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Review article

The ecodesign methodologies to achieve buildings' deconstruction: A review and framework

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ABSTRACT

The ecodesign methodologies in the design stage enable buildings to be adapted to the needs of users and deconstructed at the end-of-life. Although ecodesign methods incorporate circular economy (CE) principles, they are little explored in projects and constructions. This study analyses how the construction sector approaches ecodesign methods to achieve buildings' deconstruction. Through an integrative literature review, 288 articles were threefold analyzed: (i) bibliometric, (ii) conceptually about ecodesign methods, and (iii) categorically. The results showed a lack of understanding about the ecodesign concepts, and an integrated methodology was proposed. The most inclusive and sustainable ecodesign method for buildings deconstruction was Design for Adaptability and Disassembly (DfAD). The review shows the concentration of the studies in three categories and a framework was created relating DfAD strategies. The sector needs more information on ecodesign methods, deconstruction strategies, reusing of materials, and in the life cycle tools as decision support to make sustainable buildings.

1. Introduction

The construction sector is responsible for one of the highest amounts of resource use, waste, and emissions of all industries (Pomponi and Moncaster, 2017; Global Alliance for Buildings and Construction (GlobalABC), 2019). Despite being the world's largest consumer of raw materials, only 20–30% of these resources are recycled or reused at the end of a building's useful life (WEF, 2014). In 2018, the sector represented 36% of the end-use of energy and 39% of global carbon dioxide (CO_2) emissions (Global Alliance for Buildings and Construction (GlobalABC), 2019).

To reduce the environmental impacts produced by the sector, strategies have been adopted, mainly concerning energy efficiency and the management of construction and demolition waste (CDW). However, the demand for more energy-efficient buildings often leads to operational strategies that increase the built-in energy (Azari and Abbasabadi, 2018). The environmental savings of reusing/renovating a building can vary from 4 to 46% compared to a new building (Azari and Abbasabadi, 2018). Instead, reuse and recycling reduce waste from landfills, and even the processes involved in recycling make up for in general terms of incorporated energy and carbon emissions.

Deconstruction is an end-of-life (EOL) scenario that favors the recovery of construction components for relocation, reuse, recycling, or remanufacturing of construction (Kibert, 2003). Design for Deconstruction is an ecodesign method that enables the assembly and disassembly of buildings to recover building components. Ecodesign methodologies consider the stage design issues over the life cycle of the building linked to environmental and human health (Pigosso et al., 2010). Despite efforts to mitigate CDW through deconstruction, information on deconstruction projects and the deconstruction process is limited. To Dorsthorst and Kowalczyk (2002) less than 1% of buildings are completely demountable, and since then the scenario has not changed (Kanters, 2018).

The concept of 'Design for Deconstruction', which is also known as 'Design for Disassembly' both known by the acronym DfD, appeared in the construction sector in the 1990s (Kibert, 2003) by ecodesign methodologies from the manufacturing industry (Macozoma, 2002). DfD can be associated with Design for Adaptability (DfA). An adaptable building can be modified by users to meet their constant needs. The adaptability and deconstruction project integrates flexibility to the configuration of space and the recovery of EOL components. The method seeks to maintain building components, parts, and materials at their highest level of utility and value, supporting the introduction of circular economy (CE) principles in the sector. CE is a restorative economic model that

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seeks to dissociate economic development from the consumption of finite resources (Ellen MacArthur Foundation (EMF), 2015).

Several studies have established strategies to guide the incorporation of CE principles for buildings deconstruction. Durmisevic (2001, 2019) demonstrated a Reversible Building Design method based on spatial changes (aspects of the extensibility of the space, replaceability, and change of the functions) and technical changes (accessibility, the extensibility of systems, disassembly, and independence). Thormark (2001) developed eighteen design strategies based on the choice of materials, design of construction, and choice of joints and connections. Nordby et al. (2007) developed a system based on 31 strategies for the recovery of materials. Sassi (2008) established criteria for the closed-loop building materials cycle. Crowther (2016) listed 27 design principles for disassembly.

Although, DfD is not mainstream in the construction sector. There is a gap in the literature on circular business opportunities to introduce practices aiming at closing the material cycle (Munaro et al., 2020). In addition, the sector is conservative, has its own design process, manufacturing techniques, supply chain, and financial arrangements that fail to match the complex nature of the building resulting in inadequate development of CE-focused design guidance and tools. For these reasons, the sustainability of buildings depends on several interconnected attributes, such as building design, choice of material, operation, and maintenance (Sanchez and Haas, 2018). Beside, ecodesign methods have been studied in the sector with different terminologies and definitions. The language used by practitioners and their different interpretations about a design for buildings EOL may lead to misunderstandings about the design objectives (Pinder et al., 2017; Rockow et al., 2019). The conceptualizing of the main ecodesign terms related to deconstruction and a categorized picture of the state-of-the-art of ecodesign methods to achieve deconstruction of buildings are fundamental to understanding and implementing CE principles in the sector.

This review aimed to study how the construction sector approaches the ecodesign methods to achieve buildings' deconstruction. A study has not yet been published that explores the current state of ecodesign concepts aiming at recovery and reuse building components. Through an integrative review, this study sought to (i) provide a bibliometric analysis of studies on ecodesign methods for buildings' deconstruction; (ii) conceptualize the main ecodesign terms related to the deconstruction; and (iii) propose a framework of the categorized studies to achieve buildings' deconstruction. Fig. 1 shows the organization of the study.

2. Ecodesign definition

Sustainability and Industrial Ecology were highlighted in the environmental scenario in the 1980s and 1990s to reduce waste production and pollution in material-intensive sectors. The term eco-efficiency and methodologies such as Ecodesign or Design for the Environment (DfE) appear as alternatives to redesign existing products (Hauschild et al., 2005). Ecodesign can be defined as the consideration of the environmental performance of the product/project over the entire life cycle. Pigosso et al. (2010) consider as a method to develop products aligned with the concept of sustainable development and lifetime thinking. The methodology proposes products to be flexible, reliable, durable, modular, dematerialized, and reusable, moreover, to prove economic reasonableness and social compatibility (Hauschild et al., 2005).

2.1. Ecodesign methodologies in the construction sector

Different ecodesign methods have been developed to assess the environmental impacts of products. The term 'Design for' or 'DfX' has become common, where X represents the design objective regarding the EOL scenarios of a product. Much of the literature under the sustainable design umbrella has focused on consumer goods. To the product design and manufacture industry, such frameworks are Design for Recycling; Remanufacturing; and Disassembly (Hauschild et al., 2005).

In the construction sector the methodologies of 'Design for' started being incorporated to improve high-level recycling of the building materials and components (Dorsthorst and Kowalczyk, 2002). However, the design, construction, and maintenance characteristics of buildings are different from consumer goods. Buildings have greater longevity, large capital investments, and a multiplicity of stakeholders throughout the life cycle. Particularities increase the complexity of adopting ecodesign methods. To implement ecodesign methodologies in the sector it is needed to consider that buildings are formed by a system of components, parts, and materials with different useful lives. To the complexity of the buildings, it is pertinent that the understanding of the ecodesign terms is clarified. Particularly regarding terminology, the meanings practitioners associate with the different DfXs methods, how these meanings are communicated, and how to implement them in the building industry.

2.2. The deconstruction approach in the context of a circular economy

The need to build flexible and demountable projects began when human beings needed to be nomadic. The mobility and temporary structures became issues of survival. Later, the concept of ephemeral architecture was an important milestone for the development of cultures and structures for temporary events (Crowther, 2016). Since the 1970s, rules for deconstruction have been established in conventions, guidelines, or declarations, to increase usability and extend the functional life of buildings. In 1976 the research of DfD had included works of complete house moving and support systems (Cai and Waldmann, 2019). In 1992, Berge presented principles for the direct reuse of building materials (Nordby et al., 2007). Brand (1994) advised the design of the building on separate layers. In 1999, a group was created by the International Council for Research and Innovation in Building Construction (CIB) to produce an analysis, meetings, and reports to make deconstruction and reuse of building materials feasible options.

Methodologies to assist and evaluate deconstruction have been developed. Akinade et al. (2015) projected an evaluation system associating material selection based on Building Information Modeling (BIM). Akanbi et al. (2018) developed a model to estimate the life cycle performance of structural components recovery. Sanchez and Haas (2018) established a model for selective disassembly sequence for adaptive reuse of buildings. Recent studies have focused on cost and environmental impact analyses carried out at the end of the buildings' life cycle (Tatiya et al., 2018; Buyle et al., 2019), and on challenges and opportunities in the practice of deconstruction activities (Rios et al., 2015; Akinade et al., 2019).

At the macro level of the construction sector, policies that aim to close the material cycle have also gained prominence. Many political programs and plans have been developed to implement circular principles in the sector. Ellen MacArthur Foundation (EMF) (2015) developed a program in which organizations collaborate to enable the creation of new CE opportunities. The European Commission has developed the Circular Economy Action Plan and the Buildings as Material Banks (BAMB). BAMB adopted the concept of Reversible Building Design based on the repair, reuse, and recovery of materials (BAMB, 2021). Despite efforts, Design for Adaptability or Deconstruction/Disassembly is very limited in the sec-

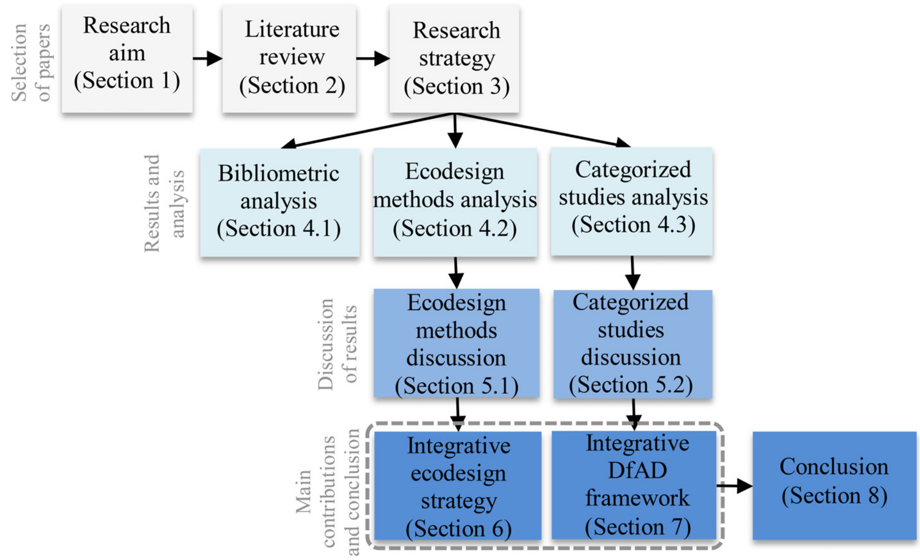

Fig. 1. The research process development.

tor. The sector is still very conservative in adopting and doing things differently (Kanters, 2018). A major challenge identified in the literature is that building projects do not have enough information about how they could be deconstructed (Adams et al., 2017; Akinade et al., 2019). Understanding the relationship between the different 'DfX' methods and the CE is essential for reducing environmental impacts, implementing circular strategies, and positioning the DfD within the building sustainability ecosystem.

3. Research strategy

The research methods adopted consist of an integrative literature review based on six stages, as summarized in Fig. 2. The process followed a succession of six steps based on Torraco (2005), Whittemore and Knafl (2005), and Tranfield et al. (2003). An integrative review is the broadest methodological approach to reviews and incorporates different purposes for a complete understanding of the analyzed phenomenon (Whittemore and Knafl, 2005).

The selected articles were analyzed under three lenses: bibliometric, analysis of the ecodesign methods, and content analysis. The content analysis attains a condensed and broad description of the topic, and the outcome is categorized by describing the phenomenon (Elo and Kyngas, 2008). Fig. 3 shows the processing of the review in the scientific literature. The search terms were based on a previous analysis of the literature. Duplicate studies, from other areas of knowledge, and that did not match the research question were removed.

4. Results and analysis

The analysis of the results was divided into three sections: (i) a bibliometric analysis, (ii) an ecodesign methods analysis, and (iii) a categorized analysis.

4.1. Bibliometric analysis

Fig. 4 shows the research methodological approach of the studies. The publications were classified according to the research approach, research aim, the procedure adopted, data source, and data collection (Malhotra, 2012). The articles presented a majority qualitative approach (59% of articles), followed by quantitative (38%), and a mixed approach (3%). The predominance of the research aim was descriptive (68%), followed by exploratory (22%), and causal type (10%). Bibliographic research was the most adopted technique (52%), followed by modeling and/or simulation (25%), experiments (10%), case studies (8%), and surveys (4%). Literature review (50%) was the most representative type of data collection. The predominance of descriptive qualitative studies shows the sector's tendency to describe and correlate aspects of deconstruction practices in buildings, in line with exploratory studies, which aim to provide greater familiarity with the problem and make it more explicit for the community of interest.

Fig. 5 shows the evolution of the number of publications and citations. The DfD concept has emerged in the 90s (Kibert, 2003) and the first publication reiterates the need to leverage the existing stock of vacant commercial buildings into new housing as an effort towards more sustainable urban development (Barlow and Gann, 1995). After 2010, the increase in publications remained constant over the years, a point that corroborates the developments in CE linked to the institution of the first circular law in China (Munaro et al., 2020). The highest number of publications in 2019 considers the publication of the proceeding's papers of the final event of BAMB-CIRCPATH: A Pathway for a Circular Future. The last four years account for 61% of the research, indicating the interest in the adoption of ecodesign practices in the sector. Citations showed an increasing trend over the years, with a peak in 2008 due to the article by Osmani et al. (2008), which is the most cited in the review and investigates the role of architects in minimizing the generation of construction waste in the design phase.

The studies are distributed in 86 journals (59%, 170 articles) and 62 proceedings papers (41%, 118 articles), emphasizing the extension and decentralization of the subject. Most of the scientific journals have environmental issues and CE as a focus of interest. The two most representative journals were the Journal of Cleaner Production and Resources, Conservation & Recycling. As for the proceedings paper, the highlight was the IOP Conference Series: Earth and Environmental Science with 42 publications (15%), because of the publications of the studies of the final BAMB-CIRCPATH conference.

Fig. 6 shows the geographical distribution of the publications according to the first author's country. Europe accounted for 64% of the research covering 24 countries, followed by North America and Asia with 14% each. These regions accounted for 90% of the review studies. Among the 41 countries, the United Kingdom (UK) is the leading in volume (48 articles) of the publications, followed

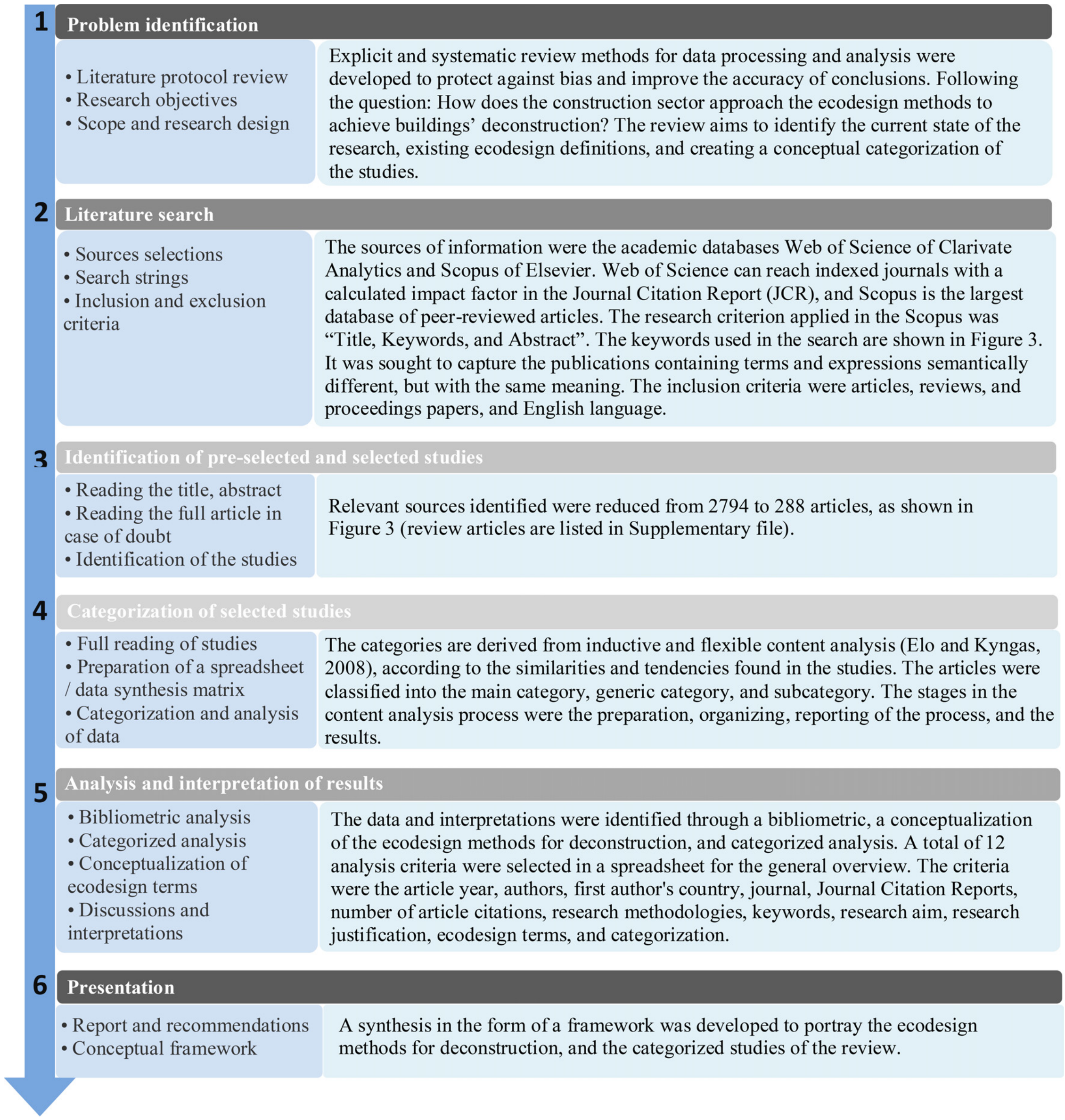

Fig. 2. Stages, decisions, and processes of the integrative review.

Search terms / Databases (No articles)			
	Search strings	Web of science	Scopus
a	("circul* buil*" OR "circul* construct*")	118	189
b	("design* for adaptab*" OR ("design* adaptab*" AND buil*) OR ("design* adaptab*" AND construct*))	45	86
c	("design* for deconst*" OR "design* deconst*")	34	48
d	("design* for disassemb*" OR ("design* disassemb*" AND buil*) OR ("design* disassemb*" AND construct*))	244	348
e	(("design* for modula*" AND buil*) OR ("design* for modula*" AND construct*) OR ("design* modula*" AND buil*) OR ("design* modula*" AND construct*))	128	223
f	(("design* for transforma*" AND buil*) OR ("design* for transforma*" AND construct*) OR ("design* transforma*" AND buil*) OR ("design* transforma*" AND construct*))	34	47
g	(("design* out waste*") OR ("design* waste*" AND buil*) OR ("design* waste*" AND construct*)	38	50
h	(("design* for change*" AND buil*) OR ("design* for change*" AND construct*))	18	35
i	(("build* deconst*") OR (build* AND deconst* AND circular*))	47	57
j	(("flexib* build*" AND "sustainab*") OR ("flexib* AND build*" AND "circular* econom*") OR ("flexib* build*" AND deconst*))	15	29
k	(("revers* build*") OR (revers* AND build* AND circular* econom*))	29	46
l	(("demount* build*") OR (demount* AND build*))	55	120
m	("transform* build*" OR (transform* AND build* AND "circular* econom*"))	136	170
n	("build* reus*" OR (build* AND reus* AND "circular* econom*"))	121	284

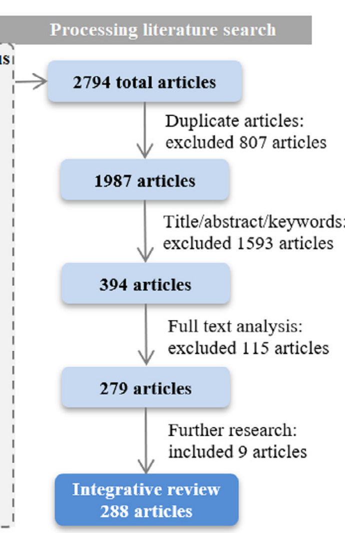

Fig. 3. Processing the review in the scientific literature (review date: February 2020).

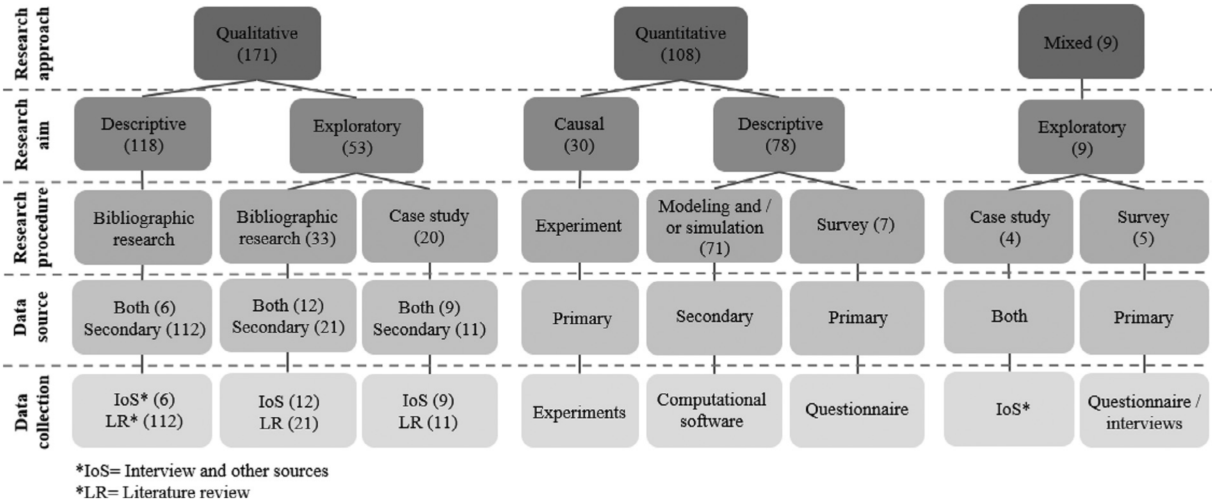

Fig. 4. Research methodological procedure (number of articles = 288).

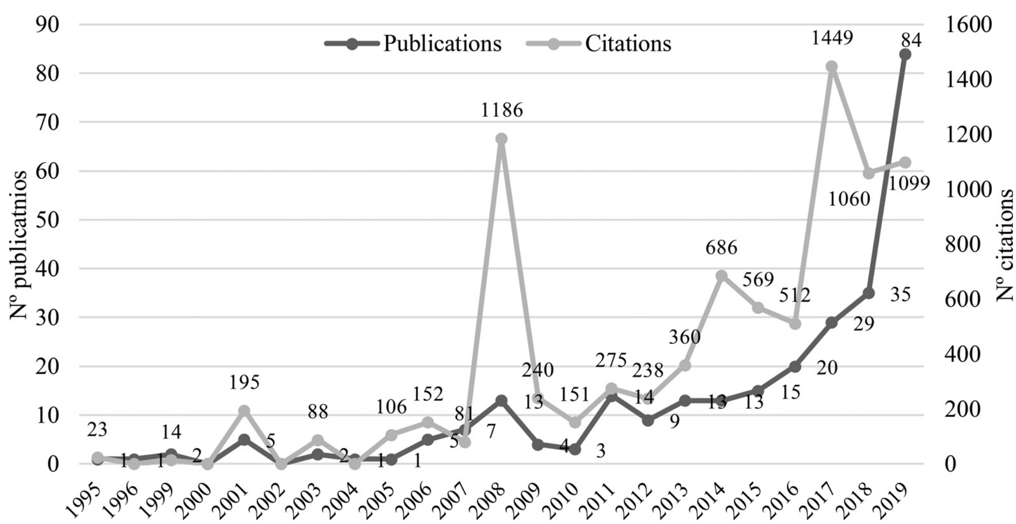

Fig. 5. Total publications and citations by year.
*The articles published in 2020 are not represented. **Total citations were obtained on November 30, 2021.

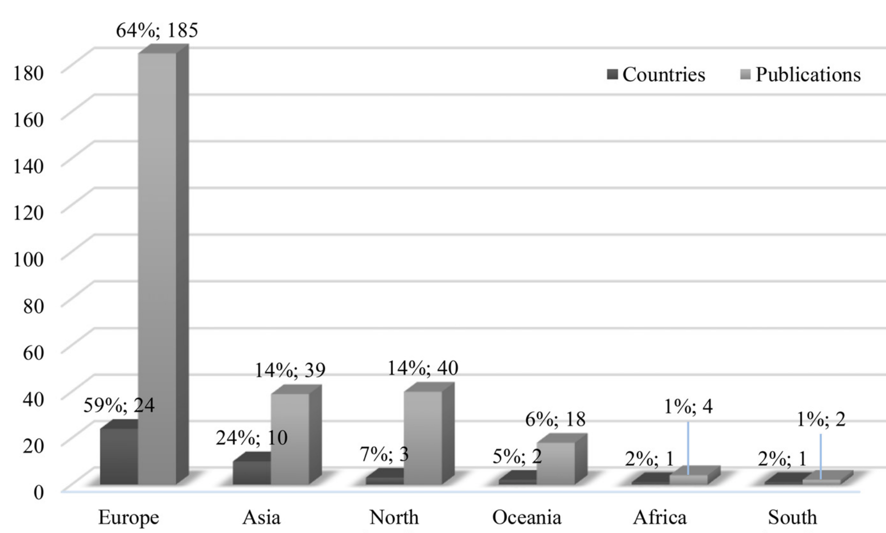

Fig. 6. Geographic distribution of publications (number of articles = 288).

Table 1
Frequent keywords identified in the review.

Keywords	Occurrence
design for disassembly/deconstruction / DfD or disassembly, demountable	68
sustainability or sustainable building/construction/design	63
demolition / construction & demolition waste / C&DW / construction waste / waste reduction/management/minimization/avoidance	55
circular economy / CE	50
reuse or material/building/product reuse	51
deconstruction or building/planning/programming deconstruction	42
life cycle assessment / LCA / life cycle costs / LCC / lifecycle building/thinking	39
recycling / recycle / reuse & recycling	32
adaptive reuse / adaptive building reuse or adaptability / design for adaptability	32
bolted joints or connections or shear connectors	22
building information modeling / BIM	20
concrete structure/component/connection or precast concrete	15
timber or wood building/structure	13
end-of-life / end-of-life stage/scenario	13
composite beam/structure/system	10
steel or steel structure/component	9

by the United States of America (25 articles), Germany (23 articles), and Italy (21 articles). The predominance of England studies is related to the adoption of public policies and regulatory support (Ajayi et al., 2017). Large countries in terms of geographical area and economy, such as Brazil, India, and Russia, still have no relevance in the subject.

The most frequent keywords in publications are listed in Table 1. The keywords were grouped according to the similarities of the meanings of the expressions. Design for Disassembly/Deconstruction leads the number of occurrences, followed by the group of expressions on sustainability, and CDW, demonstrating that the research is strongly related to these two themes. Terms as Life Cycle Assessment (LCA), BIM, and adaptive reuse indicate the growing attention and the importance of these themes to introduce CE actions in the sector.

4.2. Ecodesign methods analysis

The review studies presented different expressions of ecodesign to relate the subject of deconstruction building at the design stage, as shown in Table 2.

Adaptive reuse, Deployable design, Design for Adaptability, for Flexibility, for Durability, and for Change were terms used in studies that addressed the changing needs of users and of external factors throughout the life cycle of buildings. Adaptive reuse is intrinsically linked to urban mining, retrofit activities, and the reuse of historic buildings linked to the needs of the local population (Sanchez et al., 2019). Deployability allows opening or closing of a structure to transform it from a compact configuration to an expanded, which allows the developmental the design for change where a building system can be adapted with a minimum of intervention, giving the user the control to perform changes (Brancart et al., 2017). Design for Adaptability (DfA) was a recurring term because of increases in the capacity for change of the buildings over time (Schmidt et al., 2010). It is an opportunity to explore new design potentialities and to develop new materials and construction methods to address changing climate strategies (Boeri et al., 2016). Building technologies and designs that enable adaptability have also been identified with flexibility, as Design for Flexibility. But it is important to note that the terms ’durability’ and ’adaptability’ are closely related, and both aspects need to be considered and balanced (Pinder et al., 2017; ISO, 2020).

There is little agreement in the literature between the concepts of ‘adaptability’ and ‘flexibility’. To Gosling et al. (2008) flexibility is a proactive attribute to change or react with little penalty in time, effort, cost, or performance. To Geldermans et al. (2019) flexibility is the capacity to attend to the changing needs of users while reorganizing the infill components of the structure. Gijsbers and Lichtenberg (2014) reiterated that flexibility is the way to design a building for multipurpose and adaptability to the capacity of a building to have continuous physical changes. To Sadafi et al. (2014) flexibility refers to the adaptability of buildings’ features to the needs of its users, and adaptability is the ability to change the construction to accommodate both the physical and the user’s changes. For the authors, designing for flexibility can guarantee adaptive use and the dismantling of the materials and components for reuse or recycling. Thus, it is necessary to design for durability and for recycling to achieve a flexible design. Macozoma (2002) reiterated that a balance between durability and adaptability is called flexibility. Many authors consider that adaptability is not the same as flexibility, which has more to do with rapid changes to meet the functional needs or variety of space states, but it can be part of the general adaptive capacity of a building (Heidrich et al., 2017; Rockow et al., 2019).

Design for Deconstruction was found with definitions like the design for disassembly and dismantling. To Kibert (2003), the concept aims to close the cycle of building materials by including principles that allow their deconstruction. Kanters (2018) considers that it facilitates adaptation, renovation, and reuse of building materials and components. The method opens a new vision of design with the EOL in mind (Charef et al., 2019), and has environmental benefits, to preserve the embodied energy, to reduce carbon emissions, social benefit for creating jobs, and economic benefits. To Leso et al. (2018) DfD has the potential to improve the CDW management and reduce the environmental impact of a building.

Design for Disassembly was the most frequent term found in the review. The concept is an important strategy to conserve raw materials (Durmisevic and Yeang, 2009), to increase building material reusability (Ong et al., 2013), and in the adaptive reuse process of the buildings (Sanchez and Haas, 2018). Pongiglione et al. (2017) consider the building as a kit of components that needs planning upfront all its assembly and disassembly steps. Moreover, different terminologies have been noted with regards to ‘selective deconstruction’, ‘demountable building’, and ‘circular building’.

An emerging strategy that incorporates the principles of design wherein building components should be easy to disassemble and adapt with changing constraints is the Design for Adaptability and Disassembly (DfAD). The application of these strategies should increase the probability that the building’s useful life will be extended, allowing its components, parts, and materials to be reused or recycled (Webster, 2007). The Canadian Standards Association used the DfAD to reduce the environmental footprint of the building industry (Clapham et al., 2008).

Table 2
Main ecodesign terms, and definitions in the construction literature.

Ecodesign term	Definition	Refs.
Adaptive reuse	It is the process of reusing an obsolete and derelict building by changing its function, meeting current standards, and maximizing the reuse and retention of existing materials and structures	Sanchez et al. (2019), Vardopulos (2019)
Deployable design	Deployable structures are designed to be transportable, adaptable, flexible, easy mounting, and quick manufacturing with modular elements	Brancart et al. (2017)
Design for Adaptability (DfA)	A design characteristic that embodies spatial, structural, and service strategies which allow malleability of the structures as a response to accommodate change throughout time	Schmidt et al. (2010)
Design for Flexibility	A building that can accommodate changes or allow rearrangement of its internal fit-out and arrangement to suit the changing needs of occupants for a long period	Gosling et al. (2008), Sadafi et al. (2014)
Design for Durability	A method to ensure that a building can withstand various conditions that it will be exposed to overtime	Macozoma (2002)
Design for Change	It fosters future transformations and allows buildings to be refurbished and adapted effectively to meet changing users' demands	Brancart et al. (2017)
Design for Deconstruction	Aims to maximize flexibility and ensure deconstruction for reusing and recycling of building components at the end of a building's useful life	Kibert (2006), Shami (2006)
Design for Disassembly (DfD)	A method to design a building/product to enable the disassembly of building/components and reuse/recycling of its parts. The components need to be assembled in a sequence planning suitable for maintenance and reconfiguration of their variable parts	Crowther (2001), Thormak (2001)
Design for Adaptability and Disassembly (DfAD)	Approach oriented towards lifetime extension. The building components can be disassembled to be repaired/reuse, recycling, and replaced whenever necessary, and the layout of the building can be adjusted/adapted by the users whenever new requirements arise	Webster (2007), Anastasiades et al. (2020)
Design for Dismantling	The process of dismantling building components in the reverse order as how they are constructed based on the end-customers' needs, thus engaging them in the early decision making	Dantata et al. (2018), Elmaraghy et al. (2018)
Design for Demountability	The method is associated with Industrial, Flexible, and Dismountable systems (IFD), where the disassembly of components allows the separate replacement of components with different useful lives	Sadafi et al. (2014)
Modular building	Modular construction entails applying modules that are manufactured in a precast plant before shipment to construction sites. The method avoids unnecessary demolition and allows modules multiple cycles of use	Li et al. (2018)
IFD	It is a construction method for creating flexible housing based on mass production, demountable connections, and easy adaptation of buildings	Geraedts (2011)
Design for Recycling	A method to achieve the ideal reuse of building and materials and construction elements. It can be divided into Design for Adaptability, Design for Deconstruction, Design for Dismantling	Dorsthorst and Kowalczyk (2002)
Design for Reuse	The reclaimed building components and materials can be used again, repaired, remanufactured, or recycled and includes facilities for anticipating deconstruction	WRAP (2009)
Design out waste	A concept where waste is an opportunity to be transformed into a new resource. It considers the entire building useful life and privileges strategies and construction methods that extend the useful life of materials	Bilal (2017), Mangialardo and Micelli (2017)
Circular building	It is a building that is designed, planned, built, operated, maintained, and deconstructed consistently with CE principles. Considers the associated dynamics of processes, materials, and stakeholders that accommodate circular flows of resources and materials	Geldermans et al. (2019)
Reversible building	A method that systematically plans the decommissioning phase of the building elements, which facilitates transformation in building function and structure	Klinge et al. (2019), Wang et al. (2019)

The expressions Design for Dismantling, Design for Demountability, modular building, and Industrial, Flexible, and Demountable building system (IFD) were used in studies related to the trend in the development of the industrialization of buildings. Design for Dismantling or selective deconstruction (Dantata et al., 2005) was a term associated with deconstruction processes in alignment with the lean principles (Elmaraghy et al., 2018). Likewise, the term Design for Demountability was considered an extension of the IFD system that allows simple adaptation of buildings through replacement of components extending the life of the building (Sadafi et al., 2014). The focus of this set of terms is standardization and modularization in designs that is directly related to early decision making and appropriate compatibility focused on planning and coordinating construction projects (Jaillon and Poon, 2010).

To incorporate waste minimization into the design stage, the literature has shown efforts related to Design for Recycling (DfR), Design for Reuse, and Design out waste. Dorsthorst and Kowalczyk (2002) considered DfR according to three different levels of reuse: construction, element, or material reuse. Bilal et al. (2015) considered design out waste as a non-trivial concept that offers opportunities for preventing CDW. They developed a plan with multiple strategies of design, like the design for reuse and recovery, resource optimization, off-site construction, resource-efficient procurement, and design for future. Baldwin et al. (2009) considered the perspective of prefabrication

Table 3
Categorization of publications analyzed in the integrative review.

Main category (No;%)	Generic category (No;%)	Subcategory (No)
Design and planning process (107; 37%)	(a) Architectural values (3; 1.0%)	Communication, competence, and knowledge (2)
		User perspectives (1)
	(b) Assembly/disassembly phase (5; 1.7%)	Planning methods (5)
	(c) Construction principles (53; 18.4%)	Deployable structures (5)
		DfD overview (18)
		Functional independence and layering building (4)
		Modular systems (6)
		Open building and IFD system (20)
	(d) Materials and connections (46; 16.0%)	Aluminum structures (1)
		Composite structures (7)
		Masonry buildings (2)
		Steel elements (2)
		Steel-concrete structures (29)
		Timber and fiber composites (5)
Buildings' end-of-life (111; 39%)	(a) Building stock potential (9; 3.1%)	Material banks (5)
		Urban mining (4)
	(b) Construction and building renovation (31; 10.8%)	Adaptive reuse (24)
		Extension/regeneration (7)
	(c) Material/resource recovery assessment (32; 11.1%)	Recycling components (2)
		Reuse and recycling analysis (10)
		Reuse components (20)
	(d) Selective deconstruction (23; 8.0%)	BIM compliant tools (13)
		Deconstruction automation (2)
		Optimization approach (8)
	(e) Waste management (16; 5.6%)	BIM to reduce construction waste (2)
		Codes of practice / legislation (14)
Circular assessments and strategic values (70; 24%)	(a) Environmental and cost analysis (29; 10.1%)	GHG emissions / energy consumption (4)
		Lifecycle tools (25)
	(b) Pilots and case examples (24; 8.3%)	Circular buildings (21)
		Circular cities (3)
	(c) Transition to circular buildings (17; 5.9%)	Barriers and drivers (3)
		Management policies and circular frameworks (14)

as a significant opportunity to design out waste. For the Waste and Resources Action Program (WRAP, 2009), Design out waste is an ecodesign method that aims to influence design decisions to reduce construction waste through five strategies: a design for reuse and recovery; design for off-site construction; design for materials optimization; design for waste efficient procurement; and design for deconstruction and flexibility.

The expressions circular building and reversible building adhere to the concepts of CE and Cradle-to-Cradle, emphasizing the closing and coupling of material loops to establish effective and efficient resource flows. DfD was considered a fundamental aspect of the circular construction project where the materials are expected to be shared, maintained, reused, refurbished, and recycled (Kanters, 2018).

It is noted that the different ecodesign terms found in the literature (Table 2) have similar definitions and common objectives. However, the differentiation in the nomenclature causes a negative perception among stakeholders (Pinder et al., 2017; Rockow et al., 2019), which increases the lack of understanding of ecodesign methods in the construction sector. These issues make it difficult to implement waste management strategies in the design phase of construction and, consequently, all guidelines related to the building deconstruction.

4.3. Categorized studies analysis

The 288 studies were divided into three main categories according to their similarities: (i) Design and planning process; (ii) Buildings' end-of-life; (iii) Circular assessments and strategic values. Subcategories with similar events and incidents are grouped in the main categories. Table 3 indicates the categorization of the publications.

4.3.1. Design and planning process

The category with 37% of the studies focused on the design phase of the building's life cycle and was subdivided into four generic categories. The most eco-efficient sustainable strategies on deconstruction are those conceptualized since the beginning of the project, considering the choice of materials, the construction technique, and the needed Information and Communication Technologies (ICTs).

(a) Architectural values

The minimization of waste in the design phase leads to rethinking the values and skills of professionals involved in building projects. In the 'communication, competence, and knowledge' subcategory, Ajayi et al. (2016) recognized that proficiency in project tasks, design expertise, and knowledge related to construction are important skills to minimize CDW. While socialization and collaboration with professionals are contextual skills needed to design waste.

The holistic view when designing a building incorporating social aspects must consider specific benefits for end-users. In the 'user perspectives' subcategory, Geldermans et al. (2019) explored the synergistic potential of the criteria of flexibility, circularity, and user capacity to the circulation of material in the building and the user benefits. The authors argue that the replicability of circular concepts depends on user integration for a sustainable transformation.

(b) Assembly/disassembly phase

Hübner et al. (2017) discussed strategic and planning methods for deconstruction projects, considering requirements such as time, resource program, and project costs. Feng et al. (2015) stressed the need to increase productivity and automation in the construction industry and developed a robotic system capable of automatically generating assembly plans from computational projects on construction sites. Charef et al. (2019) used BIM to manage the asset's EOL and highlighted economic, political, sociological, and technological barriers regarding the deconstruction phase.

(c) Construction principles

In the subcategory 'deployable structures', transformable structures were explored due to the ability to adapt in form or function according to the required changes of users and local circumstances. The subject is supported by the understanding that structures are not designed in a final state (Brancart et al., 2017). Transformable structures are allowed by mechanisms implementable or reconfigurable components (de Temmerman et al., 2012).

An overview of Design for Disassembly was provided in the subcategory 'DfD overview'. The concept called 'design for deconstruction and disassembly' by Kibert (2003) is the key to the transformation capacity of buildings, evaluated in three dimensions: spatial, structural, and material dismantling (Durmisevic and Yeang, 2009). To Akinade et al. (2017) the factors for effective material recovery are related to legislation and policy, design process and competencies, design for material recovery and reuse, and for building flexibility. Kanters (2018) noted a lack of an internationally agreed set of guidelines for deconstruction projects, as well as time and cost constraints. More flexible legislation that tolerates the reusing of construction materials and the description of the environmental and financial benefits can stimulate the demand in the design process. The incorporation of the disassembly stage on the LCA can highlight the environmental advantages, and direct actions to extend the useful life of the buildings (Crowther, 1999).

'Functional independence and layering building' subcategory argue that adaptive building means designing a building to allow its hierarchical layers to change, each on its timescale (Brand, 1994; Gosling et al., 2008; Heidrich et al., 2017). By combining the concept of extending the building's useful life cycle and the concept of layers, it can be argued that the cycle of obsolescence of materials returns to the cycle of continuous relevance in buildings (Rockow et al., 2019).

The 'modular systems' subcategory encompasses studies wherein the building's flexibility is increased by decomposing it into modules. Industrialization creates new requirements for the design, where not only the performance of the construction is important, but also the needs of the production plan outside the construction site. The reduction and standardization of the interfaces between the modules can reduce the interdependencies between the installation activities (Isaac et al., 2014). Li et al. (2018) highlighted the need to integrate a modular architectural performance to meet occupants' comfort, flexibility, and energy savings requirements. Økland et al. (2017) stressed the punctuality and quality of project delivery and the need to develop more efficient suppliers to meet demand.

The 'Open building and IFD system' subcategory explored these two construction systems to achieve quality, flexibility, and sustainability in construction. The Open building design approach covers that the user should have a role in the housing process and includes other related ideas such as distinct levels of intervention in the built environment and that the design process is on constant change (Heidrich et al., 2017). IFD system is a method based on the principles of Open building and is a key to achieving building flexibility (Nijs et al., 2011). Prefabrication is the first degree of the construction sector industrialization (Jaillon and Poon, 2010), thus prefabricated buildings are the reorganization and optimization of resources and the effect of market selection, and improved productivity. Geraedts (2011) established a plan with recommendations for market players starting projects with the IFD system. Nijs et al. (2011) designed a typology of flexible interfaces to standardize connections and create compatibility between construction products. Strategies regarding the reduction of waste should consider the use of by-products, reusing spare parts and components, the design for adaptability and dismantling, and the use of tracking technologies (Minunno et al., 2018). The major challenge is a change in the mindset regarding how buildings are designed, built, and used (Jaillon and Poon, 2014).

Despite the environmental impacts concerning the life cycle of concrete structures, in terms of embedded energy and greenhouse gasses (GHG) emissions, the precast elements have positive aspects regarding their disassembly such as the use of dry connections, sizes, and weights for handling and transportation. However, DfD and IFD building systems are not common practices in the building industry (Jaillon and Poon, 2010). Beside, aspects that support the transformation capacity, such as functional decomposition, systematization, element specification, life cycle coordination, and other aspects are still missing and need to be reconsidered (Salama, 2017).

(d) Materials and connections

In the 'aluminum structures' subcategory, Mrkonjic (2007) reiterated that the environmental costs and impacts in the production of aluminum compensate due to recyclability, durability, and lightness of the material. The incorporated energy in the materials was also emphasized in the subcategory 'masonry buildings'. Youssef et al. (2019) showed a removable solution in masonry with dry joints, which allows reusing and recycling of materials.

'Composite structures' subcategory shows that the use of renewable materials stimulates the supply of new raw materials, manufacturing, reuse logistics, and data sharing. Geldermans et al. (2019) explored biodegradable compounds in the construction of walls, but possible damage during disassembly and reassembly can compromise reusing and remanufacturing cycles. Fragiacomo and Lukaszewska (2011) explored the economic advantages of prefabricated timber concrete composite slabs. Dahy (2019) used bio-based materials to produce CO_2 neutral, recyclable, and/or compostable elements.

In the 'steel elements' group, Pongiglione et al. (2017) combined the requirements of resistance and deconstruction with a steel connection model without welding and a higher degree of reuse. The authors emphasized that the flexibility and the total recycling capacity of steel speed up the assembly/disassembly processes and expand the capacity for repair and reuse of metallic structures.

The 'steel-concrete structures' subcategory presented the largest number of publications. Studies on the structural performance of concrete structures with reversible connections were evaluated in a multi-story apartment block (Ong et al., 2013), in flooring system consisting of pre-cast concrete planks (Eckelman et al., 2018), in the composite shear connector to build composite floors (Sencu et al., 2019), on demountable headed stud shear connectors (Wang et al., 2017). Moradi et al. (2016) investigated that steel fibers in precast concrete slabs can increase the load capacity and ductility of the structures. Wang et al. (2017) proposed a design formula for the shear strength of demountable headed connectors. Xiao et al. (2017) evaluated those connections fabricated of natural aggregate concrete or recycled aggregate concrete demonstrated an easily mechanical removal process.

'Timber and fiber composites' subcategory presented wood-based modular construction systems that offered the advantages of prefabrication and opportunities for reducing GHG emissions. Lehmann (2013) explored the cross-laminated timber system for the construction of residential buildings. Campbell (2019) presented suggestions to assembly solid wood systems, identify future markets, and improve the durability of constructions.

Klinge et al. (2019) explored wood waste from buildings to promote the life cycle extension of the materials.

4.3.2. Buildings' end-of-life

The 'Buildings' end-of-life' category represented 39% of the review and was subdivided into five generic categories. Different business opportunities in the end-of-life stage of buildings were explored, avoiding obsolescence, and ensuring the continued use of materials.

(a) Building stock potential

The 'material banks' subcategory understands buildings as temporary stock of materials that need to track and communicate stocks and flows of materials for reuse or recycling. The Urban Mining and Recycling unit project is a temporary storage of materials and a laboratory that monitors and evaluates the circular potential of materials through an online platform (Heisel and Rau-Oberhuber, 2020). Cai and Waldmann (2019) proposed a database/bank of materials and components based on BIM to promote the recycling and reusing of materials. Gepts et al. (2019) explored the importance of combining databases to favor the potential for reuse and recycling materials.

In the 'urban mining' subcategory, methodological approaches were developed to quantify construction material, stocks, and component and material flow that can be reused. Kootstra et al. (2019) evaluated a roadmap for the reconstruction of Amsterdam considering the flows of materials, resources, and transport movements. Arora et al. (2020) developed a methodology to estimate the potential of urban mining of public housing developments. Based on urban mining of more than 350 building components, recovery time averaged 1 to 12 min and an estimated cost of S$0.8 to S$9 per building component, evidencing regulatory requirements for demolition permits can provide sufficient time for urban mining without affecting project schedules (Arora et al., 2021).

(b) Construction and building renovation

The renovation and adaptive reuse of underutilized or unused buildings can revitalize localities and communities and obtain sustainable benefits. In the 'adaptive reuse' subcategory, Sanchez et al. (2019) observed a decrease in the environmental impacts and the construction building cost of an adaptive reuse project. Eray et al. (2019) proposed a system to optimize the building reuse process by helping to manage documents, communications, and relationships between stakeholders. Hsu and Juan (2016) developed a model with an accuracy of 89% in predicting the best type of project reuse. Chen et al. (2018) revealed that changes in economic, social, and natural factors influenced the order of priority of alternative buildings to reuse. Vardopoulos (2019) identified that land conservation, cultural heritage protection, community action, and involvement empowerment are critical factors in the development of reuse projects.

In the 'extension/regeneration' subcategory, guidelines for zero energy buildings are explored. Boeri et al. (2016) adopted a methodology to assess the environmental impacts of reform projects. Paduart et al. (2008) formulate technical principles for the use of adaptable and reusable components. Giorgi et al. (2019) identified improvements in policies, strategic partnerships, and tools for assessing the environmental and economic life cycle to support the regeneration of the building stock.

(c) Material/resource recovery assessment

Most publications prioritize reusing secondary materials instead of recycling. In the subcategory 'recycling components' Nußholz et al. (2019), compared companies that produced building materials with secondary inputs to estimate the carbon savings potential.

In the subcategory 'reuse components', Brütting et al. (2019) presented a reduction of up to 63% in the environmental impact of reused structural truss components. Höglmeier et al. (2013) found that 25% of the wood incorporated in buildings is suitable for reuse in new projects and that 21% can be used for other secondary applications. Zaman et al. (2018) analyzed those great quantities of recovery materials had great potential in saving energy, reducing carbon emissions, and creating new businesses and jobs. Van den Berg et al. (2020) concluded that an element will be recovered when an economic demand is identified; there are routines to dismantle it, and performance control until integration into a new building.

The 'reuse and recycling analysis' subcategory Gorgolewski (2006) analyzed the issues for increasing steel recycling and reuse. Sansom and Avery (2014) estimated that 91% of steel construction products are recycled in the UK. Akanbi et al. (2018) develop a BIM-based Whole-life Performance Estimator to assess the recovery performance of building components.

(d) Selective deconstruction

The subcategory 'BIM compliant' analyses the compatibility of methods for deconstruction using BIM. Sanchez et al. (2019) described a semi-automated deconstruction programming with quantitative analysis. Akinade et al. (2015) developed the BIM-based Deconstructability Assessment Score. Akanbi et al. (2019) settled an integrated disassembly system possible to create performance analyzes throughout the building's life cycle. Akbarnezhad et al. (2014) analyzed factors such as energy incorporation of materials, distances covered, energy use, and cost associated with recycling processes to obtain sustainable deconstruction strategies.

Systematic deconstruction is a promising field for the application of automated and robotic technologies to improve the productivity of resources, labor, and urban mining. In the subcategory 'deconstruction automation' Volk et al. (2018) developed a mobile sensor system combined with software for the acquisition of construction information, reconstruction, object detection, generation of construction inventory, and optimized project planning.

The subcategory 'optimization approach' presents plans for selective disassembly projects. The analysis of physical, environmental, and economic aspects of the deconstruction methods is important to assess different plans for dismantling a structure (Aidonis, 2019; Sanchez et al., 2020). Queheille et al. (2019), suggested an algorithm to integrate options of equipment's use, services, and waste treatment to assess the interrelationships between deconstruction plans. The economic issue is still a major challenge in selective deconstructions. Deconstruction costs can be 17 to 25% higher than demolition, due to the cost of labor, disposal costs, and resale value of deconstructed materials (Dantata et al., 2005).

(e) Waste management

In the 'BIM to reduce construction waste' subcategory, Bilal et al. (2016) presented an architecture based on Big Data, supported by BIM, for analysis of CDW in the design stage of a building. In the 'codes of practice/legislation' subcategory, Osmani et al. (2008) revealed that CDW management is not a priority in the design process and that restrictions such as customers' lack of interest; perception to waste minimization; and training, act as a disincentive to the implementation of waste reduction strategies. Llatas and Osmani (2016) developed a waste reduction model, considering the causes of waste, the design strategies adopted and the potential quantified reduction levels. The mitigation of waste can be improved by a collaborative delivery process, with the early involvement of contractors and the proper coordination of the project between the areas involved (Ajayi and

Oyedele, 2018). Attitudes changing and dynamic interaction between stakeholders can reduce CDW by at least 50% (Ding et al., 2016). Ajayi et al. (2017) highlighted the need for standardization and dimensional coordination, renewal of construction methods, component flexibility, and the use of BIM for waste efficient projects.

4.3.3. Circular assessments and strategic values

The third category represented 24% of the publications and sought to promote the circular vision in the construction sector, highlighting principles of CE and strategic tools for efficient choices of materials, components, and services that support a closed life cycle.

(a) Environmental and cost analysis

In the 'GHG emissions/energy consumption' subcategory the reduction in GHG emissions and energy spending was analyzed using a building classification system by Aye and Hes (2012), and in the recovery of wooden structures by Diyamandoglu and Fortuna (2015). Tingley and Davidson (2011) described the importance of a life cycle approach to materials from the perspective of minimizing the carbon incorporated.

The 'Lifecycle tools' subcategory connected deconstruction methodologies with an economic and environmental assessment of the materials' life cycle. A demountable floor system (Brambilla et al., 2019), and reusable walls (Buyle et al., 2019) have environmental and economic benefits than conventional systems, even with greater initial environmental impact. However, the high energy incorporated in the steel wall system is only compensated by high rates of reuse (Rios et al., 2019). Cost forecasting models for deconstructing buildings and reusing materials have been developed to support decision-makers, using techniques based on artificial intelligence (Tatiya et al., 2018), life cycle cost and environmental issues (Vares et al., 2020), and a multidisciplinary approach involving economic and real estate assessments (Fregonara et al., 2017). Wang et al. (2019) developed a model to assess the main value factor of flexible design that translates to higher market value.

(b) Pilots and case examples

In the 'Circular buildings' subcategory, examples of circular actions incorporated in buildings were explored. Maerckx et al. (2019) presented a public project that encourages projects to reuse materials and better manage human and material resources. Bertino et al. (2019) presented the HOUSEFUL project to demonstrate circular strategies with a focus on the optimal management of resources. Deployable designs, based on light and flexible structures have been explored in temporary projects, such as the Serpentine Gallery Pavillion in London (Bishop and Eng, 2011). In contrast to current technologies and materials, traditional Korean architecture has been explored as an example of adopting flexible and demountable structures (Sung-Hwa and Beisi, 2012). In the 'circular cities' subcategory, Gravagnuolo et al. (2019) reviewed CE actions in cities and highlighted political-strategic areas as the cultural heritage, energy, and mobility to implement circular cities.

(c) Transition to circular buildings

The 'barriers and drivers' subcategory presented the challenges and opportunities in deconstruction activities. Adams et al. (2017) stressed the lack of information about circular principles, the absence of incentives to design demountable buildings, and the need for an economic plan supported by metrics and tools. Akinade et al. (2019) mentioned the lack of legislation and policies, of information in the design phase, of the market for secondary materials, difficulty in developing business models for deconstruction, and of effective tools. Beside, Rios et al. (2015) reiterated the negative perception of the consumer regarding reusing materials, the time, and the cost of deconstruction.

The subcategory 'management policies and frameworks' emphasized the development of projects that meet circular requirements. Pomponi and Moncaster (2017) highlighted the importance of interdisciplinary research and both individual and collective initiatives to promote economic models and implement circularity. Leising et al. (2018) developed a collaborative tool to support and operate circular buildings. Clapham et al. (2008) described the development of a Canadian National Standard for building disassembly and adaptability. Rahla et al. (2019) emphasized the complexity of buildings, data collection, and management, and the use of obsolete and arbitrary indicators in the development of metrics to quantify circularity.

5. Discussion

The discussion of the review results was presented in two sections: i) the ecodesign methods discussion, and ii) the categorized studies discussion.

5.1. Ecodesign methods discussion

The variation of DfX expressions in the sector occurred due to the use of synonymous words, the lack of standardization, and different interpretations of the terms. A plausible reason for the variation is the adoption of DfX methodologies from the consumer goods industry. In Task Group 39 of CIB, Macozoma (2002) argued that technologies from industrial manufacture were adopted for application in construction. Design for Deconstruction is an emerging concept that borrows from the fields of design for disassembly, remanufacturing, and recycling in the consumer products industries (Guy and Shell, 2002).

When considering the different ecodesign terms found and, even if most publications have adopted the terms Design for Disassembly/Deconstruction, the meaning of ecodesign methodologies has not yet reached consensus in the scientific community. The language used by professionals and their interpretations of concepts and terms can be a barrier to the development of demountable and adaptable buildings. It is important to clarify and develop methods that can favor a clearer articulation of the clients' needs regarding building ecodesign methodologies.

To elucidate the meaning of ecodesign methodologies, the terminology of the terms was evaluated. Terms like deconstruction, disassembly, demountable, and dismantling have been found in publications with similar meanings. Deconstruction was referred to as selective dismantling (Dantata et al., 2005), an alternative to demolition (Kibert, 2003), the reverse of construction (Shami, 2006). Disassembly is defined as the deconstruction of the building, the reversal of the construction process (Crowther, 1999). Demountable systems are capable of major reconfiguration to be dismantled without damage (Sadafi et al., 2014).

According to the Merriam-Webster dictionary, deconstruct and disassemble means to take apart or examine something; demount means remove from a mounted position, disassemble; and dismantle disconnect the pieces of. It is perceived that the meanings of these expressions are synonyms, thus, when expanding them to DfX methodologies, the terms are shown in Table 2, Design for Deconstruction, Design for Disassembly, Design for Dismantling, and Design for Demountable have the same meaning in the construction context.

The terms Design for Recycling, Design for Reuse, and Design out waste, also defined in Table 2, both consider the reduction of CDW in the design phase. This means that the building components, parts, and materials must be planned for deconstruction, reuse, or recycling, considering the useful life of each material. Dorsthorst and Kowalczyk (2002) establish the DfR as a combination of methodologies to minimize CDW on different layers of the building. Mangialardo and Micelli (2017) considered that the principles of designing buildings in different layers should consider designing out waste, design for adaptability and disassembly. Therefore, these methods have the same practical significance as the other methodologies related to the term deconstruction, as seen above.

Researchers suggest that the DfR combined with the Design for Durability is a condition to achieve flexibility in the buildings (Sadafi et al., 2014). Flexibility can also be achieved when designing for adaptability (Schmidt et al., 2010; Gijsbers and Lichtenberg, 2014). DfA or flexibility is an important strategy that allows changes in the buildings to accommodate the needs of users. Despite being common terms in the literature, there is still no agreement on the meanings of the words in the building context. These words are being associated with the durability and recyclability of building materials. Some authors used the words as synonyms, others distinguish in conflicting ways, linking flexibility as a characteristic of adaptability and vice versa. Schmidt et al. (2010) reviewed the definitions of adaptability and subdivided the concept into six strategies (available, extendable, flexible, refitable, moveable, and recyclable) that relate to the type and frequency of changes that occur in buildings. Pinder et al. (2017) concluded that adaptability meant different things to different people, as a reflection of conventions, practices, and priorities in the sectors. Despite the lack of consensus, the word adaptability was most used than flexibility in the review, and the definition by Schmidt et al. (2010) was adopted (Table 2).

Likewise, the terms adaptive reuse, deployable design, and Design for Change relate to a range of building adaptation activities that improve existing conditions and extend the useful life of buildings. By introducing transformative capability at different design levels through DfA, the sustainability of structures and components over time will be maximized and the waste of resources will be minimized.

It is possible to consider that the different ecodesign terms found in the review can be grouped into two main parts of the circular design: Design for Disassembly (DfD), which encompasses design for deconstruction, dismantling, demountable, recycling, reuse, and design out waste; and Design for Adaptability (DfA), which covers design for flexibility, durability, change, deployability, and adaptive reuse. It is worth mentioning that although the term Design for Disassembly has origins in the consumer goods industry, it is the most widely used term among authors in the sector, and for this reason, it was adopted in this review as a standard term, instead of Design for Deconstruction.

It is observed that the terms reversible (or circular) building design can be interchangeable with DfAD. Although, the authors believe that the term 'circular building' is a broad concept, and in addition to considering ecodesign methodologies, such as DfAD, it should consider other aspects capable of turning buildings into a bank of materials. Thus, in addition to a reversible design, the use of BIM in project management and coordination, the use of a materials passport to ensure the traceability and retention of value of materials and components (Munaro and Tavares, 2021), and the use of circular business models should be considered guided by the principles of social, environmental, and economic sustainability. Thus, DfAD is one of the requirements capable of incorporating the full potential of the CE principles in the sector.

5.2. Categorized studies discussion

The categorization of the studies shown in Table 3 identified the concentration of the studies in three main stages of the life cycle of buildings. The 'Design and planning process' category concentrated on studies focused on the building design and construction phase. 'Buildings' end-of-life' underlined the buildings' deconstruction in the EOL stage. 'Assessments and strategic values' category presented both EOL studies and a more general context aimed at building a more circular vision in the sector.

In the 'Design and planning process' category, the predominance of studies was in steel-concrete structures and precast concrete elements. The use of prefabricated components and materials, modular design, and mechanical joints are the most explored construction principles in the context of DfD. Although modular and prefabricated buildings show DfD principles, they are not fully related to the methodology, as they are planned for easy transport, handling, and assembly, but not necessarily to be demountable and reused at the end-of-life. Few efforts have been noticed with the use of wood and other types of materials. Strategies must be implemented by using cleaner, more environmentally friendlier, and higher resource-efficient materials.

The design is the most important phase in waste reduction (Osmani et al., 2008). Architects and designers need the necessary knowledge and skills to obtain a systemic view of the design for a deconstructable and adaptable building. It is important to mobilize the professionals involved at the base of the projects to take the lead as drivers of change. The limited designed DfAD buildings reaffirm the sector's delay to the necessary changes towards circularity. Current legislation needs to impose efficient guidelines at the design stage to minimize CDW.

The coordination of the design process through BIM was emphasized in the review. BIM is seen as one of the main tools in the prevention of waste, in the compatibility of projects, in the provision of information, and the collaborative process. Plans and schedules, such as the assembly and disassembly plan, and the documentation of the construction materials and components for reuse is potentially facilitated by BIM. However, none of the existing BIM products yet offers waste forecasting and minimization functionality. Efforts to better explore construction modeling and barriers such as the lack of BIM knowledge by the professionals, the lack of compatibility with other software, or even the lack of storage capacity and compatibility of the models, need to be explored.

New business opportunities can be created in the design phase to make the reuse of materials more attractive. For example, indicating options for potential reuse; providing suggestions from companies or professionals in charge of the restoration, repair, or recycling of building materials; fund the demolition of structures, among others. These strategies can minimize the vision that deconstruction is not attractive in terms of cost and time and increase the viability of the secondary materials markets. Public policies should encourage the construction sector to develop technologies and materials recovery capabilities, promoting networks of partners to access secondary materials.

It is interesting to enlarge the participation of the end-user in the design process because they have a great responsibility for the sustainability of the built environment. Open building practices and greater integration would facilitate the understanding of circular design, a more conscious use/consumption of buildings, and the replicability of DfAD concepts. Also, it could improve the general perception of reused materials. According to Rios et al. (2015), they are seen as an inferior quality to virgin materials, both aesthetically and for safety reasons.

The 'buildings' end-of-life' category emphasized the focus on reusing construction materials and components, on the adaptive reuse of buildings, and on deconstruction methodologies. However, there is a lack of critical analysis of the possible effects that reuse, and recycling can have on the complete life cycle of the buildings. The reuse of building materials must overcome challenges related to insurance, warranty, quality, and performance of materials.

To enable high rates of material reuse and recycling, it is important the knowledge the composition of building materials. Designers and manufacturers should review products to make them more reusable or suitable for recycling. New roles can be created to support the design team and further integrate value chains in product creation.

Most studies focused on the reuse of steel components, as they are easier to deconstruct and reuse, than concrete and masonry structures. Beside, the reuse of other types of components is more complex due to the lack of data about material performance. The use of identification and research technologies considering aspects of contamination or effects of aging of concrete, which can lead to deterioration and reduced useful life of structural elements, must be considered. Likewise, a classification system is necessary to facilitate the standardization of recovered products according to their performance and the best type of reuse.

Storage space for recovered materials will also have a major impact on the cost and schedule of the project. Building contracts and tenders must be adapted to incorporate the EOL phase, making clear the responsibilities of each stakeholder. Reverse logistics policies can be an instrument for applying shared responsibility for the life cycle of products. It is important the regulate the management and distribution of EOL materials by creating markets and information exchange services for recovered products. For example, adaptive reuse of buildings is a subject that is gaining interest in the sector. However, economic barriers and technical difficulties, as the lack of reliability of the reused materials and the underestimation of the resources incorporated in the building make it difficult to adopt this technique.

Selective deconstruction is still a limited practice in the sector. A great effort is observed in using BIM for the disassembly process. However, the digitization of the sector is in the initial stages, and further research needs to deepen the method of recovering the disassembly data from the BIM model efficiently and automatically. Likewise, investigations of deconstruction protocols are needed, incorporating the rates and costs of labor, deconstruction time, and environmental impact of different strategies for the total or partial dismantling of structures.

The third category corroborates the importance of the life cycle tools to predict and assess the environmental impacts of different EOL scenarios. However, there are challenges related to the lack of data and information for the construction, maintenance, retrofit, and reuse/recycling phase of the materials. The different methodologies to predict the environmental impact of material could be more standardized. It is necessary to expand the assessment for reused and recycled materials and, to broaden the consensus on the quantification of the environmental impacts and benefits of the reinsertion of secondary materials. Environmental impact calculations can cover different EOL scenarios, such as incorporating components into a new structure, restoring components before reuse, recycling, or discarding parts of the system. The compatibility of LCA tools with BIM still needs to be further explored to allow an independent integration of other software and plug-ins.

6. Conceptualization of an integrative ecodesign strategy

This study proposed the integration of the main ecodesign concepts shown in the review. The integration aims to facilitate the understanding of the methodologies and expand the agreement of terminologies and meanings of ecodesign approaches in the sector. Fig. 7 presents the DfAD as the umbrella ecodesign methodology.

The Design for Adaptability and Disassembly (DfAD) methodology is not widespread in the sector, only two studies mentioned this method (Webster, 2007; Anastasiades et al., 2020). The method combines the advantages of DfD and DfA, wherein building components can be disassembled to be replaced and repaired whenever necessary, and the layout of a building can be adjusted when required. It can be considered that among the range of ecodesign methodologies, DfAD synthesizes them in a single concept. Webster (2007) assumes that DfAD will assure superior market value in buildings. To Anastasiades et al. (2020) DfAD acts as an important symbiosis between the micro and mesoscale, aligning the development of construction materials with a focus on adaptable and demountable buildings.

From this integration, it is possible to standardize the communication of the principles of CE in the sector through the term DfAD, or by the two separate methods, DfD and DfA. Eased communication makes it possible to increase the awareness and knowledge of stakeholders about the circular principles of deconstruction and adaptability of buildings. Therefore, overcoming the barrier of lack of communication on the DfAD method is crucial for the reduction of CDW and the consumption of virgin materials in the construction sector. It is noteworthy that international standardization requirements such as The Standards Council of Canada (Clapham et al., 2008) and International Organization for Standardization (ISO) 20887 (ISO, 2020) have been adopting the DfAD term as a positive contribution to construction sustainable development.

7. Conceptualization of an integrative DfAD framework in the construction sector

Fig. 8 presents a conceptual framework with the categorized studies of the review, related to the stage of the building life cycle. The framework considers that the categorized studies corroborate the unified DfAD methodology, proposed in Fig. 7. This framework is proposed to expand knowledge and the adoption of the DfAD concept in the sector. The approach emphasizes the 12 generic categories of studies, organized into the three major categories of the review, outlined in three buildings lifecycle stages.

The starting point of the framework is to consider that DfAD understands that all phases of the building life cycle must be planned in the design phase. For best results, the project must be accompanied by a CDW management plan. Therefore, clarifying the CE and deconstruction practices to the stakeholders involved in the design phase is crucial to provide a solid basis for the improvement of building deconstruction strategies and to stimulate the production of secondary materials. The subcategories of the design and construction phase present, in addition to the focus of research on the subject, strategies, and directions to enable the research and development of circular tools suitable to implement the practice of deconstruction in new construction projects.

In the EOL stage, selective renovation or deconstruction gives way to the conventional demolition of buildings. The renovation of buildings is a trend observed in the practices of adaptive use, aiming at seeking energy efficiency and conserving the historical and social values of buildings. Selective deconstruction accompanied by appropriate collection and segregation techniques maximizes efficiency in the recovery of materials and building components and the establishment of secondary material markets. The subcategories indicate areas of activity and research that will promote circular practices to make buildings a bank of materials.

The third category presents tools and examples of applying circular strategies to reinforce the creation of a circular vision in the construction value chains. The aim is to reinforce that the implementation of DfAD can be a strategic policy for the reduction of GHG emissions in the sector, by favoring the reuse and recycling of materials. Beside, the study of practices, programs, and public policies implemented in cities or regions provides guidelines and benchmarking on the deconstruction practices that are working and that need to be improved.

It is also interesting to discuss the different actions needed to increase the useful life of building materials during the 20 –

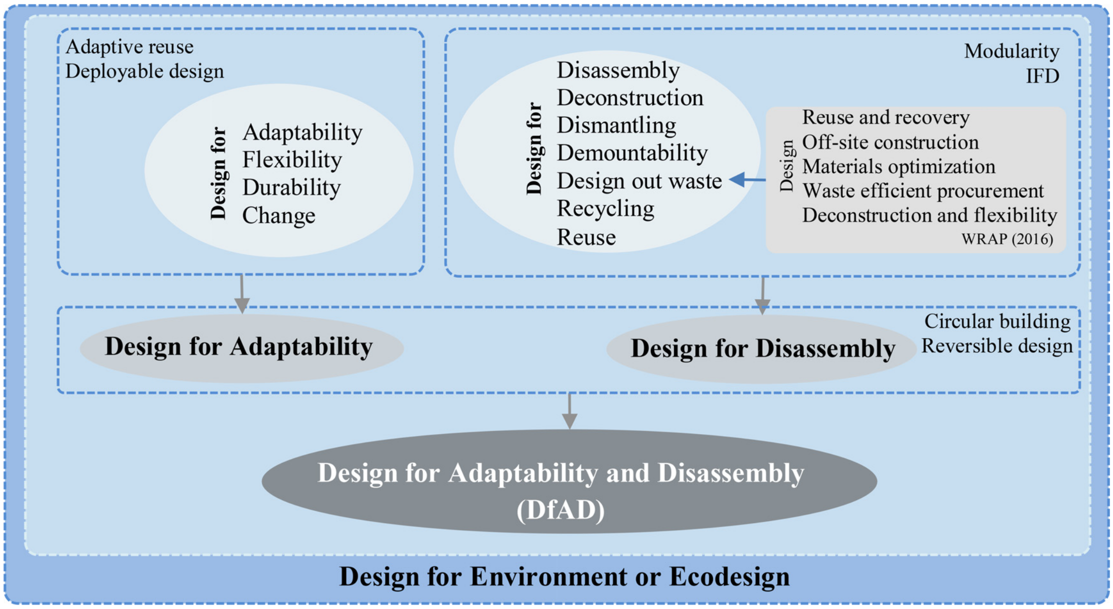

Fig. 7. Integration of the ecodesign strategies in the Design for adaptability and deconstruction (DfAD).

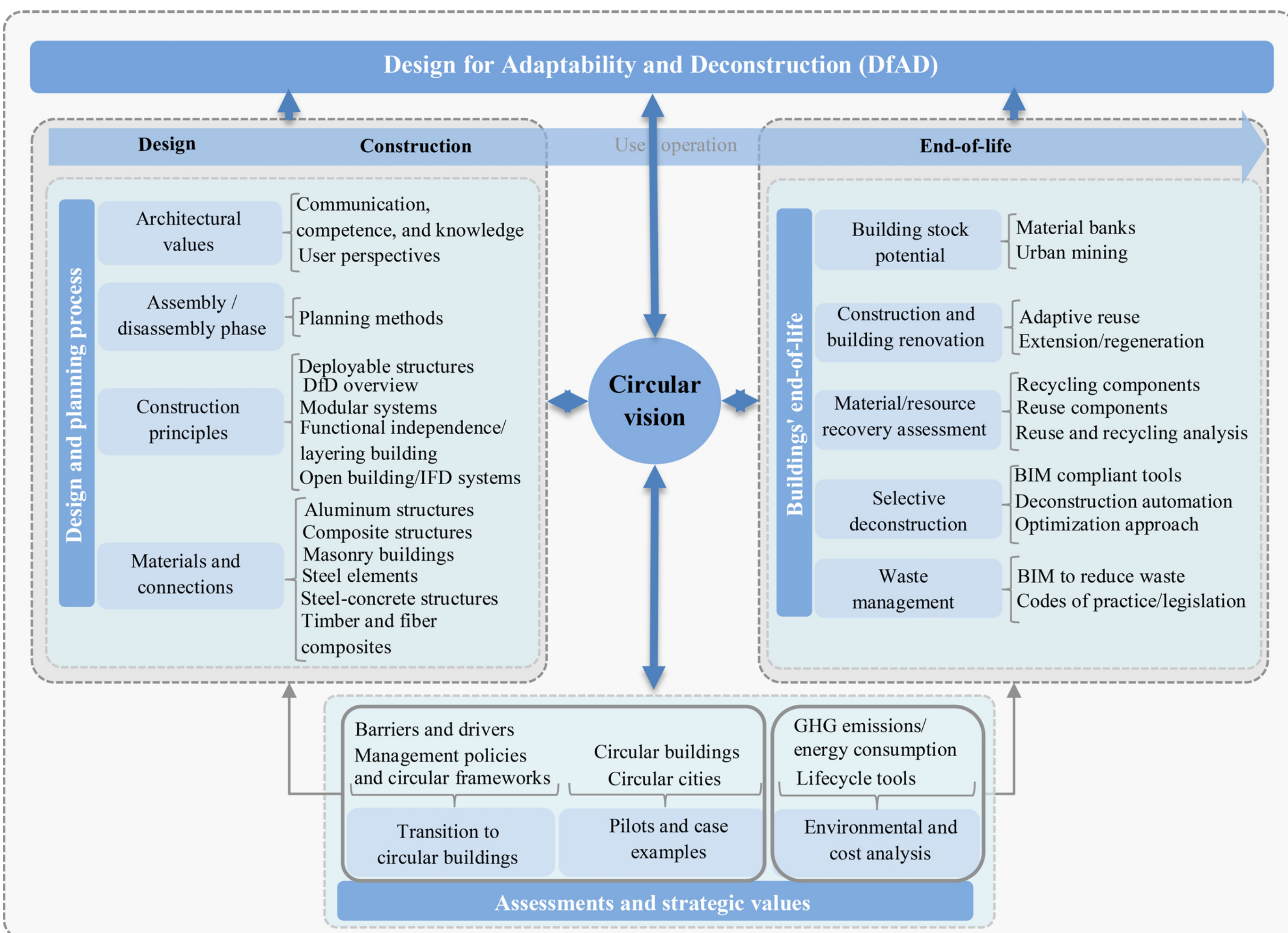

Fig. 8. Conceptual framework of categorized studies for the implementation of DfAD in the construction sector throughout the building life cycle.

50 years of the building's life. Two fundamental points need to be considered: the obsolescence of building materials and components and the energy efficiency of buildings. Monitoring the obsolescence of materials is crucial to obtain an adequate intervention plan and avoid loss of efficiency, unnecessary renovations, or demolitions. The use of tools such as the materials passport will be necessary to monitor the status of the buildings and the history of the constant maintenance actions of the materials over the time of the building (Munaro and Tavares, 2021).

Maintainability is a crucial factor in preventing physical obsolescence and ensuring an adaptable building. Lack of maintenance is one of the main reasons for the decision to demolish a building (Rockow et al., 2019). In this way, adaptability has a market value mainly in facing the accelerated changes that society faces, such as urbanization, political instability, climate change, and technological transformation (Ross et al., 2016).

Circular economy, material reuse, and open building movement play a key influence in the development of building adaptability (Heidrich et al., 2017). Several modifications can be made to return the building to relevance. According to Ross et al. (2013), the four enablers of adaptability are accurate construction information, the reserve capacity in construction systems, separation of construction systems, and internal spaces free of structures and other elements. Conejos et al. (2013) identified a list of design criteria concerning the adaptation of buildings and a model was created that predicts useful life as a function of physical life and obsolescence and allows the calculation of adaptive reuse potential at any point in the cycle of a building's life.

Both building adaptation and urban mining are linked to climate change strategies. Heidrich et al. (2017) lists different initiatives linked to the adaptability of buildings and reiterate that the adaptation of buildings aims to manage the consequences and reduce the damage that can be caused by climate change. In this sense, mitigation and adaptation efforts are synergistic in achieving energy efficiency in the use/operation phase of buildings. In addition, material reuse-driven urban building mining can contribute to net-zero carbon targets and climate mitigation efforts in the construction sector (Arora et al., 2021).

However, both the development of DfAD buildings in the design phase, as well as adaptation actions in the use/operation phase, as well as selective dismantling, and urban mining efforts at the building's EOL, require greater multi-stakeholder involvement and market push for reuse in the sector. Furthermore, the circular vision creation to allow DfAD needs greater rigor in legislation to support the ecodesign methods. Public policies could guarantee the method's compliance and comprehensiveness throughout the sector. There are no relevant approaches to include DfAD in building codes. The first approach was taken by the Canadian Standards Association (Clapham et al., 2008). Recently, a new International standard (ISO 20887) (2020) was developed considering DfAD principles, requirements, and guidance. The ISO considered adaptability based on three principles: versatility, convertibility, and expandability; and disassembly base on seven principles as simplicity, independence, and standardization. Other methodologies that assess, classify, and certify the sustainability of buildings concerning a set of eco-efficiency parameters, such as the Building Research Establishment Environmental Assessment Method (BREEAM) and the Leadership in Energy and Environmental Design (LEED) do not yet establish a score referring to DfAD.

8. Conclusions

The study presented the state-of-the-art of ecodesign methodologies to reach buildings' deconstruction in the construction sector. The main contributions were (i) integrated the ecodesign methods to simplify the understanding and implementation of the strategies for allowing building materials reuse and recycling, and (ii) a theoretical DfAD framework of the categorized studies in the sector.

Ecodesign methods aimed at buildings deconstruction are not widespread in the sector. The proposed ecodesign methodologies integration was an important strategy for enlarging the understanding and knowledge about the mechanisms on buildings' EOL. The Design for Adaptability and Disassembly (DfAD) was the main mechanism recommended to minimize the generation of waste in construction. Beside, it can create countless opportunities for business in the different building life cycle phases. The practical implications were to propose directions for future research to expand the discussion and development of the ecodesign methods, seeking cleaner productions and more circular constructions.

The categorized studies stressed the importance of modular and prefabricated structures, selective deconstruction, and the use of recovery materials. With the growth of secondary materials markets, urban mining activities, analysis of resource and material flows, and the adaptive use of buildings will be further explored. The digitization of the sector is indispensable to manage and share the large volume of data and information on construction materials and components throughout the life cycle of the building.

The proposed theoretical framework outlines the main aspects involved in CE from the perspective of implementing DfAD. This structure considers the main circular strategies found in the literature that make it possible to deconstruct and recover components, parts, and materials at the end of the building's life. This framework can be used as guidance for academics to expand knowledge about the potential applications of the DfAD concept. It can also be used by professionals in the implementation of CE in the construction sector.

The sector's delay to changes, the lack of knowledge and clarification about the different ecodesign methodologies, and the CE principles, are critical barriers. It needs to elucidate the economic, social, and environmental gains of the DfAD to the stakeholders of the construction value chain. It is noticed that the expected paradigm shift in the construction sector will be possible based on top-down and bottom-up mechanisms. Efficient legislation and public policies that promote the reuse and recycling of construction materials and components are required. The joint action of the stakeholders with the government can further promote the CE development, strengthening the supervision and implementation of green buildings, actively implementing circular actions, combined with the necessary incentive measures.

This study has limitations that must be considered. First, the literature review was focused on academic research. There would be an additional need to identify the evolution of the latest industry practices. Secondly, the review based on keywords search limits the results. Beside, although the criteria for article selection were explicit, the selection of articles for review might be subject to researcher biases. Furthermore, the literature sample includes only articles published in English. As future research, it is proposed to raise business opportunities that DfAD can develop for different stakeholders in the construction value chain. Beside, to propose a system of guidelines for the deconstruction of buildings based on different stages of implementation of the ecodesign methods for deconstruction.

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Declaration of Competing Interest

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

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Supplementary materials

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