



Review

# Design for Adaptability (DfA)—Frameworks and Assessment Models for Enhanced Circularity in Buildings

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**Abstract:** A growing interest has been expressed in the issue of building adaptability over the past decade, perceiving it as an intrinsic criterion for sustainability. In light of the circular economy (CE) and its application in the construction sector, more attention has been paid to buildings' design for adaptability (DfA) towards the realization of circular buildings. DfA is considered a key enabler for other circular design strategies such as design for disassembly (DfD), multi-functionality, spatial transformability, and design reversibility. However, implementation and assessment frameworks, and design-support tools for the circular building, are still in development as the characterization of circular buildings continues with endeavors to draw a defined shape by identifying the prerequisites for circularity where the design takes an important place. For the sake of objectifying the role of DfA in circularity frameworks in buildings, this paper carries out an analytical review and discussion on two types of assessment and design-support frameworks; the first addresses adaptability criteria and considerations in assessment frameworks that handle the concept individually while the second classifies existing circularity assessment endeavors into four main categories under which multiple tools are reviewed. A reflection on the scope and objectives for both types is later performed, illustrating the state of adaptability evaluation and criteria as well as its role in circularity frameworks. Results show that the concept of building adaptability lacks quantitative methods that quantify a building's capacity to adapt as well as empirical data that prioritize the most valuable criteria facilitating adaptations. Moreover, many circularity assessment frameworks fail to consider adaptability criteria at all hierarchical levels of a building composition. To address this shortcoming, a series of conceptual considerations and requirements is proposed towards a potential establishment of an inclusive framework of a circularity design-support tool in buildings. The study is concluded by identifying gaps and recommendations for further developments in the field.

**Keywords:** circular economy; circular building; adaptability; DfA; assessment framework; design-support tool; criteria; indicators



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## 1. Introduction

The world's population is constantly growing, facing needs for new constructions, which keeps putting enormous stress on our environment and resources. The intensified pressure on resources that are becoming increasingly scarce has largely contributed to inflating costs overall and creating uncertainty in the short term [1]. The construction industry is responsible for circa 33% of greenhouse gas (GHG) emissions, 40% of waste generation, and 40% of raw material consumption [2,3]. These figures are results of the linear economic model of “take-make-dispose” which has dominated production and consumption patterns for the last decades. In response to the growing environmental crisis and resource scarcity, among other modern-day challenges, the concept of circular economy (CE) has emerged as a new paradigm of innovative practice towards more sustainable economic growth [4]. It aims at making the most of resources and therefore eliminating

waste, reducing GHG emissions, and addressing resource scarcity. All are achieved by creating value through slow-moving, closed-loop supply chains where resources are reduced, reused, and recycled (the 3Rs of waste management hierarchy in a CE).

The CE has been explored by several scholars (e.g., [5–8]) and organizations (e.g., the Ellen MacArthur Foundation—EMF [9]) who tried to define the concept with emphasis on different aspects of resource preservation and sustainable development [10]. The Ellen MacArthur Foundation (EMF), through a series of reports [9,11–13], explored the CE concept and its ideas. Since 2010, EMF has acted as a collaboration hub for policymakers, market players, and academia to raise awareness and motivate the current generation to employ the CE approach to re-think, re-design, and build a positive future. EMF describes the circular economy as: “an industrial system that is restorative or regenerative by intention and design. It replaces the ‘end-of-life’ concept with restoration, shifts towards the use of renewable energy, eliminates the use of toxic chemicals, which impair reuse, and aims for the elimination of waste through the superior design of materials, products, systems, and, within this, business models” [9] (p. 8). In addition to the environmental benefits of implementing the CE model, other social and economic benefits include delivering larger gross domestic product (GDP) values, cutting down material prices [14], creating up to 50,000 jobs [15], and saving 200 billion EUR from primary resources by 2030 [16]. The circular economic model has been gaining momentum in academic research as well as industry and policy plans [5,9,10,17], making its way to the top of international and European political agendas. In this respect, the European Commission (EC) launched the first Circular Economy Action Plan (ECEAP) in 2015, including measures covering the whole lifecycle of products and materials. ECEAP promoted principles of; 1- “closing the loop” through intensified reuse and recycling [18], 2- “slowing the loop” through preserving products’ and materials’ values to a maximum extent, and 3- “narrowing the loop” through using fewer resources per product. ECEAP held particular promise for achieving multiple Sustainable Development Goals (SDGs), including SDG 6 on energy, SDG 8 on economic growth, SDG 11 on sustainable cities, SDG 12 on sustainable consumption and production, and SDG 13 on climate change. A new Circular Economy Action Plan (CEAP) was adopted in 2020 with more concrete measures to reduce the pressure on natural resources and create sustainable development. Circular economy (CE) action plans entail gradually decoupling economic activity from consuming finite resources and designing resources’ second life which target seven priority sectors including “construction and buildings” due to their massive share of responsibility in existing environmental crises. Recent endeavors for delivering more concrete measures also include the development of new standardization activities such as CEN/TC 350/SC 1—‘Circular Economy in the Construction Sector’, ISO/WD 59004—‘Circular Economy’, and BS ISO 20887:2020—‘Sustainability in buildings and civil engineering works—Design for disassembly and adaptability’.

#### *Circular Buildings and Design for Adaptability (DfA)*

Reassessing building operations, activities, and processes in consideration of the CE principles (as generally described by the EMF) promises significant benefits to the sector, including resource efficiency, energy conservation, and carbon footprint reduction, contributing to the mitigation policies of climate change [19,20]. However, adopting a more circular approach requires shifting the design culture, including improving construction processes, materials, and products, and creating new business model innovations. Designing buildings for a CE puts a major focus on the end-of-life (EoL) phase of buildings and their components and materials (as highlighted by the EMF definition), which must be maintained in a closed-loop through reuse, disassembly, and reintegration in new buildings. These concepts should apply to both new constructions as well as existing buildings which should be regarded as important assets where huge amounts of resources are embedded. An important aspect that should be regarded when designing circular buildings is the change impact. Change is increasingly inevitable and today, buildings are prompted to change more than ever before. Designing buildings with adaptive capacity to respond to

the different variables throughout their life span, therefore, becomes an insistent prerequisite for sustainability and circularity. The concept of Design for Adaptability (DfA) is considered as an important enabler to the circular building strategies [20–22], including design for disassembly/deconstruction (DfD) [21,23,24], design for longevity and durability [2], design for change (DfC) [25], and reversible building design [26,27], among others. DfA is the intentional design of buildings to be easily modified throughout their lifecycle in response to emerging needs and future circumstances [17,28]. By this meaning, it is a preconfigured condition embedded in the design stage of buildings. Adaptability manifests spatial, structural, and functional capacities that allow the building a level of physical flexibility against changing operational variables over time. Seeking today's sustainability demands, i.e., circularity induces us to rethink our building practices towards embracing a new vision of buildings that can flexibly change in response to the ever-changing societal needs and preferences [20,29]. Buildings that do not support change and reuse cannot be considered truly sustainable [30]. What makes adaptability in buildings recognized as an intrinsic criterion for sustainability and CE is its potential in addressing issues of buildings' obsolescence and premature demolition [20]. This happens by extending the life service of buildings, contributing to slowing resource input and waste in the built environment [17]. Provisions of increased scarcity of raw resources and therefore more elevating costs further emphasize the importance of adaptability to achieve a CE.

The capacity of a building to respond to emerging changes stems from early design decisions [31]. With this perspective, DfA relies on visualizing the end by developing evidence on possible end-of-life (EoL) scenarios early in the design process. Still, its role continues during the entire building lifecycle allowing viable durability [20]. Furthermore, this lifecycle perspective enables accommodating change at any point in time in a building's and materials' life, ensuring a prolonged service life of a building and facilitating maintenance and replacement for its elements.

However, designing buildings for adaptability and simultaneously for circularity faces multiple challenges for which a paradigm shift is necessary to meet the modern-day sustainability demands. Most of Europe's existing building stock was built a few decades ago. At the time, buildings were regarded as fixed objects of permanent status until the end of their service life. When new demands emerge and different societal needs arise, these buildings turn out to be obsolete for not having the capacity to keep up with changing standards, demands, or functional programs [29]. As a result, they either need to undergo extensive renovations or be demolished and replaced. Major renovation and rehabilitation projects require huge investments and interventions, engaging high input flows of materials and energy, as well as producing significant amounts of waste [20]. Construction and demolition waste (CDW) represents approximately 30% to 40% of global waste production [32]. Moreover, the inability to support change can have impacts beyond the building level, reaching the urban ecosystem in its wholeness [32]. Design challenges include how all components and materials are integrated into one entity in a way that facilitates its future adaptation, disassembly, and safe recovery of its components and materials as societal, technological, economic, and legal needs arise.

Nevertheless, the application of CE and DfA design strategies in buildings is still challenging due to the scarcity of practical guidelines and design-support tools that facilitate their implementation and enable their performance assessment and simulation of their added value along a full lifecycle of a building, particularly when their service life comes to an end. Although building adaptability mechanisms (e.g., open building [33] and shearing layers [34,35]) as well as some of the circularity design strategies, e.g., design for deconstruction, have existed for decades, their application in a fragmented approach has resulted in limited efficiency and kept the concepts in the theoretical perception.

Moreover, the actual implementation of CE principles in building design and management has been so far limited to the application of individual strategies that regard certain aspects of circularity, for example, the development of circular materials and management of CDW and recycling [4,14]. Meanwhile, less attention has been paid to the reuse of

products and components [36]. This is because reuse faces challenges at a building scale which still suffers from a shortage in interdisciplinary research for implementing circularity principles [37]. The majority of research on CE at a building scale has mainly addressed techniques for measuring and assessing lifecycle outcomes of buildings and their materials or innovative materials for circularity; on the other hand, less has been said regarding the design aspect of circular buildings and the role of architects and building professionals in embodying the CE principles into the building sector [38]. A circular building approach is not limited to material circularity or any other individually applied strategies. It rather transcends these single aspects to include the dynamic total of all processes that allow a circular flow of all materials and products including planning, management, design, operation, maintenance, and end-of-life aspects taking into consideration all value chain factors as well as policies that support implementation and economic value creation [39].

The current focus on certain CE strategies without others in buildings can also be justified by existing supportive legislations, which rarely address the technical aspects and rather focus on ensuring higher rates of recycling and waste management issues. In this case, the demonstration of circularity strategies' implementation and impact on waste hierarchy promotion (reduce, reuse, recycle) —which is at the heart of CE— is necessary to prompt other policies and incentives toward a holistic implementation for all stakeholders involved. Moreover, the economic viability of applications is another major challenge against the practical implementation of some circular strategies illustrated by the lack of business models and market mechanisms.

Existing frameworks to implement and assess circularity suffer from a mismatch between supply and need. There is an oversupply of theoretical guidelines and tools that illustrate the basic principles of the circular building. However, most of the tools serve the same purpose, while there is a need for practical evidence about the utility of these tools and their impact on the design process to highlight best practices and compare multiple alternatives. The reason can be attributed to the lack of technical criteria characterizing the circular building design [40] as well as practical guidelines of inclusive implementation.

The present paper aims at providing an overview of the existing models and frameworks on the concepts of adaptability and circularity giving their strong relationship with the former being a key enabler to the latter. The study design is presented in Figure 1.

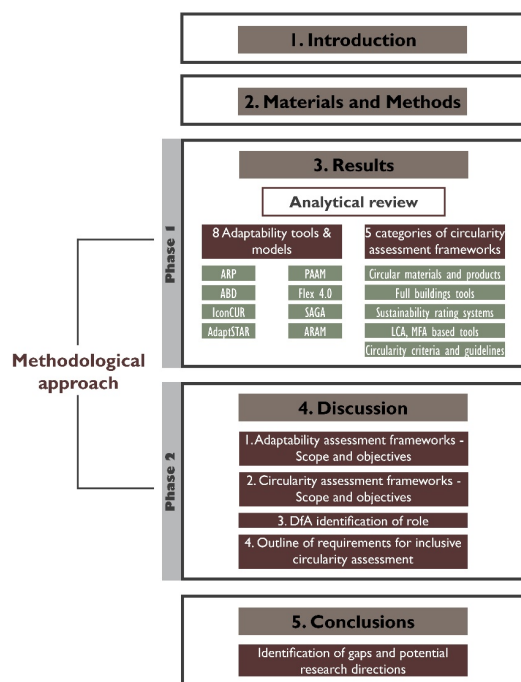


Figure 1. Research design and paper structure.

## 2. Materials and Methods

This study aims to answer the following research questions:

- What are the objectives and criteria of existing adaptability frameworks/tools? Which of these criteria are empirically proved to be most efficient in facilitating adaptations?
- What is the current role of DfA in existing circularity frameworks in buildings?
- How can the role of DfA be objectified in circularity frameworks, and what are the requirements that ensure an inclusive implementation of circularity in buildings?

The paper builds on the recognition of DfA as an essential prerequisite for circularity realization in buildings and subsequently for developing design-support tools to promote circular buildings and evaluate end-of-life options. However, in order to have insights into the different adaptability criteria, indicators, and rating methods, as well as emphasize the critical role of DfA in circularity frameworks for buildings, the study is done in two phases. First, an analytical review on two types of assessment frameworks is carried out; the first consists of eight assessment models of adaptability in buildings as a stand-alone objective. The second classifies the different categories of circularity assessment frameworks and tools outlined by the ongoing main research tracks on the development of design support tools for circular building design. Five main categories of circularity implementation in buildings are considered in the study:

- Models for circular materials and products
- Design-support tools for whole buildings
- Circularity integration in sustainability frameworks
- MFA and LCA-based tools
- Circularity criteria and guidelines

Each category is further discussed and elaborated with different examples of prominent representative tools. The tools for both framework types are collected based on the authors' own knowledge of the existence of such tools, as well as analytical literature search. The objective of reviewing the two above-mentioned types of frameworks is to first understand the objectives and various factors and criteria that enhance the adaptability of buildings then establish a linkage with circularity frameworks. By this means, integration paths are envisaged within other dimensions and important aspects of circularity, allowing to identify trade-offs when evaluating design alternatives and simulating end-of-life options. Thus, the study's second phase is a discussion and analysis of the reviewed tools/frameworks. The discussion addresses four main aspects; first, a reflection on the scope and objectives of adaptability evaluation frameworks and identification of key considerations and gaps for integration in the broader spectrum of sustainability and circularity in buildings. The second aspect is an analysis of the five categories of circularity assessment frameworks in terms of objectives and level of implementation in buildings. The analysis realizes the relation between aspects covered by current frameworks and the pressing needs of designers and professionals. The third aspect addresses the current state of the design role in general and the role of DfA in particular in existing circularity frameworks. It, therefore, identifies opportunities for a more activated role. The fourth aspect aims at identifying clear criteria for the circular building by setting key requirements and considerations for inclusive implementation and assessment.

## 3. Results

The following sections present an analytical review of two types of assessment tools and frameworks: adaptability assessment tools and circularity assessment frameworks.

### 3.1. Adaptability Assessment Tools and Models

Eight existing tools and models evaluating the adaptability of different building typologies are discussed below in chronological order from the oldest to the newest.

### 3.1.1. Adaptive Reuse Potential Model (ARP), 2007

The ARP model was developed by Langeston et al. [41] to assist the industry in identifying and evaluating buildings potentially adequate for adaptive reuse before they reach a demolition point. By this meaning, a candidate building for ARP assessment should be at a point in its age near the end of its useful life. The tool framework suggests that a building's useful life can be determined by multi-nature obsolescence criteria that manifest as reductions in its physical life. Conducting an ARP assessment requires an estimation of the expected physical life of the building and its current age. Evaluation of the physical, economic, functional, technological, social, and legal obsolescence is also required. In this respect, the authors developed a measurement methodology for each of the obsolescence criteria and created a scale to calculate each criterion's physical life reduction percentage. These data requirements allow users to determine the useful life of the building in question using Equation (1).

$$(L_u) = \frac{L_p}{\left(1 + \sum_{i=1}^6 O_i\right)^{L_p}} \quad (1)$$

where  $L_u$  = useful life (years);  $L_p$  = expected physical life (years);  $O_1$  = physical obsolescence (%);  $O_2$  = economic obsolescence (%);  $O_3$  = functional obsolescence (%);  $O_4$  = technical obsolescence (%);  $O_5$  = social obsolescence (%); and  $O_6$  = legal obsolescence (%).

According to the equation, the useful life is only a fraction of the physical life reduced by the sum of obsolescence factors' rates. The ARP index is then calculated using a mathematical algorithm and expressed in a percentage. The higher the percentage, the higher the potential for adaptive reuse.

The utilization of this method allows for prioritizing buildings with a higher potential for adaptive reuse. Although the ARP model was first developed considering Hong Kong's context, it has been tested on case studies in different cities worldwide; examples can be found in [42]. ARP has also been used to validate later adaptability assessment models such as the IconCUR [43] and AdaptSTAR [44], which will be discussed in the following sections.

The ARP model considers that all obsolescence criteria have an identical influence on a building's useful life which contradicts other literature findings that usually give more importance to technical, physical, and economic factors.

### 3.1.2. The Adaptable Building Design (ABD) Framework, 2010

The Adaptable Building Design (ABD) Framework [45] introduces a design-support tool relying on predictive uncertainty modeling to deliver buildings with adaptive capacity to change and therefore increased longevity. The framework aims to integrate multiple flexibility options in the design phase that address a variety of future uncertainties. Then, the value of these options is assessed for decision-making. The framework consists of four main phases: in phase 1, possible future uncertainties are identified, including market conditions, performance and technology, policies and standards, and climate conditions. In phase 2, based on the uncertainties identified in phase 1, flexibility options are analyzed, and necessary ones are embedded in the design of several building systems, e.g., spatial, structural, and service systems. In phase 3, a mathematical logic decision-making mechanism is applied to formulate design rules that identify when to use each embedded flexibility option. Establishing design rules relies on multiple parameters that assess the building's real estate performance at a particular time. In phase 4, value analysis and calculation are conducted using the Real Option Analysis (ROA) methodology, which allows evaluating the capacity of accommodating future uncertainties of the project as well as its economic value by carrying out probabilistic simulations of future scenarios. The simulation outcomes suggest lifecycle planning, including the initial construction and the later incremental adaptations to achieve the maximum value of the project. Although adaptability options are embedded in the early design stage of the project, the ABD methodology allows for re-evaluation during the redesign phases to refine these options [46].

The authors used an illustrative case study project to demonstrate their approach. However, due to the commercial nature of the studied project (multi-use building with office and retail spaces), only market uncertainties were addressed and evaluated for integration of flexibility options. Further cases of buildings with varying uses should be considered to validate the practical implementation of the method.

### 3.1.3. IconCUR, 2012

IconCUR [43] is a conceptual framework to support decision-making regarding the adaptive reuse of built assets using a methodological approach combining Adaptive Management (AM) and Multiple Criteria Decision Analysis (MCDA). The model uses primary criteria of condition, utilization, and reward to create a 3D modeling of a space where the property status can be mapped using three coordinates ( $x,y,z$ ) corresponding to the three initial criteria condition, utilization, and reward, respectively. The decision strength ( $z$ ) is based on the type of relationship existing between the property's physical condition ( $x$ -axis) and the current level of utilization ( $y$ -axis). The following relationship patterns are expected:

- Low condition and low utilization—reconstruct or dispose
- High condition and high utilization—retain or extend
- Low condition and high utilization—renovate or preserve
- High condition and low utilization—reuse or adapt

Condition and utilization are measured on a scale of 0 (low) to 5 (high). Reward ( $z$ -axis) quantifies the intervention value based on its financial, social, and environmental impacts. It is also measured on a scale of 0 (low) to 5 (high). However, the difference between reward values before and after the intervention determines the value of the decision.

The framework relies on a weighted matrix to objectify and justify the measurements. Each of the model's criteria (condition, utilization) and sub-criteria (collective utility, stakeholder interest) embraces a number of key attributes provided in columns and weighted according to their impact with a total equal to 100%. In turn, each of the key attributes consists of key elements provided in rows with a total also equal to 100%. Performance is measured at the intersection of each attribute and element using a scale of 0 (weak) to 5 (strong). The score for each criterion and sub-criterion can subsequently be calculated. To overcome the subjectivity of the assessments, a risk sensitivity analysis must be carried out to ensure the stability of the key variables. The criterion of reward is then calculated by multiplying the score of the two sub-criteria, collective utility and stakeholder interest, and divided by 5.

### 3.1.4. AdaptSTAR Model, 2013

AdaptSTAR is a design-rating tool developed by Conejos et al. [44] to deliver an assessment model of future adaptation potential at the design stage of new buildings. The model development is intended to aid designers in making critical design decisions by calculating an adaptive reuse star rating for newly designed buildings that adds value to urban sustainability. The AdaptSTAR model for adaptation offers 26 design criteria that comprehensively cover aspects of buildings with adaptive reuse potential. The criteria are built upon seven drivers of obsolescence: physical, technological, economic, functional, social, legal, and political. The scoring system is composed of a weighted checklist developed based on a survey of twenty-nine experienced architects. The scores are summed to calculate the number of stars. The survey was conducted using a Likert system with a scale of 5 assessment values, 1 (unimportant), 2 (not very important), 3 (no opinion), 4 (important), and 5 (very important), that evaluate the impact of the seven categories of obsolescence against the adaptive reuse of new buildings. According to the survey, physical obsolescence, including three design criteria: structural integrity and foundation, material durability, and workmanship, maintainability is found to be the most important.

### 3.1.5. Preliminary Assessment Adaptation Model (PAAM), 2014

Preliminary Assessment Adaptation Model (PAAM) [42] is a predictive model to support the decision-making regarding adaptations of existing office buildings. The research by Wilkinson [42] addresses six levels of adaptations designated as level 1 'minor', level 2 'alterations', level 3 'change of use', level 4 'alterations and extensions', level 5 'new build', and level 6 'demolition'. Together with six labels of property attributes influencing adaptation (physical, social, economic, environmental, legal, and technological), these levels are utilized to form the PAAM conceptual model. The model aims to conduct an initial assessment of building suitability for level 4 of adaptation, i.e., alteration and extensions. The author built upon previous models (e.g., Chudley (1981) [47]) and case study approach, governmental data, and building permits to identify adaptation criteria that fall into the labels of the property attributes database. The author relied on cross-sectional data of adaptation events corresponding to the period between 1998 and 2008 in a central business district in Melbourne, Australia. The Principle Component Analysis (PCA) mathematical technique was applied to 5290 adaptation events to create loadings of the individual factors of each property attribute category and therefore identify an order of relative importance on the different attributes. The PCA identified a checklist of 12 attributes falling into three categories of attributes: physical and size, land, and social. The answers to the checklist questions determine the adaptation potential ranging from very low to very high. The PAAM's checklist is applied to an illustrative case study of a 27-story existing office tower to demonstrate its practical application. The checklist delivers a simple instrument for stakeholders and non-experts to determine the overall potential of an existing office building focusing on the property attribute that develops the most variance in adaptation. However, the tool is oriented to the Australian context. Another limitation is that the PAAM model does not address functional or use changes; it rather provides an assessment tool for minor adaptation actions.

### 3.1.6. Flex 4.0, 2016

Based on the concept of "Open Building" by Habraken [33], the FLEX 4.0 instrument developed by Geraedts [48] introduces a holistic assessment model with key performance indicators to assess the level of adaptability of buildings. FLEX 4.0 is an advanced version of FLEX 2.0 and FLEX 3.0 tools and consists of two sets of indicators corresponding to the support-infill theory of Habraken [33]. The support set consists of 12 indicators that are generally applicable regardless of the type and use of the assessed building. A second category comprising 32 performance indicators and focusing on the infill components is particularly applicable to schools and office buildings. The assessment value for all indicators is expressed as; 1 (Bad), 2 (Normal), 3 (Better), and 4 (Best). The two sets of indicators are categorized into Brand's shearing layers combining the space plan and stuff layers: site, structure, skin, services, space plan, and stuff. The indicators can be used to perform a gap analysis between the adaptability level desired by stakeholders and the actual adaptability level of a building. However, weights are assigned to each indicator in relation to the others ranging from 1 (not important) to 4 (very important). This represents the default system set by the authors, which the users can change as they see fit. The final score of each indicator is determined by multiplying the weighting by the assessment value. All scores are summed to determine the final flexibility score and corresponding class.

### 3.1.7. The SAGA Method, 2019

The Spatial Assessment of Generality and Adaptability (SAGA) Method [32] delivers an assessment model of a building's capacity to support changes using a combination of unweighted and weighted graphs. The method introduces a set of five quantitative indicators that are mathematically reproducible to measure a building's passive capacity to change (generality) as well as the active capacity to change (adaptability) in terms of the spatial configuration of layouts. The SAGA method aims to analyze and compare large sets of plan graphs of a building or even at an urban scale, allowing to map generality and



adaptability throughout those. It can also inform design decisions, enabling architects and designers to improve the capacity to accommodate change through layout configuration. For example, SAGA can calculate which parts of a unit the use of removable walls would have the highest impact (i.e., the highest increase in generality). The central premise of the method is that graph permeability can serve as a measurement tool for functional uses a layout can accommodate. The method is tested on six representative floor plans of residential typologies. The SAGA model stands out among existing tools for fully automated indicators within Rhinoceros 3D BIM software.

The method is limited to evaluating the spatial configuration of floor plans (spatial adaptability) which only partially support functional changes. Moreover, although the method was developed for all building typologies, it was only tested for validation on six representative floor plans of residential use.

### 3.1.8. Adaptive Reuse Assessment Model (ARAM), 2021

Adaptive Reuse Assessment Model (ARAM) [49] is an assessment model of adaptive reuse and adaptation potential in heritage buildings at different life cycle stages. The model relies on identifying challenge categories for adaptive reuse of heritage buildings and critically analyzing existing decision-making tools and assessment models [49]. The authors identify 32 challenges related to the adaptive reuse of heritage buildings categorized into eight groups: environmental, social, economic, legal, political, physical, locational, and technical. The ARAM model is based on two previous models: Chudley's model of decision-making in building adaptation [47] and the PAAM assessment model for office buildings, as it relies on a comprehensive database for important attributes of adaptation projects. However, in the ARAM model, authors consider modifying the sequence and importance of attributes' categories to fit the value-representative characteristics of heritage buildings and the legal obligation to preserve them. They also considered adding the political category, and heritage value and authentic features not addressed by previous frameworks. The assessment methodology starts with identifying the key values, which are the ones corresponding to heritage significance and authenticity, then confirms that the adaptive reuse actions are capable of preserving those. The next step is to consider the economic viability, followed by the technical and legal considerations. The model does not view the remaining categories, i.e., locational, physical, and environmental challenges. The ARAM model was applied to two illustrative case studies of heritage-listed city halls in Queensland, Australia, to demonstrate its practical application and test its validity. The case studies' findings suggest that the physical category is the third most important challenge to adaptive reuse, which does not correspond to the reviewed literature findings. This finding resulted in alteration in the initial model by placing the physical category at the last stage after the legal consideration.

The ARAM presents a simple model of assessment that can be carried out by stakeholders regardless of their level of expertise. The model does not suggest technical solutions. It rather acts as a decision-support tool for involved stakeholders.

## 3.2. Circularity Assessment Frameworks

This study uses five types of circularity assessment frameworks for buildings and their components: 1. models for circular materials and products, 2. design-support tools, 3. circularity integration in sustainability frameworks, 4. LCA-based tools, and 5. circularity criteria and guidelines. The types along with examples of renowned tools, are discussed in the following paragraphs.

### 3.2.1. Models for Circular Materials and Products

Several metrics and assessment models have been developed to evaluate individual aspects of the circularity of products relying on the calculation of certain aspects of their composing materials circularity. These models/indicators often target companies to support the decision-making regarding the circularity versus economic viability of the products

they design and manufacture. However, they can also apply to construction and building products. Some of these models are discussed below:

1. The Circularity Calculator. The circularity calculator was developed by IDEAL and CO Explore BV [50]. The calculator uses the bill of materials of a product to compare the impacts of different circularity scenarios (e.g., reuse, refurbishment, remanufacture, and recycling) and consequently choose the best design options and business models relying on experimental trade-offs between circularity and value capture. The calculator provides four quantitative key performance indicators (KPIs): circularity indicator, value capture indicator, recycled content indicator, and reuse index, which help companies to determine the economic viability of potential design ideas for products [51].
2. Material Circularity Indicator (MCI). MCI was developed by the Ellen McArthur Foundation (EMF) and Granta Design [13] to assess the ability of material flows of a product or company to be restorative. The calculation of the MCI for a product relies on a detailed bill of materials and three types of inputs:
  - Amount of virgin, recycled, or reused content  $V$ ;
  - Mass of unrecoverable waste  $W$ ;
  - Product utility factor  $X$ .

The indicator is developed to assess the circularity of single products. However, it can be utilized at a company scale by using the sum of the material circularity of its products after normalization.

The MCI can be utilized to assess the material circularity of construction and building products. However, other indicators should be used to assess the overall circularity of a building, taking into consideration its complexity, including design aspects and hierarchical composition of systems, components, and materials.

3. The Material Reutilization Score (MRS). MRS was proposed by the Environmental Protection Encouragement Agency through the Cradle-to-Cradle certification scheme to address the recycling value of materials. A material reutilization score is estimated based on the end-of-life strategy considering the performance of input materials and reutilization options. MRS is calculated using two variables: the intrinsic recyclability ( $IR$ ) and the recycled content ( $RC$ ), according to the following formula:

$$MRS = (2 \cdot IR + RC)/3 \quad (2)$$

4. Longevity and resource duration. Longevity is a value-based performance indicator that relies on the length of time a resource is used in a product system, which can be measured in time units [52,53]. The idea is that the higher the material retention, the slower the loop and consequently, the higher the contribution to a circular economy [53]. According to the authors, the indicator can be measured using three parameters that are the three drivers for longevity: 1. the initial lifetime, 2. lifetime after refurbishment, 3. lifetime after recycling. These parameters fell short in considering the number of times a resource can be utilized, which is essential to measure resource efficiency and eventually close the loop. Moreover, the indicators do not address the complexities of refurbishment and recycling processes and assume that a resource is refurbished, recycled, and reused through a similar product which is not always the case [52]. Still, the longevity indicator provides a simple tool companies can use to determine the value chain of a product.

### 3.2.2. Design-Support Tools for Whole Buildings

The models presented under this category provide tools to assess whole building performance in terms of circular economy aspects.

### 1. The CE Meter, 2015

Geraedts and Prins [54] proposed a conceptual framework of circularity assessment in buildings; the tool is built upon a previous tool developed by the first author Flex 2.0 to measure the adaptive capacity of buildings. In the framework of the CE Meter, the authors identify the relationship between the level of circularity and the adaptive capacity of buildings. For this, the authors propose to use the shearing layers concept by Duffy [34] and Brand [35] to identify resources and components that are most valuable for conservation. However, the conceptual framework does not present a well-defined tool that can be used to measure circularity aspects of buildings.

### 2. Building Circularity Indicator (BCI) frameworks, (2016, 2018, 2019, 2020).]

Verberne [55] proposed the Building Circularity Indicators (BCI), an improved approach of the MCI by EMF and Granta Design to measure a whole building's circularity. However, in addition to materials specifications, the model considers design aspects (Design for Disassembly). The BCI is based on the MCI measures for each building product with consideration of design factors (disassembly determining factors) to calculate circularity indicators based on a hierarchal composition of a building: first, the Product Circularity Indicator (PCI) is calculated to be used in the System Circularity Indicator (SCI), which in turn is used to calculate the BCI for the whole building. By this meaning, each material has an impact on the whole building's environmental assessment since a 100% circular building is one that is fully made of non-virgin materials that should also have a second life.

A second version of the first BCI was introduced by van Vliet [56], who proposed improvements on the disassembly factors resulting in a more comprehensive weighting system. A third and a fourth version of the BCI were discussed by Alba Concepts [57]. Alba Concepts developed a new BCI based on three levels, a Product Circularity Index (PCI), an Element Circularity Index (ECI), and a Building Circularity Index (BCI), all relying on material use and material detachability considerations. Lastly, Van Schaik [58] proposed an improvement to the Alba Concept indicator in what concerns building foundations.

### 3. Circular Building Assessment Prototype (CBA)

CBA is a building-level integrated decision-making model to evaluate resource productivity considering the material choice and design options [59]. The model aims at assessing the reuse potential and transformation capacity throughout the different lifecycle stages for both new and existing buildings. The model uses a BIM-compliant prototype online tool that uses an information exchange file generated from a BIM model allowing for data extraction for the assessment. The CBA method was also connected to the Reversible Building Design strategies—also developed within BAMB—to assess the applicability of major CE building-related techniques. However, CBA remained a prototype yet not an open-access tool to support the CE practitioners.

### 4. Disassembly and Deconstruction Analytics System (D-DAS), 2019

The disassembly and deconstruction analytics system [60] is a decision-support tool developed to provide buildings' end-of-life performance assessment from the design stage. An efficient end-of-life sustainability performance of buildings relies on efficient material selection during design to later facilitate effective material use and reduce the end-of-life waste in the built environment.

The innovation of this tool is the use of Building Information Modeling (BIM) for assessing the impacts of end-of-life options through the development of a plug-in to Autodesk Revit. The plug-in has three functionalities; (i) Building Whole Life Performance Analytics (ii) Building Element Deconstruction Analytics; and (iii) Design for Deconstruction Advisor. The plug-in also provides alternative design specifications that support better end-of-life performance of buildings. The interface provides the means for architects and design engineers to try various combinations of materials on different building components and select a combination that is optimized for end-of-life performance. The plug-in

supports the decision-making regarding the most valuable materials for recoverability DfD by calculating the score of deconstructability.

D-DAS was tested and validated through a case study building design. However, the scenarios considered for the validation process were based on three types of materials: steel, timber, and concrete, which are material choice alternatives. All other aspects and design specifications were kept the same for the three scenarios. For example, the same amount and volume of the three materials were considered to be required to build the same structure. The case study results show that steel structure is the best material choice. The non-realistic specifications of the alternatives considered for testing question the adequacy of the case study and, consequently, the tool's validity.

#### 5. Design criteria for circular buildings, 2021

Attia et al. [40] recognize functional adaptability as one of four primary design criteria for increased circularity, including 1. carbon footprint, 2. reused content, 3. disassembly potential, and 4. design for flexibility and adaptability. They concluded their criteria based on a systematic literature review, deconstruction audits, and structured interviews with waste management contractors. Each criterion is evaluated on a 0 to 100 scale. Each of the four criteria is weighted equally. The final circularity score is calculated by adding up the individual scores of each criterion. This methodology does not define the influence of each criterion on the overall circularity of a building. In addition, the authors did not provide clear guidelines on evaluating each criterion which affects the scores' objectivity. However, the model is still useful to assess and compare different design alternatives.

#### 6. Circular Construction Evaluation Framework (CCEF), 2021

The Circular Construction Evaluation Framework (CCEF) introduced by Dams et al. [61] relies on the principles of Design for Disassembly (DfD) and Design for Adaptability (DfA) as keys to enhance the circularity of the building elements as well as the building itself as a whole. This happens by embracing a lifecycle perspective that allows future changes, e.g., disassembly, reuse, and reconfiguration. The framework can be utilized to perform two levels of assessment i.e., elemental and building levels, for which two sets of indicators are developed. For a whole building level, the CCEF suggests 14 criteria grouped under four groups, while for an element level of assessment, the CCEF suggests six groups of criteria encompassing 14 factors in total. However, the framework does not deliver an overall circularity score that combines both assessment levels.

The CCEF is a comprehensive framework that takes into consideration that circularity is required for multiple aspects and processes throughout the lifecycle of a building and the products composing it, including material impact, construction techniques, manufacturing styles, and a combination of several circularity strategies such as simplicity, standardization, prefabrication, and connection reversibility with respect to design codes. Limitations of the CCEF include stakeholders' subjectivity in evaluating the different criteria according to their priorities.

### 3.2.3. Circularity Integration in Sustainability Frameworks

#### 1. BREEAM

Building Research Establishment's Environmental Assessment Method (BREEAM) is the world's leading sustainability rating scheme for building design, construction, and use, focusing mainly on the UK context where a national BREEAM scheme applies. Circularity inclusion within BREEAM covers requirements on energy, water, materials, waste, reuse, and recycling within construction, refurbishment and fit-out, in-use, home quality mark, and CEEQUAL schemes. The circularity measures taken into consideration by BREEAM developers include resource reuse and efficiency, consideration of renewable resources, designing for disassembly, reuse and recycling, durable and adaptable design, material banking, and passports [62].

## 2. LEED

Leadership in Energy and Environmental Design (LEED) is a renowned green building certification system. The Materials and Resources (MR) credit category in LEED associates the implementation of circular economy principles with higher credits reward. Circularity measures include optimized use of buildings, building products, and materials throughout the project life cycle, from construction and demolition, waste management planning to product selection and ongoing sustainable procurement.

The latest versions of LEED keep advancing the circular economy. Circularity-related concepts have been introduced into the rating system, such as whole-building life cycle assessment and material ingredient reporting and optimization, which demand quantification and perception of the impacts of material use on human and environmental health. These new concepts harmonized with long-standing LEED sustainability criteria for construction waste management and responsible sourcing of materials. A novel scheme of LEED was released to advance circularity in existing buildings' operation and maintenance to support the decision-making regarding purchasing, maintenance, waste diversion, and recycling [63].

## 3. Level(s) framework

The Level(s) framework is developed to be a common EU framework for a holistic approach towards sustainability assessment in new and existing, mainly office and residential buildings. The framework is designed in view of the circular economy action plan adopting a lifecycle thinking from cradle to cradle reflected in the utilization of value and risk rating system [64]. The core sustainability indicators constituting Level(s) primarily focus on the environmental performance of buildings along their lifecycle. However, the framework also addresses some other aspects concerning comfort and health as well as lifecycle costs. The framework adopts six macro-objectives translated into nine measuring indicators contributing to EU target areas, including energy, resource use, waste production water, and indoor comfort. The framework can be used to report building performance at multiple project stages: design, implementation, completion, and operation, supporting three levels of performance assessment, common, comparative, and optimized, that allow a progression in terms of accuracy and expertise.

From a resource efficiency perspective (macro-objective 2: resource-efficient and circular material life cycles), the concept of adaptability is considered by Level(s) as an essential lifecycle tool addressing the aspects of design optimization and aiming at supporting circular flows and extending system, component and material utility. Macro-objective 2 generally proposes three strategies called scenarios for assessing a building's long-term potential and future performance. The three scenarios are:

- Scenario 1: Building and elemental service life planning.
- Scenario 2: Design for adaptability and refurbishment.
- Scenario 3: Design for deconstruction, reuse, and recyclability.

These scenarios are not indicators by themselves. Instead, they are tools that simulate future possibilities at the end-of-life of buildings. Furthermore, they are important to determine several other indicators such as indicator 1.2 Life cycle global warming potential and 2.3 Construction and demolition waste. Each scenario has different impacts on input and output flows along a building's lifecycle.

Evaluating the three scenarios enables comparisons in terms of resource efficiency and allows defining advantages and barriers for each and identifying potential trade-offs.

The Level(s) framework delivers comprehensive insights into process management of sustainability/circularity evaluation of buildings and their elements. However, it does not come up with solutions; instead, it provides detailed steps and aspects for sustainability assessment. In terms of adaptability, Level(s) helps in supporting the decision-making regarding measures adopted to realize a particular solution. The framework, in this regard, recommends the utilization of available tools and pre-existing assessment models, which

raise questions regarding the compatibility of those with the objectives and other indicators stated by the framework.

#### 3.2.4. MFA- and LCA-Based Tools

1. **Material Flow Analysis Tools (MFA).** MFA is an analytical method that captures the state and changes of materials' stocks and flows in a particular system by calculating the mass balances over time within a defined space [65]. MFA-based tools focus on specific aspects of material circularity, namely the amount of materials used by calculating their mass. However, they fail to address other aspects such as material quality and resource scarcity. The main challenges inherent to MFA analysis are data uncertainty and information availability. Still, it can be applied at every analysis level due to its flexibility and simplicity [65]. An example is STAN (subSTance flow ANalysis) tool [66] which is free software that helps to perform material flow analysis according to the Austrian standard ÖNorm S 2096 (Material flow analysis—Application in waste management) under consideration of data uncertainties.

2. **Lifecycle-Based Tools.** LCA is a tool to assess the environmental impacts of a product, process, or service along the entire life cycle. LCA is one of the tools mainly applied to quantify and evaluate the benefits/impacts of CE strategies and/or to choose between different circular strategies. Case studies in the built environment literature can be found on waste management systems and materials such as concrete and steel. Lately, LCA has been used to assess the environmental impacts of different end-of-life (EoL) alternatives for products and services [65]. However, conducting a transparent, effective LCA requires a longtime experience and holistic methodology on EoL assessments.

Similarly, LCC-based tools are used to address the economic aspect of circularity in buildings, investigate the feasibility of circular solutions, and conduct financial impact analysis of circular business models.

Integrating the lifecycle-based tools within other schemes such as sustainability certification systems helps to complement those and deliver more inclusive circularity assessments.

#### 3.2.5. Circularity Criteria and Guidelines

This type of framework delivers descriptive criteria and recommendations to deliver more creative solutions for a circular economy. Multiple guides aim to provide general guidelines that apply to different areas to develop a circular mindset and design culture for practitioners and young professionals (e.g., the circular design guide). Other guides deliver design criteria particularly for buildings (the reversible building protocols).

##### 1. The Circular Design Guide

The Circular Design Guide is developed in collaboration between the Ellen MacArthur Foundation (EMF) and IDEO to help designers create more effective solutions for a circular economy. The guide is not dedicated to building designers or the construction industry. It rather targets whichever designer and product developers in any industry can benefit from the circular economy approach. This guide consists of a series of methods to build up a circular mindset and reframe questions to get started with the circularity challenge. The value of this guide lies in experiencing, exercising, and training through multiple methods to transform designers into being intuitive about circularity. The reason is that design practice is largely based on experience and less on tools [67].

##### 2. The reversible building protocols

Based on the principle of closed-loop systems and resource productivity in a circular building, Durmisevic [26] approached the concept of adaptability by developing what she called the "Reversible Building". Building reversibility manifests at three different levels: spatial, structural, and material happening through transformation actions such as separation, elimination, addition, relocation, and substitution of parts. Durmisevic considers the level of building reversibility a key indicator of circular buildings and is measured by transformation capacity on three levels and reuse potential of all parts at a

building, system/component, and element levels. Durmesivic argues that transformable buildings' elements cannot be attributed to a fixed number of layers as different scenarios might occur. Each scenario calls for a different number configuration and hierarchy of changing layers.

The reversible building approach introduces a comprehensive framework of multiple complementary strategies taking place concurrently, including design for adaptability (DfA), design for disassembly (DfD), and material reuse and recycling. These strategies support the waste hierarchy assumed by the circular economy by questioning the end-of-life options to maintain closed-loop value chains.

To understand the physical capability of buildings to cover as many scenarios as possible, Durmesivic [26] proposes four forms of spatial reversibility of transformable buildings:

1. Trans-functional: switching between four functional scenarios: housing, office, education, and public buildings.
2. Adaptable mono-functional block: when the main use persists while the inhabitants' requirements change as the family members increase or grow older.
3. Transportable from one location to another.
4. Transformable: when it has the capacity to perform all of the three previous changes.

As for structural reversibility and reuse potential, the type of transformation required informs the type of reversibility required. For example, a simple, functional adjustment requires a partial level of reversibility. In contrast, a high level of reversibility assumes dismantling the structure to the initial set of elements so they can be reconfigured to create a new structure of new function or to perform major alterations. Key indicators are the functional independence of a building's elements and parts and the exchangeability of its systems, components, and elements with minimal interface interactions, causing no damage to juxtaposition parts.

The reversible building model has been further developed through the European project of BAMB (2015–2019) where the protocols were implemented and tested on several pilot projects.

## 4. Discussion

### 4.1. Adaptability Assessment Frameworks—Scope and Objectives

Existing adaptability assessment frameworks in large part, act in support of the decision-making at a lifecycle point when a building reaches obsolescence due to different factors (physical, social, economic, environmental, legal, technological, etc.). At this point, it is critical to choose between two alternatives (to demolish or to adapt) in terms of which would be more beneficial and economically viable. Adaptive reuse frameworks often apply to buildings that were not designed for future adaptability in the first place. These buildings often require huge interventions to be adapted to new functions or rehabilitated to carry out similar functions. Adaptive reuse tools are important to advance the circularity of existing buildings. However, other considerations are required to make more efficient decisions (e.g., the possibility of material recovery and waste management). The majority of the reviewed adaptability tools, particularly adaptive reuse models (e.g., ARP, ABD, PAAM, and ARAM), rely on the analysis of obsolescence causes being the trigger to take an adaptive reuse action (see Table 1). They, therefore, use the obsolescence criteria in their methodologies to address future uncertainties (ARP, ABD, IconCUR, AdaptSTAR, PAAM, ARAM). The literature places technical, physical, and economic factors on top of the most influential on a building's useful life. However, this study shows that prioritizing factors mainly depends on the building typology and function, tool purpose, and stakeholders' willingness to preserve it. For example, social, political and economic factors are prioritized over physical aspects for heritage buildings (as shown in the ARAM model). Table 1. presents a comparative analysis of the reviewed tools in terms of indicators' categories, prioritization and weighting methods in addition to the tools' outcomes and lifecycle stage intervention.

**Table 1.** Comparative analysis of existing adaptability models and tools (lifecycle intervention, indicators and outcomes).

Tool Designation	Lifecycle Intervention	Criteria/Indicators			Tool Purpose/Outcomes
		Categories	Prioritized Criteria/Indicators	Weighting Methods	
ARP	Use stage	1. Physical 2. Economic 3. Functional 4. Technological 5. Social 6. Legal	Equally weighted criteria	User subjective decision	ARP index: a percentage of a building potential for adaptive reuse
ABD	Design stage and later incremental adaptations for full lifecycle	1. Market conditions 2. Performance & technology 3. Policies and standards 4. Climate conditions	Case-sensitive	Case-sensitive predictive uncertainty modeling	Lifecycle planning
IconCUR	Use stage	1. Condition 2. Utilization 3. Reward	Not well-established	-Weighted matrix -Pairwise comparison for assigning weights to each sub-criterion -Risk sensitivity analysis	Conceptual decision-making support
AdaptSTAR	Design stage	1. Physical 2. Technological 3. Economic 4. Functional 5. Social 6. Legal 7. Political	Physical criteria: 1. Structural integrity and foundations 2. Material durability and workmanship 3. Maintainability	Practitioner survey using a five-point Likert scale	Star-rating scheme for design evaluation
PAAM	Use stage	1. Physical 2. Social 3. Economic 4. Environmental 5. Legal 6. Technological	1st Physical and size 2nd Land 3rd Social	Principal Component Analysis	Assessment of minor adaptation actions' potential ranging from very low to very high
FLEX 4.0	All lifecycle stages	Brand's layers: 1. Site 2. Structure 3. Skin 4. Facilities 5. Space plan	Two possibilities: 1. default: Structure <hr/> 2. Case sensitive	Author subjective relative weighting	Classification according to flexibility score
SAGA	All lifecycle stages	Space Plan layer	Spatial configuration	Plan graph permeability using a combination of unweighted and weighted graphs	Evaluation of buildings' Spatial configuration of layouts
ARAM	Use stage	1. Environmental 2. Social 3. Economic 4. Legal 5. Political 6. Physical 7. Locational 8. Technical	1st Political and social factors (heritage significance and authenticity) 2nd Economic 3rd Technical 4th Legal 5th Physical	Revision and adaptations of previous models	Conceptual decision-making support

Predicting future changes is a common attribute in adaptability assessment frameworks. However, from a circular economy perspective, the future is unpredictable. Buildings should therefore be prepared to accommodate any type of change that might run at any stage against making the maximum use of the full potentials of its life and the life of its components.

Adaptive reuse tools target a later use stage of buildings to make decisions between two end-of-life options adaptation or demolition. Meanwhile, design-support tools for new



buildings considering a whole lifecycle perspective are still in short supply (see Table 1). Existing ones only focus on specific dimensions of adaptability (e.g., layout adaptability in SAGA model) or specific typologies of buildings (e.g., commercial and office typology in ABD, office, and school building in FLEX 4.0). Table 2 synthesizes the results of the analysis of existing frameworks and methods in terms of target building typology and status, indicator type, and methodology's system and validation. The consideration of residential building typology is another shortcoming of existing models and only addressed in general adaptability frameworks with no specific tool or framework addressing the specific requirements of residential building adaptability. The focus is mostly given to commercial and office buildings because adaptations in these cases do not imply large transformations as those usually use simple layouts. Moreover, existing tools have not addressed radical functional shifts as the adaptability in these tools addresses alterations within the original use of the building.

**Table 2.** Comparative analysis of existing adaptability models and tools (domain, indicator type and methodology).

Tool Designation	Domain			Indicators/Criteria			Methodology	
	New Buildings	Existing Buildings	Typology	Qualitative	Quantitative	Mixed	Weighting System	Validation
ARP		x	General			x	Mathematical algorithm	Case studies
ABD	x		Office commercial			x	ROA and Monte Carlo simulations	One case study
IconCUR		x	General			x	Multi-Criteria Decision Analysis Adaptive Management	Case study Inter-model comparison
AdaptSTAR	x		General	x			Weighted checklist of 26 design criteria	Case study Inter-model comparison
PAAM		x	Office commercial	x			Weighted checklist of 12 indicators	Illustrative case study
FLEX 4.0	x		General Office School	x		x	The sum of indicators values after multiplying by assigned weights	Case study
SAGA	x	x	Residential		x		No final score Indicators are individually calculated using BIM software	Case study of 6 representative layouts
ARAM		x	Heritage	x			A sequence of conditions needs to be met for a building to be considered suitable for adaptation	Case study Inter-model comparison

Criteria and indicators in the reviewed tools are often of qualitative and/or qualitatively quantified nature. Moreover, tools' frameworks were only tested on illustrative single case studies representing certain scenarios. Some of the frameworks also used inter-model comparisons for validation. As a result, most of the tools do not provide evidence on which design strategies/indicators most influence the overall adaptability performance. Multiple empirical studies addressed this aspect (e.g., [28]). However, only a few of those were quantitative [17].

The tools reviewed in Section 3.1 are developed to measure adaptability as a stand-alone objective. However, other building operational and design aspects also influence the decision-making processes and the overall adaptability performance. The findings and their implications should therefore be discussed in the broadest context possible. This calls for an integrated approach within wider spectrum frameworks, i.e., building circularity, where results can be interpreted from the perspective of the working hypotheses and the experiments of case-sensitive trade-offs.

An emerging yet important issue is the visual simulation of building adaptation and the use of Building Information Modelling (BIM) technologies. Although it is still in an early stage (only the SAGA model 2019 established a BIM linkage), the development of data-driven quantitative modeling forms a potential future research direction for more efficient and multi-perspective assessments.

#### 4.2. Circularity Assessment Frameworks—Scopes and Objectives

The application of CE principles in real estate, building design, and use (adaptability, durability, waste reduction, and high-quality management according to the European Commission [68]) is mainly focused on new buildings where circularity can be embedded and facilitated since the early design stage and consequently throughout the whole life cycle of a building and its components and materials. Conversely, circularity in the context of existing buildings is not yet defined [69]. The multitude of definitions of CE, particularly circularity in the built environment, does not contribute to a coherent, systematic approach. CE needs to be viewed as a business strategy, not only waste management or a design strategy. Optimizing buildings' use should also be spotlighted instead of only viewing those as potential material banks where components and materials can be recovered, reused, or recycled for new constructions [14,69]. Still, recovered materials from existing buildings face a critical barrier in their technical compatibility and quality appraisal, which put their direct reuse in question, leading to down-cycling processes, engaging extra resources, and energy flows. On the other hand, less has been said about the design aspect of circularity integration in buildings (e.g., design for disassembly (DfD), design for adaptability (DfA), design for change (DfC), etc.) and the role of building professionals and supply chain elements in embodying the CE principles into the building sector [38]. In other words, existing practices and concerns focus on the CE principle of "closing the loop" which assumes intensified reuse and upcycling of materials and components.

Meanwhile, the CE principle of "slowing the loop" that suggests increasing building and product longevity by preserving their value, quality, and efficiency to the highest possible extent has received less attention so far. This can be justified by the influence of the prevailing construction and design culture during the last decades of viewing buildings as temporal products of limited life service and predefined destiny—demolition. Another key principle of CE that is rarely addressed by existing frameworks is "narrowing the loop" which relies on using fewer resources per product. This principle is inspired by nature's processes that mainly use a limited chemical palette, often consisting of six elements: carbon, hydrogen, oxygen, nitrogen, phosphorus, and sulfur, while industrial manufacturers follow a different approach, seeking out rare and toxic elements to reach the desired functional properties. Narrowing the loop delivers conditions for recycling by allowing efficient and facilitated material separation and recovery.

Moreover, several tools have been developed to support the decision-making of designing or/and assessing buildings for circularity. However, many of these tools serve the same purpose with slight differences in goal and scope. The majority were developed to focus on specific aspects of circularity without considering other aspects, such as supporting products and materials choice by only substantiating material-related indicators based on their environmental impacts (e.g., aspects of health, non-toxic composition) and reuse and recycling potential, such as Materials Passports (MP), Circular Materials Platforms, Material Circularity Index (MCI) developed by the Ellen McArthur Foundation [13], and material flow analysis (MFA) tools. However, these tools fail to address a comprehensive circularity conception and lead to a loss of criticality when used individually since they do not appraise all the other important design aspects, e.g., building composition and connectivity between elements, durability, and service life of building components. This is because circularity values come up when specified intrinsic properties (material and product characteristics) cross with relational properties (building design and use characteristics) [25]. For example, a building, e.g., can be made of 100% circular materials and products, but when those are unreachable for replacement or maintenance, the building system becomes non-circular.

Multiple sustainability rating tools were used to assess circularity considering it as an added value to sustainability. LCA-based tools such as SimaPro, ReCiPe, and Open LCA are widely used for the sustainability assessment of buildings. The use of LCA tools in the context of circularity assessment considering end-of-life options results in more comprehensive assessments. Yet, these tools only addressed the environmental results without other aspects. Similarly, LCC-based tools are used to address the economic aspect of circularity in buildings, investigate the feasibility of circular solutions and conduct financial impact analysis of circular business models. Still, LCA and LCC methods are considered time-consuming and complex to base design choices on [67]. They also rely in part on inaccessible data. S-LCA or Social Lifecycle Assessment is a relatively recent type of LCA, which has been investigated to complement the triple bottom line of sustainability towards a common framework of sustainability. However, S-LCA has been rarely investigated to calculate the social and socio-economic impacts of products circularity. Furthermore, renowned sustainability certification schemes such as BREEAM and LEED continuously include different aspects of circularity in their assessment models. Although these tools are constantly being upgraded, they are often adapted to marketing purposes and rarely consider the critiques posed by the theoretical and empirical research [70,71]. Moreover, their accessibility and costs are in question for young designers.

Some frameworks provide strategies to implement circularity through practical guidelines and successful practices supporting the concept of learning by doing. A prominent example is the circular design guide put forward by the Ellen McArthur Foundation (EMF) and IDEO [72]. Another guide that targets building designers and professionals, in particular, is introduced by VUB Architectural Engineering [73]. This guide illustrates 16 design qualities and principles for a circular economy implementation in buildings. Although useful to establish a circular mindset, these guides do not provide evidence on what circularity measures are the best fit for a certain case.

More recent tools have been developed in the spectrum of the CE, such as Circular Building Assessment Prototype (CBA) developed by the European Union (EU) project of BAMB, Circularity Calculator [50], and Building Circularity Index [57]. These tools introduce rating systems to calculate a circularity score aiming at objectifying the circularity performance of a building or a building element. However, they are criticized for their lack of a participatory and practice-oriented approach, which is fundamental to the need to appraise the impact of rating tools on the design process. Moreover, there is no clear link between the outcome of these tools and the actual environmental impact of the investigated solution. The Level(s) framework developed by the European Commission introduced a more inclusive approach towards circularity in this regard. However, the consideration of circularity here is mainly featured in macro-objective 2—resource efficiency and circular material lifecycles—consisting of three lifecycle tools. Although Level(s) provides guidelines for doing simplified, detailed, or optimization studies, it delivers a less concrete framework for circular design strategies such as DfA, which is assessed relying on simple checklists. Moreover, the market uptake of Level(s) is still limited, and a strong position still has to be found in the playing field of international frameworks such as LEED and BREEAM and other national frameworks.

The multiple aspects addressed by the different types of tools and the similarities among most objectives point out the need to create complementarity rather than establish new ones from scratch. Still, most existing tools are developed to support design decisions and perform comparative analyses. They do not develop solutions and strategies to implement circularity in buildings nor sufficiently consider the role of design which is not merely at the initial planning process but rather persisting along the lifecycle of products and services and remains relevant at any point.

Indicators and circularity evaluation methods for building are still under development [40]. The emergence of Building Information Modeling (BIM) has created new opportunities to improve process efficiency and productivity, which have already been considered in multiple tools frameworks, e.g., the Design Criteria for Circular Buildings [40]

and C-Calc [74]. However, the application of BIM to address these issues is still in its early stages. Among the tools presented above, only one tool has been found using the tool of BIM to track information flows: the D-DAS. Among the several applications of BIM for the construction industry, authors have recognized its influence on building sustainability, mainly on decision support, material information storage, managing the building end of life scenarios, and waste minimization [60,75]. Despite the great opportunity to link BIM with CE principles, it is still a growing topic with few related investigations. BIM has been widely integrated into some circularity-related fields, such as automated LCA, LCC, or sustainability assessment [76]. The role of BIM for circular thinking concerns the ability to accumulate multidisciplinary lifecycle information about a building, together with the possibility of process automation [77]. Lately, Akanbi et al. [77] developed a BIM-based Whole-life Performance Estimator to forecast the end-of-life performance of building materials by simulating their reusability or recovery scenarios. They have also contributed to a BIM-based disassembly and deconstruction system to manage the end-of-life performance of buildings during the design and construction stages [60]. A couple of attempts have been made in another CE-related field to develop BIM-based Material Passports [78,79]. Concerning the practical assessment of circularity, Di Biccari et al. [80] developed a BIM-based framework to evaluate circularity through an Autodesk Revit add-in, based on MP, circular business models, LCA, and LCC. Still, researchers have recognized the infancy and barriers of BIM integration on CE, as well as the lack of circularity-oriented tools, the existence of different material databases and data gaps during the early modelling stage [78,80].

#### 4.3. DfA Role in Circularity Frameworks

Generally, the role of design has been recognized by existing circularity assessment models for buildings where DfA has been identified as a key criterion for circularity and, consequently, sustainability. This can be found in the examples of categories addressed in Sections 3.2.2, 3.2.3 and 3.2.5. However, DfA has been dealt with in different manners. The CE meter [54] introduces a conceptual framework for circularity assessment in buildings where DfA is the core component. The authors consider that circularity criteria should be based on the DfA criteria provided by a previous model developed by the authors to assess the adaptability of buildings (FLEX 2.0 Light). Although the DfA principles were discussed by Verberne [55] to create the BCI, aspects of life expectancy and duration were not considered as much as aspects of multiple-life products. The calculation of the BCI helps determine the level of circularity. However, it does not aid in comparing design alternatives. Attia et al. [40] recognize functional adaptability as one of four primary design criteria for increased circularity. C-Calc [74] evaluates three aspects equally weighted in all projects: material use, adaptability, and information flow. The adaptability in this model relies on a building's passive capacity to change its use, limiting the scale of intervention and minimizing engagement of extra resources and energy. The adaptive capacity relies on the reversibility of the component which allows safe recovery of materials with minimal damage. Transformation capacity and functional adaptability are not considered as much. Another aspect about this tool is the emphasis on information tracking during the project's full lifecycle, which is important to establish a closed-loop feedback system ensuring more efficient end-of-life options; i.e., future adaptability, disassembly, and components recovery.

As for sustainability rating systems such as BREEAM and LEED, aspects related to buildings' adaptive capacity are considered a consequence of integrating the circular economy perspective into these schemes. However, these tools are developed for commercial purposes and certifications, limiting their adequacy for comparison design alternatives. The European common framework Level(s) provide a promising method with an integrated approach accessible for all. The use of the DfA lifecycle tool can be carried out at three levels of performance assessment: common, comparative, and optimized. The common level provides a simple checklist of design aspects that facilitate a building's adaptability. Two forms of the checklist are available for office and residential buildings. The comparative performance assessment relies on using a pre-existing index or assessment tool to deliver

a numerical score. In this regard, the Level(s) framework provides some guidance and recommendations regarding the tool to be utilized for the assessment. The optimization assessment includes more complex modeling and consideration of various factors to ensure comprehensive reporting on the improvement potential of the considered adaptability measures. At this level, the framework recommends using a simulation software tool to analyze adaptability scenarios. Given all, the framework is not self-sufficient in terms of adaptability. The reliance on external models brings up questions of compatibility with the scope and objectives of the framework. Since the framework is still under development, future research may address this question together with others related to possible trade-offs among the three lifecycle scenarios and the utilization of BIM tools.

An overall shortcoming of the frameworks reviewed in this study is that they have not addressed the magnitude of DfA's impact on the overall building circularity rates. They also fail to compile and embed DfA principles altogether into the four hierarchal levels of a building composition, i.e., materials, products, systems, and building design.

#### 4.4. Outline of Requirements for Inclusive Circularity Assessment

It can be concluded that circularity in buildings can be incorporated at different yet interconnected scales: materials, products, systems, and building design. The most comprehensive requirements for circularity assessment in buildings are delivered by Dams et al. [61], who took into account factors of life cycle assessment for materials and multiple factors for DfA and DfD, including varying durability of elements, prefabrication, connections, element reuse, and foundation design. However, the authors used these requirements to develop two levels of assessment, elementary and building levels, which are conducted separately.

This study identifies the circularity requirements on four assessment levels, presented in Figure 2.

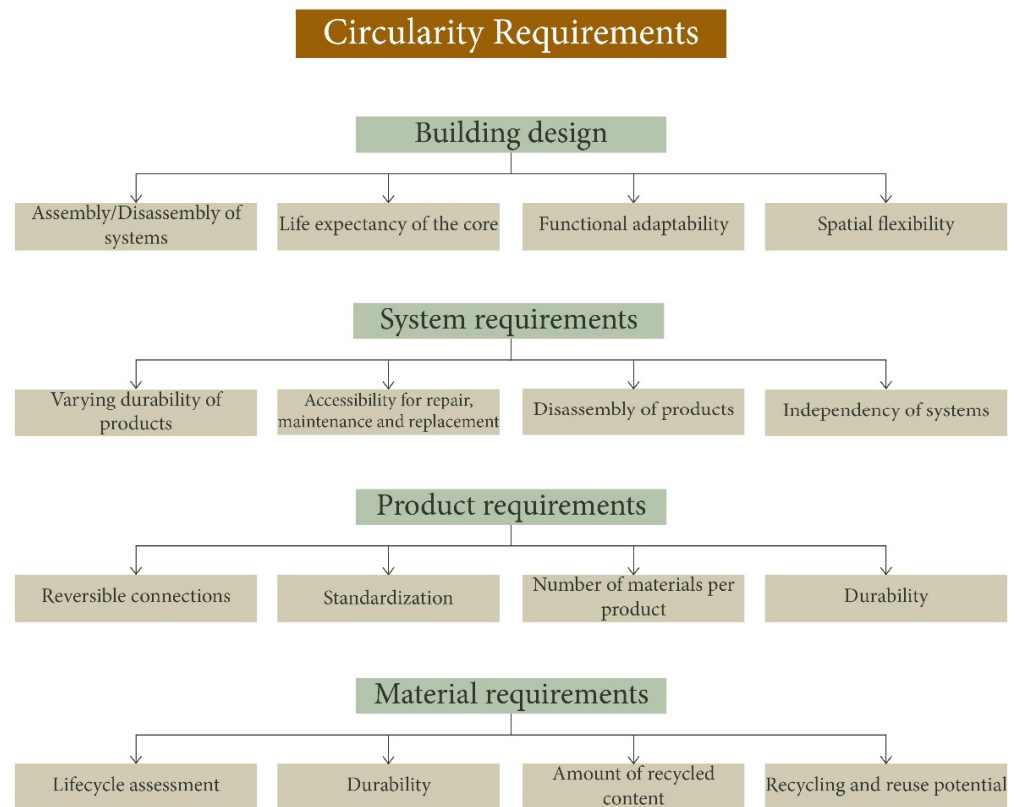


Figure 2. Circularity requirements.

A holistic framework to create, rate, and benchmark circularity in buildings must consider all the lifecycle stages from planning to end-of-life options with all the associated input–output flows of materials as well as the engagement of a diverse group of stakeholders with interlocking specialties.

## 5. Conclusions

The existing adaptability assessment frameworks often address changes within the same building typology and function, relying on methods and indicators mostly subjective. In addition, the effectiveness and validity of those are not sufficiently tested or verified. Therefore, more empirical data prioritizing the most valuable criteria that facilitate adaptations are required for all building typologies.

The wide variety of existing CE frameworks' objectives and scopes can be attributed to the open nature of the CE definition and conceptualization, which has led to controversial understanding by the different stakeholders.

Integrating DfA assessment in building circularity frameworks helps objectify its role as a key enabler to circularity strategies. It also informs more accurate and inclusive decision-making as well as performance assessment.

One of the major shortcomings of most circularity frameworks developed so far is the lack of integration of the triple bottom line of sustainable development, which is supposed to be the ultimate goal for the circular economy. However, it is not the case for sustainability assessment frameworks that recognize circularity as the contemporary enabler to sustainability which upgrades its requirements over time.

An integrated approach to benchmark the new generation of sustainable buildings, therefore, requires measures that address the complexity of a building system consisting of different hierarchical levels with their adaptability and circularity respective requirements. Furthermore, the technical integration of circularity must be coupled with value chain management and reconciliation with the other sustainability factors.

From the review and analysis presented in this study, the following gaps are identified:

1. There is a lack of quantitative models for adaptability assessment as well as evidence on the effectiveness of their indicators and criteria on the different typologies of buildings.
2. There is a lack of multi-criteria approaches supporting design that allow to deal with conflicting situations, as well as assess design options and advise better circularity scenarios at whatever point throughout a building's lifecycle. More automated indicators are essential to evaluate design options and facilitate necessary trade-offs for enhanced circularity.
3. Future research should tackle the practicality questions of some of the application of the prominent tools on real-life case studies and identify further obstacles and rooms for innovation that on-desk research methods could not identify.

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## References

1. ARUP. *The Circular Economy in the Built Environment*; ARUP: London, UK, 2016; p. 94.
2. Ness, D.A.; Xing, K. Toward a Resource-Efficient Built Environment: A Literature Review and Conceptual Model. *J. Ind. Ecol.* **2017**, *21*, 572–592. [[CrossRef](#)]
3. Hossain, U.; Thomas Ng, S.; Antwi-Afari, P.; Amor, B. Circular Economy and the Construction Industry: Existing Trends, Challenges and Prospective Framework for Sustainable Construction. *Renew. Sustain. Energy Rev.* **2020**, *130*. [[CrossRef](#)]
4. Anttonen, M.; Lammi, M.; Mykkänen, J.; Repo, P. Circular Economy in the Triple Helix of Innovation Systems. *Sustainability* **2018**, *10*, 2646. [[CrossRef](#)]
5. Geissdoerfer, M.; Savaget, P.; Bocken, N.M.P.; Hultink, E.J. The Circular Economy—A New Sustainability Paradigm? *J. Clean. Prod.* **2017**, *143*, 757–768. [[CrossRef](#)]
6. Murray, A.; Skene, K.; Haynes, K. The Circular Economy: An Interdisciplinary Exploration of the Concept and Application in a Global Context. *J. Bus. Ethics* **2017**, *140*, 369–380. [[CrossRef](#)]
7. Prendeville, S.; Cherim, E.; Bocken, N. Circular Cities: Mapping Six Cities in Transition. *Environ. Innov. Soc. Trans.* **2018**, *26*, 171–194. [[CrossRef](#)]
8. Korhonen, J.; Nuur, C.; Feldmann, A.; Birkie, S.E. Circular Economy as an Essentially Contested Concept. *J. Clean. Prod.* **2018**, *175*, 544–552. [[CrossRef](#)]
9. Ellen MacArthur Foundation. *Towards the Circular Economy Vol. 1: Economic and Business Rationale for an Accelerated Transition*; Ellen MacArthur Foundation: Cowes, UK, 2013; p. 98.
10. Nikolaou, I.E.; Jones, N.; Stefanakis, A. Circular Economy and Sustainability: The Past, the Present and the Future Directions. *Circ. Econ. Sustain.* **2021**, *1*, 1–20. [[CrossRef](#)]
11. Ellen MacArthur Foundation. *Towards the Circular Economy Vol. 2: Opportunities for the Consumer Goods Sector*; Ellen MacArthur Foundation: Cowes, UK, 2013; p. 112.
12. Ellen MacArthur Foundation. *Towards the Circular Economy Vol. 3: Accelerating the Scale-Up across Global Supply Chains*; Ellen MacArthur Foundation: Cowes, UK, 2014; p. 41.
13. Ellen MacArthur Foundation. *Granta Design Circularity Indicators: An Approach to Measuring Circularity*; Ellen MacArthur Foundation: Cowes, UK, 2015.
14. Adams, K.T.; Osmani, M.; Thorpe, T.; Thornback, J. Circular Economy in Construction: Current Awareness, Challenges and Enablers. *Proce. Inst. Civ. Eng.-Waste Resour. Manag.* **2017**, *170*, 15–24. [[CrossRef](#)]
15. Environmental Services Association. *Planning for a Circular Economy*; Environmental Services Association: London, UK, 2017; p. 20.
16. Ellen MacArthur Foundation. *Growth within: A Circular Economy Vision for a Competitive Europe*; Ellen MacArthur Foundation: Cowes, UK, 2015; p. 98.
17. McFarland, D.; Ross, B.; Naser, M.Z.; Blok, R.; Teuffel, P. Quantitative Evaluation of the Relationship between Physical Parameters and Building Demolition or Adaptation Outcomes. *Archit. Struct. Constr.* **2021**. [[CrossRef](#)]
18. De Schoenmakere, M.; Gillabel, J.; European Environment Agency. *Circular by Design: Products in the Circular Economy*; European Environment Agency: Luxembourg, 2017; p. 56.
19. Heidrich, O.; Kamara, J.; Maltese, S.; Re Cecconi, F.; Dejaco, M.C. A Critical Review of the Developments in Building Adaptability. *Int. J. Build. Pathol. Adapt.* **2017**, *35*, 284–303. [[CrossRef](#)]
20. Askar, R.; Bragança, L.; Gervásio, H. Adaptability of Buildings: A Critical Review on the Concept Evolution. *Appl. Sci.* **2021**, *11*, 4483. [[CrossRef](#)]
21. Guy, B.; Ciarimboli, N. *Design for Disassembly in the Built Environment: A Guide to Closed-Loop Design and Building*; The Pennsylvania State University: Hamer Center, PA, USA, 2008; p. 69.
22. Kamara, J.M.; Heidrich, O.; Tafaro, V.E.; Maltese, S.; Dejaco, M.C.; Re Cecconi, F. Change Factors and the Adaptability of Buildings. *Sustainability* **2020**, *12*, 6585. [[CrossRef](#)]
23. Rios, F.C.; Chong, W.K.; Grau, D. Design for Disassembly and Deconstruction—Challenges and Opportunities. *Procedia Eng.* **2015**, *118*, 1296–1304. [[CrossRef](#)]
24. Akinade, O.O.; Oyedele, L.O.; Ajayi, S.O.; Bilal, M.; Alaka, H.A.; Owolabi, H.A.; Bello, S.A.; Jaiyeoba, B.E.; Kadiri, K.O. Design for Deconstruction (DfD): Critical Success Factors for Diverting End-of-Life Waste from Landfills. *Waste Manag.* **2017**, *60*, 3–13. [[CrossRef](#)]
25. Geldermans, R.J. Design for Change and Circularity—Accommodating Circular Material & Product Flows in Construction. *Energy Procedia* **2016**, *96*, 301–311. [[CrossRef](#)]
26. Durmisevic, E. Dynamic and Circular Buildings by High Transformation and Reuse Capacity. In *Circular Economy Innovation & Design*; The Centre for Sustainable Design: Surrey, UK, 2016; p. 15.
27. Van den Berg, M.; Durmisevic, E. BIM Uses for Reversible Building Design Identification, Classification & Elaboration. In *Vital Cities and Reversible Buildings*; Sarajevo Green Design Foundation: Mostar, Bosnia and Herzegovina, 2017.
28. Rockow, Z.; Ross, B.; Becker, A. Comparison of Building Adaptation Projects and Design for Adaptability Strategies. *J. Archit. Eng.* **2021**, *27*. [[CrossRef](#)]
29. Askar, R.; Bragança, L.; Gervásio, H. Designing Buildings for Adaptability, Flexibility, and Durability. In *Sustainable Urban Development—Topics, Trends and Solutions*; IOP Publishing Ltd.: Bristol, UK, 2021; Volume 10, pp. 11–15. ISBN 978-0-7503-3971-1.

30. Knecht, B. Architectural Record. 2003, pp. 181–188. Available online: <https://www.architecturalrecord.com/authors/1256-barbara-knecht> (accessed on 8 February 2022).
31. Schmidt, R.; Eguchi, T.; Austin, S.; Gibb, A. What is the meaning of adaptability in the building industry? In Proceedings of the 16th International Conference on Open and Sustainable Buildings, Bilbao, Spain, 17–19 May 2010; pp. 227–236.
32. Herthogs, P.; Debacker, W.; Tunçer, B.; De Weerd, Y.; De Temmerman, N. Quantifying the Generality and Adaptability of Building Layouts Using Weighted Graphs: The SAGA Method. *Buildings* **2019**, *9*, 92. [[CrossRef](#)]
33. Habraken, N.J. *Supports: An Alternative to Mass Housing*; Praeger Publishers: New York, NY, USA, 1972; ISBN 978-0-85139-625-5.
34. Duffy, F. Measuring Building Performance. *Facilities* **1990**, *8*, 17–20. [[CrossRef](#)]
35. Brand, S. *How Buildings Learn: What Happens after They're Built*; Penguin Books: New York, NY, USA, 1994; ISBN 978-0-14-013996-9.
36. Calheiros, C.S.C.; Stefanakis, A.I. Green Roofs Towards Circular and Resilient Cities. *Circ. Econ. Sustain.* **2021**, *1*, 395–411. [[CrossRef](#)]
37. Pomponi, F.; Moncaster, A. Circular Economy for the Built Environment: A Research Framework. *J. Clean. Prod.* **2017**, *143*, 710–718. [[CrossRef](#)]
38. Kanters, J. Circular Building Design: An Analysis of Barriers and Drivers for a Circular Building Sector. *Buildings* **2020**, *10*, 77. [[CrossRef](#)]
39. Geldermans, B.; Tenpierik, M.; Luscuere, P. Circular and Flexible Infill Concepts: Integration of the Residential User Perspective. *Sustainability* **2019**, *11*, 261. [[CrossRef](#)]
40. Attia, S.; Al-Obaidy, M. Design Criteria for Circular Buildings. In Proceedings of the Crossing Boundaries-Towards a Circular, Sustainable and Vital Built Environment, Parkstadt, The Netherlands, 24 March 2021.
41. Langston, C.; Wong, F.K.W.; Hui, E.C.M.; Shen, L.-Y. Strategic Assessment of Building Adaptive Reuse Opportunities in Hong Kong. *Build. Environ.* **2007**, *43*, 1709–1718. [[CrossRef](#)]
42. Wilkinson, S. The preliminary assessment of adaptation potential in existing office buildings. *Int. J. Strateg. Prop. Manag.* **2014**, *18*, 77–87. [[CrossRef](#)]
43. Langston, C.; Smith, J. Modelling Property Management Decisions Using ‘IconCUR’. *Autom. Constr.* **2012**, *22*, 406–413. [[CrossRef](#)]
44. Conejos, S.; Langston, C.; Smith, J. AdaptSTAR Model: A Climate-Friendly Strategy to Promote Built Environment Sustainability. *Habitat Int.* **2013**, *37*, 95–103. [[CrossRef](#)]
45. Allahaim, F.; Alfaris, A.; Leifer, D. Towards changeability—The Adaptable Buildings Design (ABD) Framework. In Proceedings of the 5th International Conference of the Arab Society for Computer Aided Architectural Design, Fes, Morocco, 19 October 2010; pp. 190–200.
46. Rockow, Z.R.; Ross, B.; Black, A.K. Review of Methods for Evaluating Adaptability of Buildings. *Int. J. Build. Pathol. Adapt.* **2019**, *37*, 273–287. [[CrossRef](#)]
47. Chudley, R. *The Maintenance and Adaptation of Buildings*; Longman: London, UK, 1981.
48. Geraedts, R. FLEX 4.0, A Practical Instrument to Assess the Adaptive Capacity of Buildings. *Energy Procedia* **2016**, *96*, 568–579. [[CrossRef](#)]
49. Mehr, S.Y.; Wilkinson, S. A model for assessing adaptability in heritage buildings. *Int. J. Conserv. Sci.* **2021**, *12*, 88–104.
50. IDEAL&CO. Explore BV Circularity Calculator. Available online: <http://www.circularitycalculator.com/> (accessed on 23 November 2021).
51. De Pauw, I.; van de Grinten, B.; Flipsen, B.; Alvarez-Mendez, L. *The Circularity Calculator, a Tool for Circular Product Development with Circularity and Potential Value Capture Indicators*; University of Limerick: Limerick, Ireland, 2021; pp. 1–8.
52. Franklin-Johnson, E.; Figge, F.; Canning, L. Resource Duration as a Managerial Indicator for Circular Economy Performance. *J. Clean. Prod.* **2016**, *133*, 589–598. [[CrossRef](#)]
53. Figge, F.; Thorpe, A.S.; Givry, P.; Canning, L.; Franklin-Johnson, E. Longevity and Circularity as Indicators of Eco-Efficient Resource Use in the Circular Economy. *Ecol. Econ.* **2018**, *150*, 297–306. [[CrossRef](#)]
54. Geraedts, R.; Prins, M. The CE Meter: An Instrument to Assess the Circular Economy Capacity of Buildings. In Proceedings of the CIB International Conference Going North for Sustainability, London South Bank University, London, UK, 23–25 November 2015; pp. 60–69.
55. Verberne, J.J.H. *Building Circularity Indicators—An Approach for Measuring Circularity of a Building*; Eindhoven University of Technology: Eindhoven, The Netherlands, 2016.
56. Van Vliet, M.M. Disassembling the Steps towards Building Circularity—Redeveloping the Building Disassembly Assessment Method in the Building Circularity Indicator. Master’s Thesis, Eindhoven University of Technology, Eindhoven, The Netherlands, 2018.
57. Alba Concepts. Building Circularity Index. Available online: <https://albaconcepts.nl/building-circularity-index/> (accessed on 3 October 2021).
58. Van Schaik, C.W. Circular Building Foundations—A Structural Exploration of the Possibilities for Making Building Foundations Contribute to a Circular Economy. Master’s Thesis, Delft University of Technology, Delft, The Netherlands, 2019.
59. BAMB Circular Building Assessment Prototype. Available online: <https://www.bamb2020.eu/post/cba-prototype/> (accessed on 19 March 2021).



60. Akanbi, L.A.; Oyedele, L.O.; Omotoso, K.; Bilal, M.; Akinade, O.O.; Ajayi, A.O.; Davila Delgado, J.M.; Owolabi, H.A. Disassembly and Deconstruction Analytics System (D-DAS) for Construction in a Circular Economy. *J. Clean. Prod.* **2019**, *223*, 386–396. [[CrossRef](#)]
61. Dams, B.; Maskell, D.; Shea, A.; Allen, S.; Driesser, M.; Kretschmann, T.; Walker, P.; Emmitt, S. A Circular Construction Evaluation Framework to Promote Designing for Disassembly and Adaptability. *J. Clean. Prod.* **2021**, *316*, 128122. [[CrossRef](#)]
62. BRE Circularity and BREEAM. Available online: <https://sway.office.com/sQm9vWVxxUY9Hc9n> (accessed on 22 December 2021).
63. Hughes, E. How LEED v4.1 Addresses the Circular Economy. Available online: <https://www.usgbc.org/articles/how-leed-v41-addresses-circular-economy> (accessed on 22 December 2021).
64. Dodd, N.; Cordella, M.; Traverso, M.; Donatello, S. *Level(s): A Common EU Framework of Core Sustainability Indicators for Office and Residential Buildings: Parts 1 and 2, Introduction to Level(s) and How It Works (Beta v1.0)*; Publications Office of the European Union: Brussels, Belgium, 2017; ISBN 978-92-79-76914-6.
65. Corona, B.; Shen, L.; Reike, D.; Rosales Carreón, J.; Worrell, E. Towards Sustainable Development through the Circular Economy—A Review and Critical Assessment on Current Circularity Metrics. *Resour. Conserv. Recycl.* **2019**, *151*, 104498. [[CrossRef](#)]
66. Cencic, O.; Rechberger, H. Material Flow Analysis with Software STAN. *J. Environ. Eng. Manag.* **2008**, *18*, 3–7.
67. Cambier, C.; Galle, W.; De Temmerman, N. Research and Development Directions for Design Support Tools for Circular Building. *Buildings* **2020**, *10*, 142. [[CrossRef](#)]
68. EC Circular Economy—Principles for Buildings Design. 2020. Available online: <https://ec.europa.eu/docsroom/documents/39984> (accessed on 22 December 2021).
69. Kyrö, R.K. Share, Preserve, Adapt, Rethink—A Focused Framework for Circular Economy. *IOP Conf. Ser. Earth Environ. Sci.* **2020**, *588*, 042034. [[CrossRef](#)]
70. Gou, Z.; Xie, X. Evolving Green Building: Triple Bottom Line or Regenerative Design? *J. Clean. Prod.* **2017**, *153*, 600–607. [[CrossRef](#)]
71. Hossain, M.U.; Ng, S.T. Critical Consideration of Buildings’ Environmental Impact Assessment towards Adoption of Circular Economy: An Analytical Review. *J. Clean. Prod.* **2018**, *205*, 763–780. [[CrossRef](#)]
72. Ellen MacArthur Foundation; IDEO. The Circular Design Guide. Available online: <https://www.circulardesignguide.com/> (accessed on 23 September 2021).
73. VUB Architectural Engineering. *Building a Circular Economy. Design Qualities to Guide and Inspire Building Designers and Clients*; Vrije Universiteit Brussel: Brussels, Belgium, 2019; ISBN 978-94-91912-13-9.
74. Cenergie C-CalC. Available online: <https://www.cenergie.be/nl/diensten/advies/c-calc> (accessed on 23 September 2021).
75. Charef, R.; Emmitt, S. Uses of Building Information Modelling for Overcoming Barriers to a Circular Economy. *J. Clean. Prod.* **2021**, *285*, 124854. [[CrossRef](#)]
76. Carvalho, J.P.; Alecrim, I.; Bragança, L.; Mateus, R. Integrating BIM-Based LCA and Building Sustainability Assessment. *Sustainability* **2020**, *12*, 7468. [[CrossRef](#)]
77. Akanbi, L.A.; Oyedele, L.O.; Akinade, O.O.; Ajayi, A.O.; Davila Delgado, M.; Bilal, M.; Bello, S.A. Salvaging Building Materials in a Circular Economy: A BIM-Based Whole-Life Performance Estimator. *Resour. Conserv. Recycl.* **2018**, *129*, 175–186. [[CrossRef](#)]
78. Honic, M.; Kovacic, I.; Sibenik, G.; Rechberger, H. Data- and Stakeholder Management Framework for the Implementation of BIM-Based Material Passports. *J. Build. Eng.* **2019**, *23*, 341–350. [[CrossRef](#)]
79. Atta, I.; Bakhoun, E.S.; Marzouk, M.M. Digitizing Material Passport for Sustainable Construction Projects Using BIM. *J. Build. Eng.* **2021**, *43*, 103233. [[CrossRef](#)]
80. Di Biccari, C.; Abualdenien, J.; Borrmann, A.; Corallo, A. A BIM-Based Framework to Visually Evaluate Circularity and Life Cycle Cost of Buildings. *IOP Conf. Ser. Earth Environ. Sci.* **2019**, *290*, 012043. [[CrossRef](#)]