned ASHRAE55.

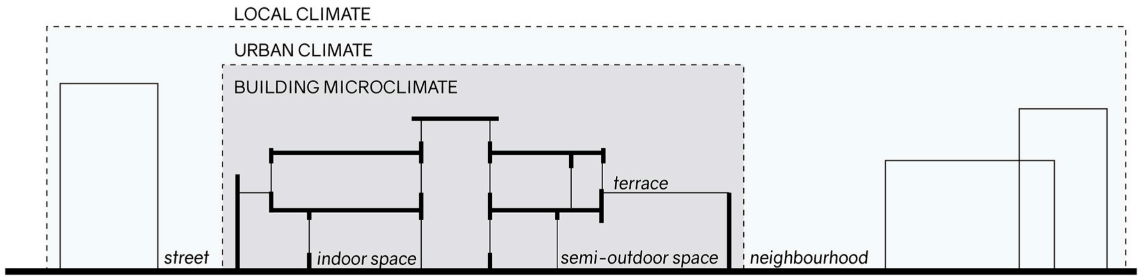

Fig. 5. The spatial features of building micro-climate adapted from Ref. [29] (p. 217).

performed, and the predicated degree of insulation (amount of clothing), are behaviours that influence comfort [78,82]. Hence, behaviour is closely related to schedule as the activities followed by the users follow patterns.

4.3. Responses to the economy

Responses to economic aspects are often drivers for innovative research and the related contextual aspects identified are: industrial ecology models, economy, function, and schedule. Industrial Ecology partly addresses the economic contextual aspect as it includes the parameters related to resources and metabolism. Parameters such at the resources needed to build and maintain the built environment are important to include in the framework with regards to the global challenge of resource depletion. Industrial Ecology maps the flows of resources within a defined system to highlight bottlenecks and opportunities to close the loops [83]. All of these flows, as well as the stocks, represent the metabolism of a system. These parameters are often used to enable a CE, especially in an urban environment but also on other architectural scales such as the urban fabric, which is seen as systems thinking [84]. The economic aspect is also cited as context in order to concentrate on the direct effects the economy has on politics, legislations, and growth of the built environment. But it is also included as the built environment exerts an influence on GDP's which this study by Wu and Yan [85] suggests by showing that the energy consumption of buildings influences the economic growth in China. The third economy contextual aspect of this framework is the function. Following Leupen's [86] discussion on functionalism theory and Habraken's [32] ideas on housing, it can be derived that the function of a building is the most important driver for design. However, both approaches are very different; with functionalism analysing in detail the most efficient use of space and Habraken [32] pleading for flexibility. However, both these approaches can be combined in a flexible yet efficient manner. Indeed, if the changes occurring over time are leading the design of a building and its flexibility, then it is not *changes* themselves that are leading, but the *changing functions* needed over time. This was also highlighted in Schmidt and Austin [69] as many strategies aim at reacting to these changes in functions. In the context of function, we understand the different scales of function following building regulations, which show four categories: residential, commercial, industrial, and speciality. The last economy contextual aspect is schedule which is closely related to the behaviour of the users. It is often researched as users occupancy profiles also affects building design and performance [87–89]. Schedule is driven by the cycle of activities related to the function of the building and economic aspects. Both behaviour and schedule have the same parameters of MET and clothing but the influence of these aspects differ as behaviour emerge from the users themselves and schedule emerges from socio-economic aspects.

5. Discussion: Rhythmic Buildings vision

In Fig. 4, we try to capture a wide range of parameters of the context that influence adaptable architecture, all of which change over time with varying frequency. Schmidt and Austin [9] identified two types of changes: certain and uncertain changes. Certain changes are changes that occur in a repetitive pattern and are therefore also called rhythmic or cyclical changes. These changes are predictable in their frequency and magnitude. Uncertain changes are unexpected changes that don't present any pattern [9]. This uncertainty is difficult to predict; therefore, the built environment often retrofits for unexpected changes that have already happened such as natural disasters. All of the contextual parameters change over time following different patterns and frequencies, and these can be considered certain changes. Indeed, the parameter of daylight has an obvious daily rhythm which also influences schedules around the globe. All the parameters mapped have a specific rhythm depending on how the other parameters influence each other. For example, the temperature rhythms have different frequencies depending on the local climate: in a temperate climate the temperature follows a strong seasonal rhythm, while in an arid climate the temperature has a stronger daily rhythm of very cold nights and very hot days.

Therefore, we developed the Rhythmic Buildings vision to have the potential to be intrinsically sustainable as the envisioned rhythmic built environment intuitively reacts to all the rhythms of the context. Developing visions has been stressed by Wang et al. [18] as an imperative step towards the long term benefits of a sustainable built environment. This adaptability strategy combines aspects of bioclimatic design, adaptive comfort theories, regenerative design, and designing with Time. Although the vision for rhythmic buildings reacts to all the parameters of the context highlighted in Fig. 4, the first rhythmic buildings could respond to a few of these parameters rhythms. So even though this vision is a novel approach, we can already identify some rhythmic interventions in the current built environment. For example, the conceptual BARBA project [90] showcases a spatial environment that adapts according to users daily and weekly schedule. The inhabitants of the BARBA project "exchange" space and layout when introducing visitors or specific activities within their space. For instance, the layout of a nurse might shrink when working outdoors while their neighbour borrows this space for a tennis practice. On a materials scale, the futuristic design of a habitat for Mars using ice as main material can also be seen as rhythmic. Indeed, the extreme temperature variations between day and night on Mars (-20 °C and -80 °C respectively), allows the ice structure to go through daily thawing and freezing cycles which reinforces the structure and allows it to repair itself as the water will fill any cracks formed by micrometeorites and then expand upon freezing, creating an even stronger structure [91]. Some built projects are identified as partially rhythmic such as the BIQ House in Hamburg which utilizes algae as bioreactors in façade panels. These algae produce energy as heat and biomass but also provide dynamic shading to the apartments [92]. This design strategy can be considered rhythmic as the algae growth is directly related to the amount of daylight and temperature hitting the façade panels. The more algae are duplicating and growing, the more effective they are at shading the interior of the building. Another project that presents a rhythmic approach is the 2226 House by Baumschlager Eberle Architekten. This project uses passive approaches to building physics by using radiant heating and thermal mass over conventional HVAC units as well as dynamic natural ventilation [93]. The 2226 House reflects the seasonal cycles of the outdoor environment, e.g. local climate context (environment), rhythmic behaviours e.g. metabolic context (society responses), and schedules emerging from the users e.g. occupancy (economy responses). The two conceptual examples and the two built examples show rhythmic aspects which in the future could lead to gradually introducing more rhythms emerging from the context in the built environment to reach the vision. However, only these four examples are found, as most adaptable buildings do not include the rhythms or cycles emerging from the context as input for design, but rather focus on adaptability dimensions.

Currently in the built environment, a building is designed based on the context: these are both the location and a set of requirements known as the design brief [86]. These requirements form the basis for any design decisions, strategies and technologies, and in order to incorporate the dimension of time, the rhythmic changes emerging from the framework are needed as input. Not only does the framework add the dimension of time, it also reinforces the aspect of place as opposed to global solutions. This type of thinking of place and time is, of course, not a novel approach to architecture and has been developed in other theoretical frameworks such as Frampton's [94] Critical Regionalism. However, including the specific rhythmic changes of the sustainability context gives opportunities to structure this adaptability strategy. Indeed, the rhythmic changes can be gathered using online tools or field work in a similar approach to Du et al. [29] and Alders [55] and a systems thinking approach (e.g. using material flow analysis tools) to inform the design of Rhythmic Buildings. The potentials of Rhythmic Buildings are all circling back to adaptation and sustainability. As the concept is still quite open ended, there are many potential outputs for this adaptability strategy. For example, the retrofit of current building stock such as terraced housing could gain substantially in terms of comfort and energy reduction as highlighted by Ozarisoy and Elsharkawy [5]; but also socially and economically, by applying the rhythmic strategy. By using this rhythmic strategy, buildings become interactive and intuitive to the needs of the users/inhabitants in relationship with their cyclical context be it at a neighbourhood scale or micro-climate scale. For example, we know that being socially isolated has detrimental effects on wellbeing [95]. This is especially relevant at the time of the COVID19 pandemic where everyone is isolated from their loved ones and the house becomes hosts for multiple functions such as home and workplace. The negative effects can, however, be mitigated using the new adaptability strategy by using a changing and flexible indoor environment, that follows the new schedules of the users. Flexible strategies have been demonstrated to have a positive effect on wellbeing for people living and working in extremely isolated habitats such as the ISS and the Antarctic survey [96]. Another example, on how these strategies can be implemented for users wellbeing is to include the rhythms of daylight temperatures, intensities, and colour into the design. These daylight rhythms adjust our circadian rhythm and improve our overall health and wellbeing [81]. The systems thinking approach of the framework enables identification and design of relationships between the different parameters and aspects, much like an ecosystem does in nature. This approach is already well established in regenerative design and the field of Industrial Ecology. As some of these relationships are benefitting the overall system such as symbiotic relationships, a systems thinking that is inspired by ecosystems might be worth investigating.

This framework of Rhythmic Buildings is still in its conceptual phase and, although the theory indicates that including the wider context can improve the sustainability of the built environment, the framework still needs to be tested. Moreover, the methodology used to analyse existing strategies and dimensions followed a strong thematic pattern emerging from the three main literature reviews. This focus might have left gaps in the analysis of this established field which should be addressed in future work. The authors also wish to stress that the implementation of such concepts into technology of high readiness level requires further research including how this framework fits with current legislation and how it can be cost effective. The next steps of the research should explore both technicalities of rhythmic buildings and the contextual integration within the current built environment. Some emerging material technologies offer great potential for rhythmic buildings such as the use of phase change materials or engineered living materials [97] which are dynamic and responsive to their context. Further improvement of this research would be to perform a systematic review of the adaptable architecture literature as well as an analysis of case studies. The valuable insights gained from connecting theory and practice would then inform Table 1 and subsequently Figs. 2 and 3.

6. Conclusions

This manuscript looks at the field of adaptable architecture and how it responds to global challenges related to sustainability. It was found that adaptable architecture implements different adaptability dimensions and strategies to respond to different contextual aspects. The adaptability dimensions point to the components or elements of buildings that change while different adaptability strategies usually focus on responding to a specific aspect. Fig. 2 shows that the field has evolved over time to form three distinct categories of strategies that respond to (1) the environment, (2) society, and (3) the economy. Through qualitative analysis methods of the relevant literature, the main drivers identified behind these adaptability strategies are to tackle some of the global challenges such as climate change and resources depletion in order to transition towards a sustainable built environment. However, a gap was identified as the strategies do not include all three pillars of sustainability (society, environment, and economy). The aim of this conceptual paper is to develop a framework for adaptable architecture that involves the whole sustainability context together with a systems thinking approach. This was suggested through analysis of some literature works on strategies and visualised, using design methods, in Figs. 2 and 4. The resulting framework proposes the use of a new adaptability vision and strategy called Rhythmic Buildings. These Rhythmic Buildings would be designed to react to the rhythms of the sustainability context following the parameters found in the literature and depicted in Fig. 4. In conclusion, we believe that using the framework and concept of rhythmic buildings will guide designers and researchers towards a more holistic approach of building adaptability. Indeed, the framework supports the society, environment and economy aspects of the context in one clear overview and shows the relations between the contextual parameters. It is believed that using the framework could enable sustainable adaptation of the built environment by addressing the current high energy demand for water, space heating and cooling, and low comfort range. This vision of Rhythmic Buildings will be critical in the future to tackle all the impacts of the global challenges on both people's health and wellbeing, and the built environment.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This research is funded by Research England's Expanding Excellence in England (E3) Fund as part of the Hub for Biotechnology in the Built Environment (HBBE).

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