The current issue and full text archive of this journal is available on Emerald Insight at:
https://www.emerald.com/insight/2398-4708.htm

Circular building adaptability and its determinants – A literature review

Mohammad B. Hamida, Tuuli Jylhä, Hilde Remøy and Vincent Gruis
Department of Management in the Built Environment, Faculty of Architecture and the Built Environment, Delft University of Technology, Delft, The Netherlands

Received 15 November 2021
Revised 13 January 2022
25 March 2022
Accepted 27 April 2022

Abstract

Purpose – Adaptability is an inherent quality in building circularity, as adaptability can physically facilitate the reversibility of materials in a closed-reversible chain, also called "loops". Nevertheless, positioning adaptability in circularity-oriented models could overlook some of the contextual considerations that contribute to the utility for the built environment. This paper reconceptualises building adaptability to incorporate circularity, in order to facilitate for the resource loops whilst preserving the long-lasting functionality in buildings.

Design/methodology/approach – An integrative literature review on adaptability and circularity of buildings was conducted using systematic search approach. From the initial database of 4631 publications, 104 publications were included for the final analysis. A comparative analysis of definitions and determinants of both concepts was conducted to reconceptualise circular building adaptability.

Findings – The findings of the literature study show that incorporating circularity and adaptability is possible through 10 design and operation determinants, namely configuration flexibility, product dismantlability, asset multi-usability, design regularity, functional convertibility, material reversibility, building maintainability, resource recovery, volume scalability, and asset refit-ability. The study concludes that considering the defined determinants in a holistic manner could simultaneously facilitate: building resilience to contextual changes, creation of asset value, and elimination of waste generation.

Originality/value – This paper expands the relevant bodies of literature by providing a novel way of perceiving building adaptability, incorporating circularity. The practical value of this paper lies in the discussion of potential strategies that can be proactively or reactively employed to operationalise circular building adaptability.

Keywords Adaptability, Building adaptation, Built environment, Circularity, Circular economy, Circular building

Paper type Conceptual paper

1. Introduction

Buildings are static objects, but need to undergo changes to respond to internal, external or building-related triggers (Kamara *et al.*, 2020). For example, changes in operation can trigger a need to add new building features or services (Estaji, 2014; Patel and Tutt, 2018). External socio-economic changes could include changes in market dynamics (Sadafi *et al.*, 2014), demographics, climate or technology (Ross, 2017). Thus, buildings need to be adapted to meet these changes (Slaughter, 2001). It is anticipated that the majority of existing buildings will be frequently adapted in the upcoming decades to meet future demands (Bullen, 2007; Conejos *et al.*, 2014; Perolini, 2013; Rasmussen, 2012). Consequently, it is argued that adaptability should be proactively and reactively incorporated, meaning that existing and new buildings should facilitate the accommodation of future changes (Huuhka, and Saarimaa, 2018; Langston, 2014a).

International Journal of Building Pathology and Adaptation
Vol. 41 No. 6, 2023
pp. 47-69
Emerald Publishing Limited
2398-4708
DOI 10.1108/IJBPA-11-2021-0150

Adaptability has not only been perceived as a key quality enabling building alterations (Douglas, 2006), but also as a means to sustainable development. For instance, adaptable buildings enable the user or owner to accommodate changes in an affordable manner (Arge, 2005), while reducing the amount of waste generated from building changes (Manewa *et al.*, 2016). Adapting existing buildings is also seen as a coping strategy to deal with market-related crises, such as property oversupply (Remøy, 2014a; Waston, 2009), as well as building-related issues, such as deterioration (Langston *et al.*, 2008; Rockow *et al.*, 2019; Swallow, 1997).

Recently, building adaptability and adaptation have been understood as key concepts that fit with the principles of the circular economy (CE) and a circular built environment (Ness and Xing, 2017). Building adaptability plays a vital role for reversibility of building products in the reversible chain (Geldermans, 2016). However, positioning adaptability in CE-oriented frameworks may overlook other contextual aspects, and thus, many authors emphasised the need to adopt a multidimensional framework (Cerreta *et al.*, 2020; Girard, 2020), as the CE paradigm prioritises economic prosperity in an environmentally sustainable way, followed by fulfilling other social needs (Kirchherr *et al.*, 2017).

Literature indicates numerous determinants that articulate the capacity of a building to adapt to future demands (Arge, 2005; Eguchi *et al.*, 2011; Heidrich *et al.*, 2017), while there is a gap in integrating and aligning adaptability determinants with circularity. Considering the need to proactively and reactively incorporate and align circularity and adaptability in buildings, this study aims to bring the concepts together. The paper considers adaptability of buildings for in-use and across-use adaptations.

2. Research methodology

An integrative literature review, following a systematic search, was conducted to understand circular building adaptability. Integrative literature review is a useful methodology for reconceptualising mature concepts to embody emerging developments or synthesising a conceptual model for an emerging concept (Snyder, 2019). In this paper, Torraco's (2005) guidelines for writing an integrative literature review – particularly the form of synthesising conceptual frameworks or alternative models – were followed. PRISMA guidelines were followed to systematically identify, select, and report literature sources (Moher *et al.*, 2015).

2.1 Search strategy

The reviewed literature included peer-reviewed journal papers, conference papers and book series, and some additional grey literature sources. The systematic search was conducted in two databases: Web of Science and Scopus. In the two databases, a Boolean operator was used to combine the interrelated terms in one search query. Figure 1 presents the search terms and the logic of the searches. To obtain relevant sources to the research context, the terms were linked to built environment-related terms. The search was conducted in March 2021. The grey literature sources were selected to cover other relevant or supplementary sources related to adaptability and circularity.

2.2 Screening process

Based on multiple searches, the initial database contained 7,227 papers or publications: 5,161 from Scopus; 2,052 from Web of Science; and 14 from other sources (Figure 2). The screening was done in three sequential phases. Each phase adopted the same inclusion and exclusion criteria (Table 1).

2.3 Integrative analysis and synthesis methods

A comparative analysis of the adaptability and circularity was conducted to define the interrelationships and contrasts between the concepts. Based hereupon, a definition of

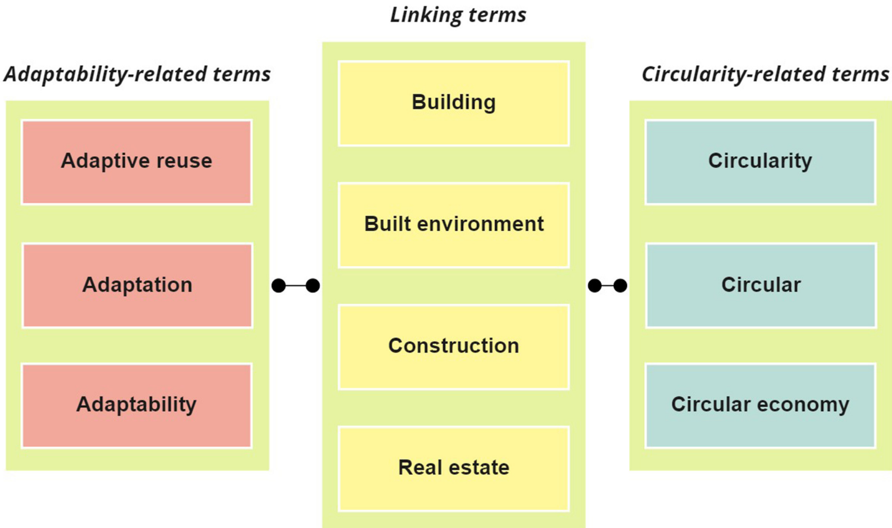

Figure 1.
Used search terms

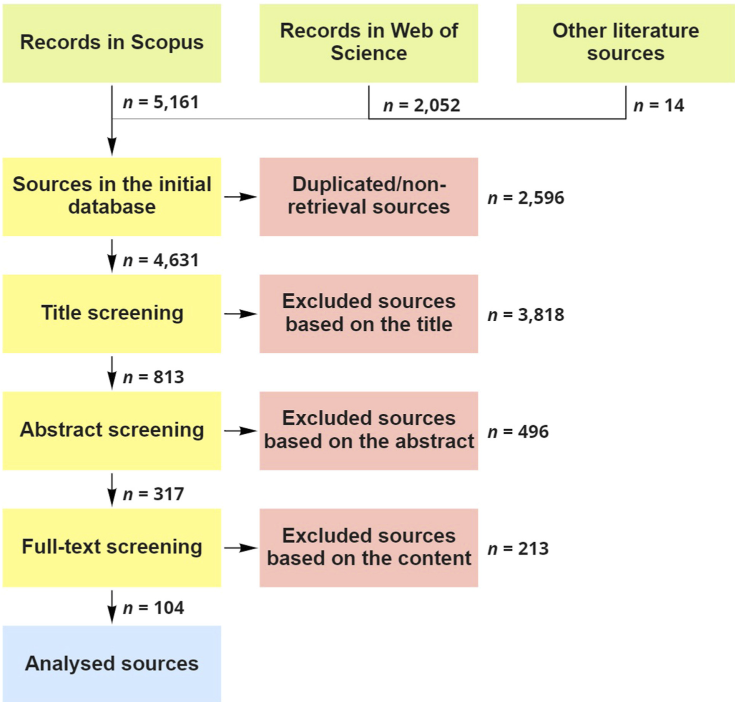

Figure 2.
Screening process

circular building adaptability was proposed. As Torraco (2005) guidelines recommend the use of a matrix to structurally guide the identification of determinants of a concept under review, two matrices were developed to present the determinants of both concepts.

Table 1.
Inclusion and exclusion criteria

Inclusion	Exclusion
Type of sources: Literature reviews, theoretical studies, empirical studies	*Type of sources:* Testing building material, systems or components, research methods in the built environment
Adaptability variables: Adaptable buildings, adaptability attributes, open/hybrid building design, built environment/building adaptability, adaptable strategies, fixable building design, adaptation strategies	*Adaptability variables:* Landscape adaptability, thermal adaptation, behavioural adaptation, climate change adaptation, urban economic adaptability
Circularity variables: Circular economy in the built environment, circular buildings, circular economy in construction	*Circularity variables:* Circularity and circular economy in cities, circular economy in product chain, organisation/corporate circular economy, circular economy in food chains, circular economy measurements, circular design (geometry)
Other variables: Regeneration strategies, disassembly and reusability of building components	*Other variables:* Renovation processes, vernacular heritage, housing governance, material flow analysis
Subject: Sustainable building adaptation, building adaptative reuse potential, and circular economy operationalisation in the built environment	*Subject:* Adaptation of user with the building environment – e.g. thermal, lighting, acoustical, communal adaptation, and circular economy measurements

The integrative analysis served to recognise the overlaps, interrelationships, and dependencies between the two concepts; thus, conceptually incorporating them.

3. Findings

3.1 Building adaptation and adaptability

Building adaptation expresses the process of altering built assets. Douglas' (2006) definition is frequently used, defining building adaptation as *"any work to a building over and above maintenance to change its capacity, function or performance (i.e. any intervention to adjust, reuse or upgrade a building to suit new conditions or requirements)."* Although the definition has been used quite often, it is generic (Wilkinson, 2014b). Thus, different categorisations were made to classify the building adaptation practice. In general, building adaptation can be categorised in terms of the level and type of intervention. Adaptation can range from minor adaptations – such as decoration or installation of fittings – to major adaptations such as building reconfiguration (Wilkinson and Reed, 2011). In terms of the form, building adaptation can be categorised as in-use adaptation, or refurbishment; and across-use adaptation, or adaptive reuse, or building conversion (Shahi *et al.*, 2020; Wilkinson, 2014a). Due to rapid development of communities and socio-economic changes, buildings are expected to be adapted during their lifecycle; hence, adaptations need to be facilitated by the building configuration and composition (Ross, 2017). The adaptability of buildings depends on building-related attributes (Stone, 2005), and could moreover be enhanced by amendments in context-related issues – e.g. legislations and market conditions (Remøy and Wilkinson, 2012; Terlikowski, 2017; Wilkinson, 2014c).

The building adaptability concept, also known as "adaptivity" or "adaptive capacity", has emerged as a quality indicating the capacity of a building to be adapted. Different definitions for adaptability were formulated. Pinder *et al.* (2017) indicated that the majority of adaptability definitions are context-specific and influenced by the aim of delivering a quality – e.g. changeability or meeting future demands. Table 2 lists building adaptability-related definitions. Overall, most of the definitions tend to express the ability of a building to accommodate change or keep its functionality, as for example: facilitate physical modifiability

Term	Definition	Implied quality and aim
Building adaptability	"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." (Heidrich *et al.*, 2017)	*Quality:* The ability to accommodate building changes in general *Aim:* Facilitation of modification
	"The capacity of a building to accommodate effectively the evolving demands of its context, thus maximising value through life." (Eguchi *et al.*, 2011)	*Quality:* The ability to meet the future demands *Aim:* Maximisation of value and building longevity
	"The capacity to be modified for a new purpose." (Hudec and Rollova, 2016)	*Quality:* Ability to accommodate building changes *Aim:* Facilitation of embodying new function
	"The ease with which a building can be physically modified, deconstructed, refurbished, reconfigured, expanded, and/or repurposed." (Ross, 2017)	*Quality:* Ability to accommodate building changes *Aim:* Ease of implementing physical modifications and embodying new function
	"Building's ability to meet shifting demands without physical changes". (Geraedts *et al.*, 2017)	*Quality:* Ability to meet future demands *Aim:* No physical alteration
Adaptive reuse potential	"Propensity of an asset to be 'recycled' to perform a significantly different function while keeping the basic attributes of the asset in place". (Langston, 2014b)	*Quality:* Functional recyclability *Aim:* Preservation of basic physical features of the building
Adaptive capacity of building	"Characteristics that enable it to keep its functionality during its technical life cycle in a sustainable and economic profitable way, withstanding changing requirements and circumstances." (Geraedts *et al.*, 2017)	*Quality:* Ability to preserve building functionality *Aim:* Sustainability, economic profitability, and changeability to future needs and conditions

Table 2. Building adaptability-related definitions

(Heidrich *et al.*, 2017; Ross, 2017), keep the building value or usefulness (Eguchi *et al.*, 2011; Geraedts *et al.*, 2017; Hudec and Rollova, 2016), and preserve the physical condition or attributes (Geraedts *et al.*, 2017; Langston, 2014b). Different studies argues the effectiveness of building adaptability as a means to contribute to the society, through smoothing the way for regenerating the built environment or bringing vitality to existing premises (Mahtab-uz-Zaman, 2011; March *et al.*, 2012; Mısırlısoy and Günçe, 2016; Philokyprou, 2014).

To indicate the embodiment of building adaptability, different studies investigated the changes that could take place in buildings over their service life; thus, captured the way in which adaptability cold be configured. Brand's (1994) concept of "shearing layers" in buildings was amongst the first attempts to capture how adaptability can be configured. The concept describes that building changes occur in physical building layers during different timespans. The "shearing layers" concept divides the building into 6 layers: site, structure, skin, services, space plan, and stuff, indicating that the first layer is the longest and the last is the shortest in terms of the rate of temporal changes. Accordingly, building layers should be independently configured; the longest should be the strongest to create building longevity, whilst the shortest should be the most flexible part, to ensure the space functionality (Brand, 1994).

As the "shearing layers" concept is oriented to the physical building composition, other design and spatial aspects are apparently overlooked. Thus, different determinants were defined later by different authors. Overall, different terms have been used by authors to articulate adaptability determinants (Manewa *et al.*, 2016), while some determinants overlap in meaning or context (Geraedts *et al.*, 2017). Table 3 illustrates 10 common determinants of building adaptability. Overall, these determinants relate to the physical and spatial attributes of buildings, and generally put forward configuration-oriented and active composition and use-oriented design solutions (Milwicz and Pasławski, 2018). Next, these determinants are briefly presented.

3.1.1 Flexibility/adjustability. Flexibility – also called adjustability – is the most common determinant of building adaptability (Geraedts *et al.*, 2017). It refers to the possibility to adjust the spatial configuration of the building through minor interventions (Douglas, 2006; Eguchi *et al.*, 2011), and potentially by users within a short period of time (Arge, 2005; Pinder *et al.*, 2017). For instance, the provision of adjustable and movable building products is an example of flexibility (Alhefnawi, 2018; Heidrich *et al.*, 2017; Pizzi *et al.*, 2012; Scuderi, 2019).

3.1.2 Generality/multifunctionality/versatility. Generality – also called multifunctionality or versatility – refers to the possibility of using the spaces in a building for different purposes without conducting any changes (Arge, 2005). The provision of a multi-purpose space (Kyrö *et al.*, 2019), as well as smart technologies and control systems (Unzurrunzaga and Branchi, 2013), are exemplary for generality.

3.1.3 Elasticity/expandability/scalability. Elasticity – also called expandability or scalability – relates to the possibility to increase the volume of the building, vertically or horizontally (Beadle *et al.*, 2008), or divide and merge building spaces (Arge, 2005). Provision of a surplus capacity in the building is an exemplary strategy for expandability (Geraedts *et al.*, 2017), while the provision of an open floor and separation of infills from supports (Capolongo *et al.*, 2016; Meng and Fu, 2017), and adjustable partitions are exemplary strategies for enabling space reconfiguration (Ross, 2017).

3.1.4 Movability/relocate-ability. Movability – also called relocate-ability – relates to the possibility to easily change the location of building assets (Heidrich *et al.*, 2017; Pinder *et al.*, 2017), or displace the building components (Alhefnawi, 2018; Beadle *et al.*, 2008). Movability can be embedded by using demountable and independent products (Eguchi *et al.*, 2011), or relocatable systems (Kyrö *et al.*, 2019). However, this determinant apparently overlaps with flexibility and is a part of it, as it considers the configurational changeability.

3.1.5 Dismantlability (dismountable/deconstruct-able)/removability. Dismantlability – also called dismountable, deconstruct-able, or removability – refers to the possibility of removing the physical objects easily and effectively (Douglas, 2006). Dismantlability can be realised by using demountable products as well as prefabricated and standardised components (Sturgis, 2017; Webb *et al.*, 1997). This determinant apparently interrelates with movability, as it considers the mobility of physical objects in buildings.

3.1.6 Convertibility/transformability. Convertibility – also called transformability – relates to the possibility to give the building a new function in light of physical, legal and economic constraints (Douglas, 2006; Remøy, 2014b). Hence, this determinant is a context-specific dimension (De Gregorio *et al.*, 2020). Other issues that could influence the building convertibility include architectural, cultural and locational aspects (Aydin, 2010; Dyson *et al.*, 2016; Remøy and Vander Voordt, 2014; Yaldiz and Asatekin, 2013). Building conversion can be facilitated by providing a central core for building services (Remøy *et al.*, 2011), modularising and opening the plan configuration, and enabling mixed-use (Raith and Estaji, 2020; Szarejko and Trocka-Leszczynska, 2007; Włodarczyk and Włodarczyk, 2015). Convertibility partially interrelates with generality in terms of providing multifunctionality, but generality refers to the spaces within the building while convertibility refers to the building as a whole.

3.1.7 Recyclability/reusability/disaggregatability. Recyclability – also called reusability or disaggregatability – relates to the possibility of facilitating material reuse and recycling (Douglas, 2006; Eguchi *et al.*, 2011), which can be achieved by using discrete products (Beadle *et al.*, 2008), as well as using standardised building components, and procuring the service of building products (Webb *et al.*, 1997).

Source (temporal order)	Determinants Flexibility/ adjustability	Generality/ multifunctionality/ versatility	Elasticity/ expandability/ scalability	Movability/ relocate-ability	Dismantlability (dismountable/ deconstruct-able)/ removability	Convertibility/ transformability	Recyclability/ reusability/ disaggregatability	Refit-ability	Accessibility/ availability	Modularity/ regularity
Arge (2005)	X	X	X							
Douglas (2006)	X		X		X	X	X			
Beadle *et al.* (2008)	X	X	X	X	X		X	X		
Eguchi *et al.* (2011)	X		X	X			X	X	X	
Saghafi and Ahmadi (2011)	X		X		X	X	X			
Estaji (2014)	X	X							X	
Sadafi *et al.* (2014)	X	X			X	X				
Hudec and Rollová (2016)	X		X	X		X	X			
Heidrich *et al.* (2017)	X	X	X	X		X		X		
Manewa *et al.* (2016)	X	X	X		X	X	X	X		X
Geraedts *et al.* (2017)	X		X		X	X				X
Orłowski *et al.* (2017)	X		X		X				X	
Pinder *et al.* (2017)	X	X	X	X		X		X		

(continued)

Table 3. Building adaptability determinants

Source (temporal order)	Determinants									
	Flexibility/ adjustability	Generality/ multifunctionality/ versatility	Elasticity/ expandability/ scalability	Movability/ relocate-ability	Dismantlability (dismountable/ deconstruct-able)/ removability	Convertibility/ transformability	Recyclability/ reusability/ disaggregatability	Refit-ability	Accessibility/ availability	Modularity/ regularity
Ross (2017)	X		X		X				X	X
Kyrö *et al.* (2019)	X	X	X							
Bettaieb and Alsabban (2021)	X	X	X	X		X				X
Frequency	16	9	14	6	8	9	6	5	4	4

Table 3.

3.1.8 Refit-ability. Refit-ability relates to the possibility to manipulate and improve the performance of components and systems (Heidrich *et al.*, 2017; Pinder *et al.*, 2017). Building refit-ability can be achieved through using dismountable products (Eguchi *et al.*, 2011), coordinating the interaction amongst systems, and providing a surplus capacity in the building design (Geraedts *et al.*, 2017).

3.1.9 Accessibility/availability. Accessibility – also called availability – relates to the capacity of accessing the building components and systems, for further reprocessing and changes (Eguchi *et al.*, 2011; Ross, 2017). This can be achieved through providing redundant spaces for technical works, using dismountable products and coordinating the interaction among technical systems (Orłowski *et al.*, 2017; Sadafi *et al.*, 2009). This determinant overlaps with refit-ability, as both consider adjusting the technical performance besides the provision of a redundancy in the technical capacity of the building.

3.1.10 Modularity/regularity. Modularity – also called regularity – refers to the potential of increasing the regularity in the building pattern (Sadafi *et al.*, 2014). Building modularity can be embodied spatially and physically (Geraedts *et al.*, 2017), through modularising the layout of spaces and services (Ladinski, 2017), as well as using unitised and prefabricated building components (Montoliu-Hernández and Rodríguez-Álvarez, 2017).

3.2 Circular economy and circularity in buildings

CE is an emerging economic and development paradigm that is aimed at realising economic prosperity and environmental quality using the principles of the R-strategies such as reduction, reuse, and recycling (Kirchherr *et al.,* 2017). CE applies the R-strategies to avoid waste generation and negative environmental impacts, through creating an entirely closed-reversible resource chain of "loops" (Sanchez and Haas, 2018). Many conceptual frameworks have been synthesised to depict CE, such as the "Butterfly Diagram" (Ellen MacArthur Foundation, 2019). The "Butterfly Diagram" model indicates that technical and biological resources should flow in a closed reversible system through closed-reversible chains, or "value cycles". Particularly, this framework indicates that all technical resources are reprocessed and restored through R-strategies or operational measures, while biological resources are cyclically regenerated in the system through returning them to nature.

Operationalising circularity in the built environment has been perceived as a crucial step to reduce resource consumption and eliminate waste generation (Geldermans *et al.*, 2019a). CE operationalisation in buildings has not only been perceived as an environmental protection action (Huuhka and Vestergaard, 2020), but also as a strategy to add value to the built asset (Zimmann *et al.*, 2016). Operationalising circularity in the built environment means that cities should be perceived and strategically operated as urban mines and buildings as material banks, meaning that building products should be processed and utilised in a closed-reversible product chain (Giorgi *et al.*, 2020). The adoption of the cradle-to-cradle concept – integration between lifecycle thinking and quality control – is important for the transition to circularity (Geldermans, 2016). In addition, a multi-level framework that coordinates the three levels, macro, meso and micro, is needed to incorporate circularity in practice (Foster *et al.*, 2020). This implies that circularity in buildings cannot be embodied only through active or passive design solutions, but rather it needs an operational interaction on all societal levels (Cottafava and Ritzen, 2021). In the tactical part, operationalising CE in the built environment is enabled by numerous actions, such as: industrial symbiosis (Ness and Xing, 2017), stakeholder collaboration (Acharya *et al.*, 2018; Valdebenito *et al.*, 2021), provision of a material reuse market (Cai and Waldmann, 2019), adoption of new business models (Acharya *et al.*, 2018; Kaya *et al.*, 2021a), utilisation of enabling technologies (Antonini *et al.*, 2020), and legislative amendments (Tserng *et al.*, 2021; Foster *et al.*, 2020).

Circularity has emerged and gained importance as a new research and sustainability paradigm in the built environment-related literature (Akhimien *et al.*, 2021; Eberhardt *et al.*, 2022).

Based on the literature review, four built environment-oriented circularity definitions were found. As shown in Table 4, all definitions indicate the capacity to fulfil the loops “closed-reversible chains” for building materials through dynamics in the building configuration and operation. However, the implied aims of the definitions slightly differ upon the context, but overall, they imply efficiently keeping the usefulness of the built asset. All definitions indicate that design and process coordination is a fundamental principle for circularity operationalisation in buildings.

Different studies linked building-related practices to CE-oriented models as an attempt to illustrate how circularity can be operationalised in buildings. For instance, building-related practices could be positioned in ReSOLVE, a framework that is intended to facilitate the transition to CE through industries (Zimmann *et al.*, 2016). Other studies have captured or contextualised research narratives of CE applications in the built environment (Abadi and Sammuneh, 2020; Akhimien *et al.*, 2021; Eberhardt *et al.*, 2022). Based on the integrative literature analysis, Table 5 summarises 10 common circularity determinants in buildings, showing the variety of terms that scholars and practitioners use.

As shown in Table 5, most of the circularity determinants interrelate with the determinants of building adaptability. This indicates that adaptability in buildings is fundamental for operationalising CE in buildings, agreeing with Geldermans’s (2016) argument, indicating that adaptability is an effective means that smoothens the way for the closed-reversible chain. Next, the identified circularity determinants are briefly presented.

3.2.1 Flexibility/adaptability. Flexibility is a key determinant of building circularity, as it supports the dynamics that are associated with the circularity processes (Geldermans *et al.*, 2019b). However, many authors used both terms: adaptability and flexibility. This kind of semantic permutations is possible, as Pinder *et al.* (2017) indicated that there is a misconception in the distinction between the adaptability concept and flexibility as an adaptability component. To incorporate circularity in the built environment, flexibility should be incorporated in the design of new buildings (Geldermans, 2016), as well as in the adaptation of existing buildings (Kaya *et al.*, 2021b). According to the literature, flexible strategies for circular buildings are similar to those mentioned in the building adaptability-

Term	Definition	Implied quality and aim
Circular building (process)	“The dynamic total of associated processes, materials and stakeholders that accommodate circular flows of building materials and products at optimal rates and utilities.” (Geldermans *et al.*, 2019b)	*Quality:* Circularity of material flow *Aim:* Optimal utility “efficient usefulness”
Circular building (object)	“Is the manifestation of this in a temporary configuration.” (Geldermans *et al.*, 2019b) Note: this definition refers to the context of the previous definition	*Quality:* Circularity of material flow *Aim:* Optimal utility “efficient usefulness”
Circular economy in buildings	“A strategic programming of a building to easily change its configuration for longevity and potentially be susceptible to the loop of reduce, reuse and recycle for resource efficiency.” (Akhimien *et al.*, 2021)	*Quality:* Resource reprocessing (restoration) and longevity *Aim:* Configuration changeability
Circular built environment	“Circular built environment is that “embeds the principles of a circular economy across all its functions, establishing an urban system that is regenerative, accessible and abundant by design.” (Acharya *et al.*, 2018)	*Quality:* Circularity of the economy “system of closed-resource loop” *Aim:* Regenerative and available built environment

Table 4.
Building circularity-related definitions

Table 5. Building circularity determinants

Source (temporal order)	Determinants: Flexibility/ adaptability	Serviceability/ maintainability (operation)	Materiality	Dismantlability/ disassembly/ (dismountable/ deconstruct- able) (Material independency)	Exchangeability/ re-distribution	Recyclability/ reusability reversibility (looping)	Modularity/ regularity/ standardisation	Re-generativity (material/ energy)/ renewability/ recovery	Virtuality// dematerialisation	Shareability/ multi- usability
Geldermans (2016)	X	X	X	X		X	X	X		
Zimmann *et al.* (2016)	X	X	X	X	X	X		X	X	X
Gravagnuolo *et al.* (2017)	X	X	X		X	X		X	X	X
Ness and Xing (2017)	X	X	X	X	X	X	X	X	X	X
Acharya *et al.* (2018)			X			X		X		
Geldermans *et al.* (2019b)	X	X	X	X	X	X	X	X		
Huovila *et al.* (2019)	X		X	X		X	X	X		
Iyer-Raniga (2019)	X	X	X	X	X	X	X	X	X	X
Abadi and Sammuneh (2020)		X		X		X	X			
Antonini *et al.* (2020)	X		X	X		X		X		
Eberhardt *et al.* (2022)	X		X	X		X	X	X		X
Kanters (2020)	X		X	X		X				
Akhimien *et al.* (2021)	X	X	X	X	X	X	X			
Cottafava and Ritzenb (2021)	X	X	X	X		X		X		
Frequency	12	10	13	12	6	14	8	11	4	5

related literature (Eberhardt *et al.*, 2022), including design for material independency (shearing layers) and utilisation of moveable components (Geldermans *et al.*, 2019c).

3.2.2 Serviceability/maintainability (operation). Serviceability – also called maintainability – concerns the possibility to operate the built assets, to prolong their lifespan, maximise their utilisation, and thus, reduce the need for consuming energy (Abadi and Sammuneh, 2020) or new materials (Akhimien *et al.*, 2021). Serviceability can be operationalised through repairing and preserving the building assets (Huuhka and Vestergaard, 2020), as well as applying an effective maintenance regime (Iyer-Raniga, 2019; Tserng *et al.*, 2021).

3.2.3 Materiality. As material circularity is a fundamental and rooted principle in the CE paradigm, materiality concerns the entire chain of products in the built environment (Giorgi *et al.*, 2020). In this context, materiality is the determinant that expresses the possibility to facilitate entire processes of selecting, using, managing, storing and reusing/recycling building materials and products (Akhimien *et al.*, 2021; Kanters, 2020). Materiality can be operationalised through: using secondary products instead of new products – to avoid the use of primary resources and raw materials (Foster, 2020), properly storing and managing the materials (Iyer-Raniga, 2019), applying material passports in new and existing buildings – a documentation of specifications of the material used (Huovila *et al.*, 2019; Tserng *et al.*, 2021), and contribute to the construction and waste (C&W) management industry (Cai and Waldmann, 2019; Abadi and Sammuneh, 2020).

3.2.4 Dismantlability/disassembly/material independency. Dismantlability of building components is amongst the key adaptability-related determinants for operationalising circularity in buildings, as it is a means to keep material in the chain (Antonini *et al.*, 2020; Geldermans, 2016). Dismantlability can be achieved through using dismountable products (Kanters, 2020) and standardising the building design and its systems (Akhimien *et al.*, 2021). However, dismantlability in existing buildings could be low, because the majority of them were built using low-dismantlability construction techniques (Cottafava and Ritzen, 2021). In this regard, selective dismantling is a possible strategy (Cai and Waldmann, 2019; Sanchez and Haas, 2018). Selective dismantling is a systematic process of deconstructing and removing building components, part by part, to avoid building collapse or deterioration (Bertino *et al.*, 2021).

3.2.5 Exchangeability/re-distribute. Exchangeability is an operation-oriented determinant, as it refers to the possibility of coordinating the product flow in case of replacement or return. This determinant contributes to keep the physical asset in the closed-reversible chain, to avoid sending building components back to landfills, while enabling asset replacement with more energy-efficient alternatives (Zimmann *et al.*, 2016). This can be achieved in different ways, including: providing a user-centred design – e.g. system per user (Geldermans *et al.*, 2019b, c), procuring the service of building products – e.g. performance-based servicing of asset – instead of ownership (Foster, 2020), replacing existing systems with efficient technologies (Iyer-Raniga, 2019). Operational lease contracts are new business models that could facilitate the exchangeability of building material and components (Ploeger *et al.*, 2019).

3.2.6 Recyclability/reusability reversibility (looping). Recyclability – also called reusability, reversibility or looping of materials – is a key to keep all the building materials and products in a reversible closed-reversible chain through restoring or reprocessing them (Zimmann *et al.*, 2016). In building design, recyclability can be embodied by using second-hand materials and reusable products (Akhimien *et al.*, 2021; Eberhardt *et al.*, 2022; Geldermans, 2016). For buildings in-use or that are approaching their end of life, recyclability can be operationalised through reusing and recycling material as well as managing C&D (Abadi and Sammuneh, 2020; Foster, 2020; Valitutti and Perricone, 2019). For all buildings, new, in-use or to be demolished, applying material passports is an effective strategy to realise the closed-reversible material loop (Tserng *et al.*, 2021). To some extent, the recyclability determinant overlaps with "materiality", and seems to be an inherent element in the building materiality.

3.2.7 Modularity/regularity/standardisation. Modularity – also called regularity or standardisation of design – relates to building adaptability and is often mentioned in the building-circularity-related literature (Akhimien *et al.*, 2021). This is justifiable, as circularity operationalisation in buildings entails an appropriate level of standardisation (Geldermans, 2016). However, the literature indicates that the dimensions of building components need to be configured in a modular pattern and a standardised geometry (Huovila *et al.*, 2019), to facilitate their reuse in other projects (Eberhardt *et al.*, 2022). Prefabrication of components enables for controlling their modularity and quality (Tserng *et al.*, 2021).

3.2.8 Re-generativity (material/energy)/renewability/recovery. Re-generativity of material and energy – also called renewability or recovery – relates to the possibility to regenerate resources, either material or energy, in buildings to safeguard the ecosystem (Acharya *et al.*, 2018; Girard and Vecco, 2021). Re-generativity can be achieved in numerous ways, including the provision of: regenerative design (Geldermans *et al.*, 2019a), renewable energy systems (Foster and Kreinin, 2020; Sivo *et al.*, 2019), heat storage systems (Dane *et al.*, 2019; Roders *et al.*, 2013), and natural ventilation and lighting (Zimmann *et al.*, 2016).

3.2.9 Virtuality/dematerialisation. Virtuality – also called dematerialisation – relates to the possibility to reduce the extraction of new material, through digitising and virtualising the processes and physical services in buildings (Zimmann *et al.*, 2016). The aim is to reduce the CO_2 emissions that are produced by the embodied energy in the physical asset and operations (Ness and Xing, 2017). Virtuality can be operationalised through adopting smart technologies in the building operation and maintenance (Iyer-Raniga, 2019), besides transferring the paper-based operations into online applications (Gravagnuolo *et al.*, 2017).

3.2.10 Shareability/multi-usability. Shareability – also called multi-usability – expresses the possibility of optimally sharing and diversifying building assets. Shareability provides an indication about the utility and efficiency of the asset use (Iyer-Raniga, 2019), and can be achieved by providing: on-demand space (Acharya *et al.*, 2018), multi-purpose space, and shared facilities (Zimmann *et al.*, 2016). Shareability in buildings has been perceived as a strategy that can prolong the life of buildings (Gravagnuolo *et al.*, 2017). Shareability apparently overlaps with the second adaptability determinant “generality”, as both indicate the ability of multiple uses of the assets.

3.3 Circularity–adaptability interrelationships and contrasts

To summarise, building adaptability indicates the capacity to accommodate change and maintain functionality in buildings in light of changing contextual demands or dynamics. Building adaptability definitions indicate: facilitating physical modification, keeping usefulness of buildings, and preserving physical building attributes (Table 2). Adaptability can be embodied through passive and active solutions that mainly consider physical attributes and spatial configuration of buildings (Table 3). Some determinants overlap with each other, as argued by Geraedts *et al.* (2017) and Manewa *et al.* (2016).

Circularity is still an emerging concept in the built environment. However, building circularity definitions indicate the quality of realising closed-reversible chains – loops – in the built environment through dynamics in the building configuration and operation. Circularity definitions indicate the aim of efficiently keeping the usefulness of the assets (Table 4). As building circularity requires dynamics in the configuration of the physical asset, it relies on half of the adaptability determinants that are related to the physical and spatial attributes (Table 5). Figure 3 semantically maps the five interrelated determinants of building adaptability and circularity. Figure 3 reveals the vital role of building adaptability in facilitating the reversible chain of the technical resources, which is in line with the argument of Geldermans (2016). However, circularity is operation-driven and is aimed at creating a

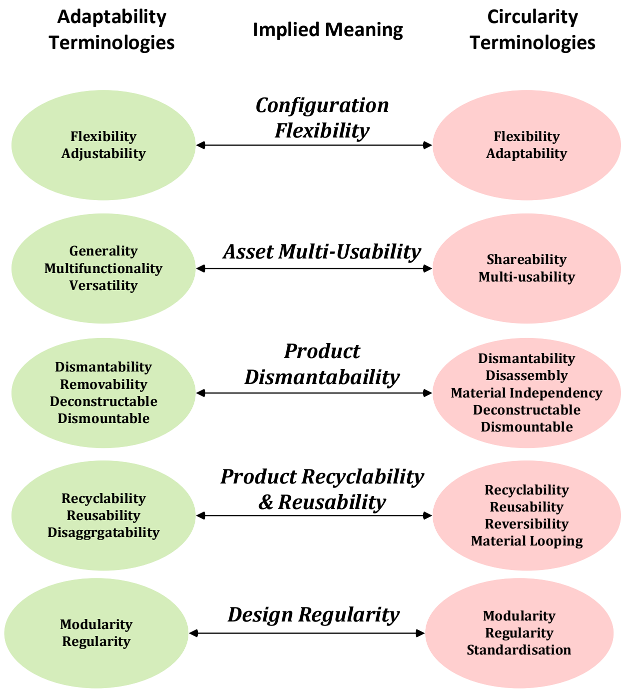

Figure 3.
Semantic mapping of the 5 interrelated determinants between building adaptability and circularity

well-controlled and closed-reversible product chain, meaning that it relies on operational interventions that could coordinate the supply, use and reversible flow of assets.

Figure 4 presents the interrelationship between circularity and adaptability in buildings, with directly or partially overlapping determinants. For instance, refit-ability and accessibility/availability overlap, as both refer to the technical ability to provide further upgrade to the performance (Heidrich *et al.*, 2017; Ross, 2017). In addition, movability is an

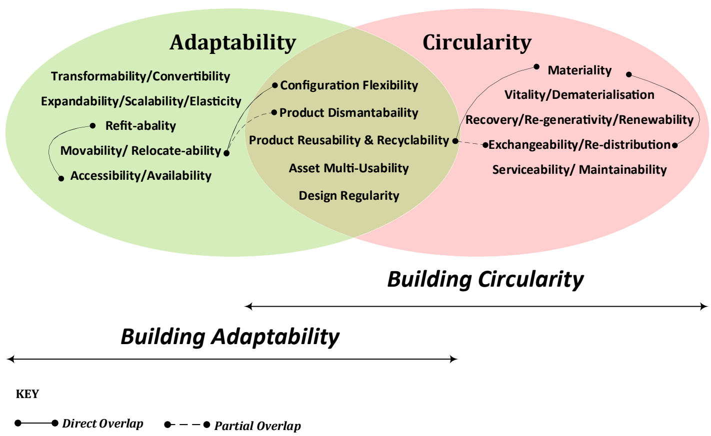

Figure 4.
Circularity–adaptability interrelationship in buildings

inherent aspect in flexibility, as providing a flexible space requires providing movable and demountable products (Geldermans *et al.*, 2019b; Scuderi, 2019). In building circularity, the reusability and recyclability of building products is a prerequisite aspect that is rooted in materiality (Akhimien *et al.*, 2021), where materiality also comprises the reversible chain that facilitates product redistribution (Antonini *et al.*, 2020; Cai and Waldmann, 2019).

To recap, both adaptability and circularity consider the ability to enhance dynamic building use. Adaptability considers this capacity from the perspective of building changeability and functionality. Circularity considers it from the view of how to fulfil resource efficiency and reversibility within a closed-reversible value chain. Circularity operationalisation in buildings immediately relies on adaptability-driven solutions, besides operational measures. Overall, both concepts share the aim of keeping the usefulness of buildings.

3.4 Circular building adaptability

Based on the analysis, the following definition was formulated: *Circular building adaptability* is the capacity to contextually and physically alter the built environment and sustain its usefulness, while keeping the building asset in a closed-reversible value chain.

Prefixes were added to the determinants of circular building adaptability to clearly indicate the embodied characteristics. Hence, circular building adaptability can be defined by 10 determinants (Figure 5), namely: the configuration flexibility, product dismantlability, asset multi-usability, design regularity, functional convertibility, material reversibility, building maintainability, resource recovery, volume scalability, and asset refit-ability.

Next, brief descriptions of the circular building adaptability determinants and strategies are presented.

3.4.1 Configuration flexibility. Configuration flexibility is the possibility to reconfigure the space layout without neither using external resources nor generating waste (Eberhardt *et al.*, 2022). This can be achieved by using demountable and movable components (Geldermans *et al.*, 2019c).

3.4.2 Product dismantlability. Product dismantlability is the possibility to demount building components without causing damage or waste, to facilitate their use within the building or in another building (Bertino *et al.*, 2021). The use of demountable products and design standardisation are proactive strategies for designing dismantlable buildings (Geldermans, 2016). Selective dismantling is a possible strategy for dismantlability incorporation while adapting existing buildings (Sanchez and Haas, 2018).

3.4.3 Asset multi-usability. Asset multi-usability is the possibility to create multiplicity in the use of building assets, to maximise their efficiency (Zimmann *et al.*, 2016). This can be achieved through the provision and management of multi-purpose spaces (Acharya *et al.*, 2018), and shared facilities (Foster, 2020).

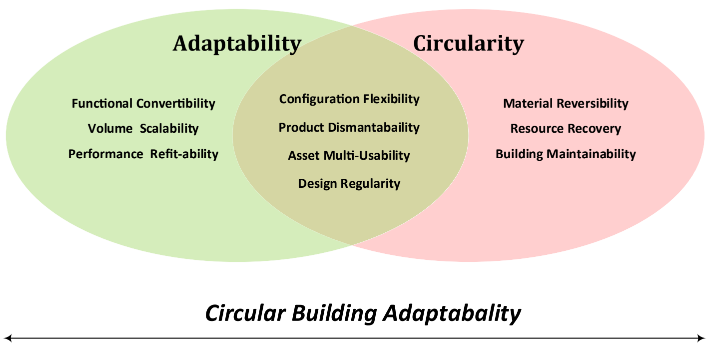

Figure 5.
Determinants of circular building adaptability

3.4.4 Design regularity. Design regularity is the possibility to provide a regular pattern in the spatial configuration and physical composition of buildings (Sadafi *et al.*, 2014), to facilitate the possibility of reusing or remanufacturing assets (Eberhardt *et al.*, 2022). This can be achieved through providing modular layout and standardised components (Tserng *et al.*, 2021).

3.4.5 Functional convertibility. Functional convertibility is the possibility to refunction the building or part of it (Heidrich *et al.*, 2017), while keeping its value and prolonging its lifespan (Valitutti and Perricone, 2019). This can be achieved by providing: a modular and mixed-use design (Iyer-Raniga, 2019), and a central core for the building services (Remøy *et al.*, 2011).

3.4.6 Material reversibility. Material reversibility is the possibility to provide, use and reuse building material as efficient as possible in a reversible value chain (Akhimien *et al.*, 2021). This can be achieved by using secondary material, applying material passports, and sending-back discarded material to the C&W industry (Abadi and Sammuneh, 2020).

3.4.7 Building maintainability. Building maintainability is the possibility to prolong the usefulness of the building and sustain its performance (Abadi and Sammuneh, 2020). This can be achieved by using smart technologies in the operation (Iyer-Raniga, 2019), conducting proactive maintenance (Gravagnuolo *et al.*, 2017), and procuring the service of building components (Foster, 2020).

3.4.8 Resource recovery. Resource recovery is the possibility to regenerate the resources consumed in the building, to reduce the use of new material and energy (Acharya *et al.*, 2018). This can be achieved by using renewable energy techniques and facilitating the use of natural ventilation and lighting (Zimmann *et al.*, 2016).

3.4.9 Volume scalability. Volume scalability is the possibility to increase or reduce the size of the building or its spaces according to user or organisational demand – to avoid spatial shortage and redundancy (Beadle *et al.*, 2008), while eliminating waste generation (Zimmann *et al.*, 2016). This can be achieved by providing surplus capacity in the design – through over dimensioning – to allow for upgrade (Geldermans, 2016), while using adjustable and dismantlable components for allowing reducing the capacity of systems or spaces (Huovila *et al.*, 2019). Procurement of building products and components could be a possible strategy to enable the implementation of such changes (Ploeger *et al.*, 2019).

3.4.10 Asset refit-ability. Asset refit-ability is the possibility of providing state-of-the-art products and technologies in the building (Heidrich *et al.*, 2017), while eliminating waste generation or over investment (Zimmann *et al.*, 2016). This can be achieved by procuring the service of building asset – including components, products and systems (Ploeger *et al.*, 2019).

3.5 Summary and discussion

Building adaptation is a wide term that is used to express the alteration works that are implemented in existing premises to change their performance, condition, or function in a response to building-related, internal or external triggers. The possibility to adapt buildings is generally known as "building adaptability", and could apply to in-use or across-use adaptations and ranging from minor to major changes. Building adaptability could be defined by 10 interrelated determinants referring to the physical composition and configuration of buildings. Building adaptability can be embodied proactively or reactively by numerous passive and active design strategies.

Circularity in buildings has emerged as a new sustainability paradigm that is aimed at realising closed and reversible resource chains, using the principles of the R-strategies. The operationalisation of circularity in buildings relies on half of the adaptability determinants that could facilitate the reversibility of the assets in the chain, besides other process-oriented determinants. This implies that building circularity includes passive, active and operational strategies. Exemplary strategies for these three types of strategies are:

standardising the building layout, providing moveable building components, and procuring the service of building systems instead of ownership, respectively.

According to the integrative analysis, both qualities – adaptability and circularity – share the aim of prolonging the asset usefulness and require dynamics in the building configuration and composition. Adaptability perceives that prerequisite from the perspective of facilitating the building alteration, while circularity perceives it from the perspective of achieving the reversibility and efficient flow of building assets within the closed-reversible value chain. Therefore, the integrated synergy between both qualities could facilitate the resilience of buildings to meet future demands while adding value to the built assets without generating waste.

Based on the integrative analysis, circular building adaptability can be defined by 10 determinants, namely: configuration flexibility, product dismantlability, asset multi-usability, design regularity, functional convertibility, material reversibility, building maintainability, resource recovery, volume scalability, and asset refit-ability. The integrative analysis points out that the operationalisation of circular building adaptability is not only dependent on passive and active design solutions, but also on process-oriented interventions.

4. Conclusion and recommendations

Adaptability is an inherent quality in the operationalisation of building circularity, as it can physically facilitate the reversibility of materials in the reversible value chain. However, its positioning in circularity models could overlook some aspects that contribute to long-lasting building functionality. Accordingly, this paper focused on reconceptualising building adaptability to incorporate circularity for the resource efficiency while contributing to the long-lasting building functionality.

An integrative literature review, using systematic search, was conducted. Definitions of circularity and adaptability were critically reviewed, to define the implied qualities and aims in both concepts. Two matrices were developed to identify the determinants of circularity and adaptability. Accordingly, definition, determinants and strategies of circular building adaptability were defined and synthesised. The following was concluded:

(1) Adaptability and circularity consider the ability to cope with dynamics of the built environment. Adaptability considers building changeability and functionality in light of contextual dynamic, while circularity considers resource efficiency and reversibility within a closed-reversible value chain – loops.

(2) Overall, both concepts share the aim of keeping the usefulness of buildings. Adaptability determinants are related to passive and active design solutions aimed at facilitating the physical and spatial dynamics. Circularity operationalisation in buildings relies on half of the adaptability determinants besides process-oriented interventions to control the supply, use and reversible chain of resources.

(3) Circular building adaptability can be operationalised through applying 10 circularity- and adaptability-related determinants, comprising design- and operation-oriented strategies, namely: configuration flexibility, product dismantlability, asset multi-usability, design regularity, functional convertibility, material reversibility, building maintainability, resource recovery, volume scalability, and asset refit-ability.

(4) This study concludes that considering and implementing the circularity and adaptability determinants, proactively or reactively, would simultaneously create numerous benefits, namely: embodying the adaptive responsiveness in buildings to withstand contextual dynamics, creating value for the building assets, and reducing waste generation and environmental degradation resulting from buildings.

The outcomes of this research are theoretical and limited to a reconceptualisation of interrelated concepts based on an integrative literature analysis. Thus, the recommendations of this paper are threefold. First, development of a practical and evidence-based framework for circular building adaptability would be needed to provide an empirically validated methodological tool. Such a framework would be useful for practitioners for proactively or reactively operationalise circular building adaptability. Second, operational research is needed to test the applicability and facilitate the operationalisation of circular building adaptability in a pragmatic way. This kind of research would lay the ground for regulating and operationalising the development of circular and adaptable buildings. Within the context of operationalising the proposed concept and framework, the legislative dimension should be inherent and seriously considered, as laws and regulations can play a vital role in this process.

References

Abadi, M. and Sammuneh, M.A. (2020), "Integrating circular economy and constructability research: an initial development of a lifecycle 'circularity' assessment framework and indicators", *Proceedings 36th Annual ARCOM Conference*, UK, 7-8 September 2020, Association of Researchers in Construction Management, ARCOM, Leeds, pp. 516-525.

Acharya, D., Boyd, R. and Finch, O. (2018), *From Principles to Practices: First Steps towards a Circular Built Environment*, ARUP and Ellen MacArthur Foundation, London.

Akhimien, N.G., Latif, E. and Hou, S.S. (2021), "Application of circular economy principles in buildings: a systematic review", *Journal of Building Engineering*, Vol. 38, p. 102041.

Alhefnawi, M.A.M. (2018), "Sustainability in deconstructivism: a flexibility approach", *Arabian Journal for Science and Engineering*, Vol. 43 No. 10, pp. 5091-5099.

Antonini, E., Boeri, A., Lauria, M. and Giglio, F. (2020), "Reversibility and durability as potential indicators for circular building technologies", *Sustainability*, Vol. 12 No. 18, p. 7659.

Arge, K. (2005), "Adaptable office buildings: theory and practice", *Facilities*, Vol. 23 Nos 3-4, pp. 119-127.

Aydin, D. (2010), "Socio-cultural sustainability and an assessing model for reuse adaptation", *Proceedings of Central Europe towards Sustainable Building 2010 (CESB 2010): From Theory to Practice - Assessment Methods*, Prague, Czech Republic.

Beadle, K., Gibb, A., Austin, S., Fuster, A. and Madden, P. (2008), "Adaptable futures: sustainable aspects of adaptable buildings", in Dainty, A. (Ed.), *Procs 24th Annual ARCOM Conference*, Cardiff, UK, 1-3 September 2008, Association of Researchers in Construction Management, pp. 1125-1134.

Bertino, G., Kisser, J., Zeilinger, J., Langergraber, G., Fischer, T. and Österreicher, D. (2021), "Fundamentals of building deconstruction as a circular economy strategy for the reuse of construction materials", *Applied Sciences*, Vol. 11 No. 3, p. 939.

Bettaieb, D.M. and Alsabban, R. (2021), "Emerging living styles post-COVID-19: housing flexibility as a fundamental requirement for apartments in Jeddah", *Archnet-IJAR*, Vol. 15 No. 1, pp. 28-50.

Brand, S. (1994), *How Buildings Learn: What Happens after They're Built*, Penguin Books, New York, NY.

Bullen, P. (2007), "Adaptive reuse and sustainability of commercial buildings", *Facilities*, Vol. 25 Nos 1-2, pp. 20-31.

Cai, G. and Waldmann, D. (2019), "A material and component bank to facilitate material recycling and component reuse for a sustainable construction: concept and preliminary study", *Clean Technologies and Environmental Policy*, Vol. 21 No. 10, pp. 2015-2032.

Capolongo, S., Buffoli, M., Nachiero, D., Tognolo, C., Zanchi, E. and Gola, M. (2016), "Open building and flexibility in healthcare: strategies for shaping spaces for social aspects", *Ann Ist Super Sanità*, Vol. 52 No. 1, pp. 63-96.

Cerreta, M., Elefante, A. and Rocca, L.L. (2020), "A creative living lab for the adaptive reuse of the Morticelli Church: the SSMOLL project", *Sustainability*, Vol. 12 No. 24, p. 10561.

Conejos, S., Langston, C. and Smith, J. (2014), "Designing for better building adaptability: a comparison of adapt STAR and ARP models", *Habitat International*, Vol. 41, pp. 85-91.

Cottafava, D. and Ritzen, M. (2021), "Circularity indicator for residential buildings: addressing the gap between embodied impacts and design aspects", *Resources, Conservation and Recycling*, Vol. 164, p. 105120.

Dane, G.Z., Houpert, C. and Derakhshan, S. (2019), *Guidelines for Sustainable Adaptive Reuse for CH*, Regeneration and Optimization of Cultural heritage in Creative and Knowledge Cities, ROCK, Bologna, Italy.

De Gregorio, S., De Vita, M., De Berardinis, P., Palmero, L. and Risdonne, A. (2020), "Designing the sustainable adaptive reuse of industrial heritage to enhance the local context", *Sustainability*, Vol. 12 No. 21, p. 9059.

Douglas, J. (2006), *Building Adaption*, 2nd ed., Butterworth-Heinemann, Oxford.

Dyson, K., Matthews, J. and Love, P.E.D. (2016), "Critical success factors of adapting heritage buildings: an exploratory study", *Built Environment Project and Asset Management*, Vol. 6 No. 1, pp. 44-57.

Eberhardt, L.C.M., Birkved, M. and Birgisdottir, H. (2022), "Building design and construction strategies for a circular economy", *Architectural Engineering and Design Management*, Vol. 18 No. 2, pp. 93-113, doi: 10.1080/17452007.2020.1781588.

Eguchi, T., Schmidt, R., Dainty, A., Austin, S. and Gibb, A. (2011), "The cultivation of adaptability in Japan", *Open House International*, Vol. 36 No. 1, pp. 73-85.

Ellen MacArthur Foundation (2019), *Circular Economy Diagram*, Ellen MacArthur Foundation, available at: https://ellenmacarthurfoundation.org/circular-economy-diagram (accessed 21 September 2021).

Estaji, H. (2014), "Flexible spatial configuration in traditional houses, the case of Sabzevar", *International Journal of Contemporary Architecture 'The New ARCH'*, Vol. 1 No. 1, pp. 26-35.

Foster, G. (2020), "Circular economy strategies for adaptive reuse of cultural heritage buildings to reduce environmental impacts", *Resources, Conservation and Recycling*, Vol. 152, p. 104507.

Foster, G. and Kreinin, H. (2020), "A review of environmental impact indicators of cultural heritage buildings: a circular economy perspective", *Environmental Research Letters*, Vol. 15 No. 4, 043003.

Foster, G., Kreinin, H. and Sagl, S. (2020), "The future of circular environmental impact indicators for cultural heritage buildings in Europe", *Environmental Sciences Europe*, Vol. 32, p. 141.

Geldermans, R.G. (2016), Design for change and circularity–Accommodating circular material and product flows in construction, *Energy Procedia*, Vol. 96, pp. 301-311.

Geldermans, B., Tenpierik, M. and Luscuere, P. (2019a), "Human health and well-being in relation to circular and flexible infill design: assessment criteria on the operational level", *Sustainability*, Vol. 11 No. 7, p. 1984.

Geldermans, B., Tenpierik, M. and Luscuere, P. (2019b), "Circular and flexible infill concepts: integration of the residential user perspective", *Sustainability*, Vol. 11 No. 1, p. 261.

Geldermans, B., Tenpierik, M. and Luscuere, P. (2019c), "Circular and flexible indoor partitioning – a design conceptualization and value chains", *Buildings*, Vol. 9 No. 9, p. 194.

Geraedts, R., Olsson, N.O.E. and Hansen, G.K. (2017), "Adaptability", in Jensen, P.A. and van der Voordt, T. (Eds), *Facilities Management and Corporate Real Estate Management as Value Drivers: How to Manage and Measure Adding Value*, Routledge, Oxon, pp. 159-183.

Giorgi, S., Lavagna, M. and Campioli, A. (2020), "Circular economy and regeneration of building stock: policy improvements, stakeholder networking and life cycle tools", in Torre, S.D., Cattaneo, S., Lenzi, C. and Zanelli, A. (Eds), *Regeneration of the Built Environment from a Circular Economy Perspective*, Springer, Cham, Switzerland, pp. 291-301.

Girard, L.F. (2020), "The circular economy in transforming a died heritage site into a living ecosystem, to be managed as a complex adaptive organism", *Aestimum*, Vol. 77, pp. 145-180.

Girard, L.F. and Vecco, M. (2021), “The ‘intrinsic value’ of cultural heritage as driver for circular human-centered adaptive reuse”, *Sustainability*, Vol. 13 No. 6, p. 3231.

Gravagnuolo, A., Girard, L.F., Ost, C. and Saleh, R. (2017), “Evaluation criteria for a circular adaptive reuse of cultural heritage”, *BDC. Bollettino Del Centro Calza Bini*, Vol. 17 No. 2, pp. 185-216.

Heidrich, O., Kamara, J., Maltese, S., Cecconi, F.R. and Dejaco, M.C. (2017), “A critical review of the developments in building adaptability”, *International Journal of Building Pathology and Adaptation*, Vol. 35 No. 4, pp. 284-303.

Hudec, M. and Rollová, L. (2016), “Adaptability in the architecture of sport facilities”, *Procedia Engineering*, Vol. 161, pp. 1393-1397.

Huovila, P., Iyer-Raniga, U. and Maity, S. (2019), “Circular economy in the built environment: supporting emerging concepts”, *IOP Conference Series: Earth and Environmental Science, Volume 297, SBE 19 - Emerging Concepts for Sustainable Built Environment*, Helsinki, Finland, 22-24 May 2019.

Huuhka, S. and Saarimaa, S. (2018), “Adaptability of mass housing: size modification of flats as a response to segregation”, *International Journal of Building Pathology and Adaptation*, Vol. 36 No. 4, pp. 408-426.

Huuhka, S. and Vestergaard, I. (2020), “Building conservation and the circular economy: a theoretical consideration”, *Journal of Cultural Heritage Management and Sustainable Development*, Vol. 10 No. 1, pp. 29-40.

Iyer-Raniga, U. (2019), “Using the ReSOLVE framework for circularity in the building and construction industry in emerging markets”, *IOP Conference Series: Earth and Environmental Science, Volume 294, Sustainable Built Environment Conference 2019 Tokyo (SBE19Tokyo) Built Environment in an era of climate change: how can cities and buildings adapt?*, Japan, 6-7 August 2019, University of Tokyo.

Kamara, J.M., Heidrich, O., Tafaro, V.E., Maltese, S., Dejaco, M.C. and Re Cecconi, F. (2020), “Change factors and the adaptability of buildings”, *Sustainability*, Vol. 12 No. 16, p. 6585.

Kanters, J. (2020), “Circular building design: an analysis of barriers and drivers for a circular building sector”, *Buildings*, Vol. 10 No. 4, p. 77.

Kaya, D., Pintossi, N. and Dane, G. (2021a), “An Empirical analysis of driving factors and policy enablers of heritage adaptive reuse within the circular economy framework”, *Sustainability*, Vol. 13 No. 5, p. 2479.

Kaya, D.I., Dane, G., Pintossia, N. and Kootc, C.A.M. (2021b), “Subjective circularity performance analysis of adaptive heritage reuse practices in The Netherlands”, *Sustainable Cities and Society*, Vol. 70, p. 102869.

Kirchherr, J., Reike, D. and Hekkert, M. (2017), “Conceptualizing the circular economy: an analysis of 114 definition”, *Resources, Conservation and Recycling*, Vol. 127, pp. 221-232.

Kyrö, R., Peltokorpi, A. and Luoma-Halkola, L. (2019), “Connecting adaptability strategies to building system lifecycles in hospital retrofits”, *Engineering, Construction and Architectural Management*, Vol. 26 No. 4, pp. 633-647.

Ladinski, V. (2017), “Designing for adaptability: the gateshead civic centre”, *International Journal of Building Pathology and Adaptation*, Vol. 35 No. 4, pp. 380-396.

Langston, C. (2014a), “Designing for future adaptive reuse”, in Wilkinson, S.J., Remøy, H. and Langston, C. (Eds), *Sustainable Building Adaptation: Innovations in Decision-Making*, John Wiley & Sons, Chichester, West Sussex, Chapter 12, pp. 250-272.

Langston, C. (2014b), “Identifying adaptive reuse potential”, in Wilkinson, S.J., Remøy, H. and Langston, C. (Eds), *Sustainable Building Adaptation: Innovations in Decision-Making*, John Wiley & Sons, Chichester, West Sussex, Chapter 9, pp. 187-206.

Langston, C., Wong, F.K.W., Hui, E.C.M. and Shen, L.Y. (2008), “Strategic assessment of building adaptive reuse opportunities in Hong Kong”, *Building and Environment*, Vol. 43 No. 10, pp. 1709-1718.

Mahtab-uz-Zaman, Q.M. (2011), "Adaptive re-use and urban regeneration in Dhaka - a theoretical exploration", *Open House International*, Vol. 36 No. 2, pp. 45-58.

Manewa, A., Siriwardena, M., Ross, A. and Madanayake, U. (2016), "Adaptable buildings for sustainable built environment", *Built Environment Project and Asset Management*, Vol. 6 No. 2, pp. 139-158.

March, A., Rijal, Y., Wilkinson, S. and Özgür, E.F. (2012), "Measuring building adaptability and street vitality", *Planning Practice and Research*, Vol. 27 No. 5, pp. 531-552.

Meng, X. and Fu, B. (2017), "A study on residential area's adaptability design for the aged in China based on open building theory", *Civil, Architecture and Environmental Engineering - Proceedings of the International Conference ICCAE, Taipei, Taiwan, November 4-6, 2016*, CRC Press, Taylor & Francis Group, London, pp. 501-505.

Milwicz, R. and Pasławski, J. (2018), "Adaptability in buildings – housing context – literature review", *3rd International Workshop on Flexibility in Sustainable Construction (ORSDCE 2018), MATEC Web of Conferences 222*, Poznan, Poland, Vol. 01011.

Mısırlısoy, D. and Günçe, K. (2016), "A critical look to the adaptive reuse of traditional urban houses in the Walled City of Nicosia", *Journal of Architectural Conservation*, Vol. 22 No. 2, pp. 149-166.

Moher, D., Shamseer, L., Clarke, M., Ghersi, D., Liberati, A., Petticrew, M., Shekelle, P. and Asewart, L.A. (2015), "Preferred reporting items for systematic review and meta-analysis protocols (PRISMA-P) 2015 statement", *Systematic Reviews*, Vol. 4 No. 1, p. 1.

Montoliu-Hernández, J. and Rodríguez-Álvarez, J. (2017), "Renascent urbanism: reviving derelict structures in the wake of the crisis", *Architectural Science Review*, Vol. 60 No. 4, pp. 286-298.

Ness, D. and Xing, K. (2017), "Toward a resource-efficient built environment: a literature review and conceptual model", *Journal of Industrial Ecology*, Vol. 21 No. 3, pp. 572-592.

Orłowski, Z., Radziejowska, A. and Orłowski, M. (2017), "Characteristic of Adaptability - one of basic categories of the social aspect of sustainable housing construction", *IOP Conference Series: Materials Science and Engineering, 251, 3rd International Conference on Innovative Materials, Structures and Technologies (IMST 2017)*, Riga, Latvia, 27-29 September 2017, p. 012069.

Patel, H. and Tutt, D. (2018), "This building is never complete': studying adaptations of a library building over time", in Sage, D.J. and Vitry, C. (Eds), *Societies under Construction: Geographies, Sociologies and Histories of Building*, Palgrave Macmillan, London, pp. 51-85.

Perolini, P.S. (2013), "Adaptation and the constructed environment", *Proceedings of Central Europe towards Sustainable Building 2013 (CESB 2013): Sustainable Building and Refurbishment for Next Generations - Urban Planning*, Prague, Czech Republic.

Philokyprou, M. (2014), "Adaptation of new university uses in old buildings: the case of rehabilitation of listed buildings in Limassol Cyprus for University purposes", *International Journal of Architectural Heritage*, Vol. 8 No. 5, pp. 758-782.

Pinder, J.A., Schmidt, R., Austin, S.A., Gibb, A. and Saker, J. (2017), "What is meant by adaptability in buildings?", *Facilities*, Vol. 35 Nos 1-2, pp. 2-20.

Pizzi, E., Iannaccone, G. and Ruttico, P. (2012), "Innovative strategies for adaptive buildings in large cities", *International Journal for Housing Science*, Vol. 36 No. 2, pp. 99-107.

Ploeger, H., Prins, M., Straub, A. and Van den Brink, R. (2019), "Circular economy and real estate: the legal (im)possibilities of operational lease", *Facilities*, Vol. 37 Nos 9-10, pp. 653-668.

Raith, K. and Estaji, H. (2020), "Traditional house types revived and transformed: a case study in Sabzevar, Iran", in Arefian, F.F. and Moeini, S.H.I. (Eds), *Urban Heritage along the Silk Roads: A Contemporary Reading of Urban Transformation of Historic Cities in the Middle East and beyond*, Springer, Cham, Switzerland, pp. 157-173.

Rasmussen, T.V. (2012), "A strategic approach for existing buildings to withstand climate change", *Open House International*, Vol. 37 No. 4, pp. 81-88.

Remøy, H. and Vander Voordt, D.J.M. (2014), "Adaptive reuse of office buildings: opportunities and risks of conversion into housing", *Building Research and Information*, Vol. 42 No. 3, pp. 381-390.

Remøy, H.T. and Wilkinson, S.J. (2012), "Office building conversion and sustainable adaptation: a comparative study", *Property Management*, Vol. 30 No. 3, pp. 218-231.

Remøy, H., de Jong, P. and Schenk, W. (2011), "Adaptable office buildings", *Property Management*, Vol. 29 No. 5, pp. 443-453.

Remøy, H. (2014a), "Building obsolescence and reuse", in Wilkinson, S.J., Remøy, H. and Langston, C. (Eds), *Sustainable Building Adaptation: Innovations in Decision-Making*, John Wiley & Sons, Chichester, West Sussex, Chapter 5, pp. 95-120.

Remøy, H. (2014b), "Reuse versus demolition", in Wilkinson, S.J., Remøy, H. and Langston, C. (Eds), *Sustainable Building Adaptation: Innovations in Decision-Making*, John Wiley & Sons, Chichester, West Sussex, Chapter 6, pp. 121-133.

Rockow, Z.R., Ross, B. and Black, A. (2019), "Review of methods for evaluating adaptability of buildings", *International Journal of Building Pathology and Adaptation*, Vol. 37 No. 3, pp. 273-287.

Roders, M., Straub, A. and Visscher, H. (2013), "Evaluation of climate change adaptation measures by Dutch housing associations", *Structural Survey*, Vol. 31 No. 4, pp. 267-282.

Ross, B.E. (2017), "The learning buildings framework for quantifying building adaptability", *Resilience of the Integrated Building, In Proceedings of the Architectural Engineering National Conference 2017*, Oklahoma City, Oklahoma, United Sates, April 11-13, 2017, pp. 1067-1077.

Sadafi, N., Mzain, M.F. and Jamil, M.F. (2009), "Prospects of flexible design strategies for easy change and adaptation", *Proceedings of the International conference on Chemical, Biological and Environmental Engineering (CBEE)*, Singapore, 9th -11th Oct,2009, Nanyang Technological University (NTU), Singapore.

Sadafi, N., Zain, M.F. and Jamil, M. (2014), "Design criteria for increasing building flexibility: dynamics and prospects", *Environmental Engineering and Management Journal*, Vol. 13 No. 2, pp. 407-417.

Saghafi, M.D. and Ahmadi, M. (2011), "A study of adaptable architecture pertinence in Iran", *Procedia Engineering*, Vol. 21, pp. 256-265.

Sanchez, B. and Haas, C. (2018), "Capital project planning for circular economy", *Construction Management and Economics*, Vol. 36 No. 6, pp. 303-312.

Scuderi, G. (2019), "Designing flexibility and adaptability: 'The answer to integrated residential building retrofit'", *Deigns*, Vol. 3 No. 1, p. 3.

Shahi, S., Esfahani, M.E., Bachmann, C. and Haas, C. (2020), "A definition framework for building adaptation projects", *Sustainable Cities and Society*, Vol. 63, p. 102345.

Sivo, M., Ladiana, D., Santi, G. and Rrjolli, L. (2019), "Technological and social retrofit strategies for the public residential buildings of the second post-war", *Proceedings of the Tenth International Structural Engineering and Construction, Conference Chicago*, Illinois, United States, May 20-25, 2019, ISEC Press, Fargo, North Dakota, HOS-04.

Slaughter, E.S. (2001), "Design strategies to increase building flexibility", *Building Research and Information*, Vol. 29 No. 3, pp. 208-217.

Snyder, H. (2019), "Literature review as a research methodology: an overview and guidelines", *Journal of Business Research Journal*, Vol. 104, pp. 333-339.

Stone, S. (2005), "Re-readings: the design principles of remodelling exiting buildings", *Structural Studies, Repairs and Maintenance of Heritage Architecture IX, WIT Transactions on the Built Environment*, WIT Press, Southampton, Vol. 83, pp. 125-134.

Sturgis, S. (2017), "Adaptability: a low-carbon strategy", *Architectural Design*, Vol. 87 No. 5, pp. 46-53.

Swallow, P. (1997), "Managing unoccupied buildings and sites", *Structural Surve*, Vol. 15 No. 2, pp. 74-79.

Szarejko, W. and Trocka-Leszczynska, E. (2007), "Aspect of functionality in modernization of office buildings", *Facilities*, Vol. 25 Nos 3-4, pp. 163-170.

Terlikowski, W. (2017), "Interdisciplinary diagnostics in the process of revitalization of historic buildings, in terms of changing their function", *MATEC Web of Conferences 117, RSP 2017 – XXVI R-S-P Seminar 2017 Theoretical Foundation of Civil Engineering*, Warsaw, Poland.

Torraco, R.J. (2005), "Writing integrative literature reviews: guidelines and examples", *Human Resource Development Review*, Vol. 4 No. 3, pp. 356-367.

Tserng, H.P., Chou, C.M. and Chang, Y.T. (2021), "The key strategies to implement circular economy in building projects-a case study of Taiwan", *Sustainability*, Vol. 13 No. 2, p. 754.

Unzurrunzaga, A.I. and Branchi, P. (2013), "ACORDE: adaptable residential buildings for a new social framework", *2013 International Conference on New Concepts in Smart Cities: Fostering Public and Private Alliances (SmartMILE)*, Gijon, Spain, 11-13 Dec. 2013.

Valdebenito, G., Vásquez, V., Prieto, A.J. and Alvial, J. (2021), "The paradigm of circular economy in heritage preservation of southern Chile", *ArquiteturaRevista*, Vol. 17 No. 1, pp. 73-89.

Valitutti, A. and Perricone, S.R. (2019), "A creative the application of minimum environmental criteria (CAMs) construction and sustainable transformation of public building stock", *Modern Environmental Science and Engineering*, Vol. 5 No. 12, pp. 1100-1107.

Waston, P. (2009), "The key issues when choosing adaptation of an existing building over new build", *Journal of Building Appraisal*, Vol. 4 No. 3, pp. 215-223.

Webb, R.S., Kelly, J.R. and Thomson, D.S. (1997), "Building services component reuse: an FM response to the need for adaptability", *Facilities*, Vol. 15 Nos 12-13, pp. 316-322, .

Wilkinson, S.J. (2014a), "Defining adaptation", in Wilkinson, S.J., Remøy, H. and Langston, C. (Eds), *Sustainable Building Adaptation: Innovations in Decision-Making*, John Wiley & Sons, Chichester, West Sussex, Chapter 1, pp. 3-17.

Wilkinson, S. (2014b), "The preliminary assessment of adaptation potential in existing office buildings", *International Journal of Strategic Property Management*, Vol. 18 No. 1, pp. 77-87.

Wilkinson, S.J. (2014c), "Drivers and barriers for adaptation", in Wilkinson, S.J., Remøy, H. and Langston, C. (Eds), *Sustainable Building Adaptation: Innovations in Decision-Making*, John Wiley & Sons, Chichester, West Sussex, Chapter 2, pp. 18-41.

Wilkinson, S.J. and Reed, R. (2011), "Examining and quantifying the drivers behind alterations and extensions to commercial buildings in a central business district", *Construction Management and Economics*, Vol. 29 No. 7, pp. 725-735.

Włodarczyk, J.W. and Włodarczyk, A.M. (2015), "The age of inhabitants and the age of buildings as a guide for the architecture design", *International Journal for Housing Science*, Vol. 39 No. 4, pp. 193-204.

Yaldiz, E. and Asatekin, N.G. (2013), "Definition of a new design process for the reuse of monumental buildings", *Proceedings of Central Europe towards Sustainable Building 2013 (CESB 2013): Sustainable Building and Refurbishment for Next Generations - Sustainable Refurbishment of Existing Building Stock*, Prague, Czech Republic.

Zimmann, R., O'Brien, H., Hargrave, J. and Morrell, M. (2016), *The Circular Economy in the Built Environment*, ARUP, London.

Corresponding author
Mohammad B. Hamida can be contacted at: M.B.Hamida@tudelft.nl