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DESIGN FOR ADAPTABILITY AND DISASSEMBLY: A REVIEW TO ACHIEVE BUILDINGS' DECONSTRUCTION

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ABSTRACT

Reusing and recycling building materials and components are an alternative to minimizing construction and demolition waste (CDW). The introduction of ecodesign methodologies in the design stage enables buildings to be adapted to the needs of users and deconstructed at the end-of-life. Design for Adaptability and Disassembly (DfAD) is a method that incorporates sustainable principles and brings environmental, social, and economic benefits to the construction sector. Although, seeks to maintain materials at their highest level of utility and value, supporting the implementation of the circular economy (CE) principles, is little explored in projects and constructions. This study analyses how the construction sector approaches the DfAD to achieve buildings' deconstruction. Through an integrative literature review, 279 articles were selected and categorically analyzed. The results show the concentration of the studies in three major categories: i) design and planning process; (ii) buildings' end-of-life; and (iii) circular assessments and strategic values, and a framework was proposed. The framework outlines the main circular strategies found in the literature that make it possible to deconstruct and recover components, products, and materials at the end of the building's life. This framework can be used as guidance for academics, professionals, and decision-makers to expand knowledge about the potential applications of the DfAD method. The need for more explanations and knowledge on DfAD, on deconstruction strategies, on reusing of materials and components, and on the life cycle tools as decision support at the material end-of-life is crucial to make buildings resilient and adaptable.

1. INTRODUCTION

The construction sector is responsible for the highest amount of resource use, waste, and emissions of all industries. 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). To reduce the environmental impacts produced by the sector, strategies have been adopted, mainly concerning construction and demolition waste management (CDWM). Deconstruction is an end-of-life (EOL) scenario that favors the recovery of construction components for relocation, reusing, 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. Despite efforts to mitigate CDW through deconstruction, information on deconstruction projects 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 (Dorsthorst and Kowalczyk, 2002). DfD can be associated with Design for Adaptability (DfA). Users to meet their constant needs can modify an adaptable building. The Design for Adaptability and Disassembly (DfAD) integrates flexibility to the configuration of space and the recovery of EOL components. The method seeks to maintain components, products, and materials at their highest level of utility and value, supporting the introduction of the circular economy (CE) principles. CE is a restorative economic model that seeks to dissociate economic development from the consumption of finite resources (EMF, 2015).

Several studies have established strategies to guide the incorporation of CE principles for buildings deconstruction. Durmisevic (2019) denominated a Reversible Building Design a methodology 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 18 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, and Crowther (2016) listed 27 principles for disassembly.

Although, DfAD 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 design process, manufacturing techniques, supply chain, and financial arrangements. Buildings have complexities about several interconnected attributes, such as building design, choice of material, operation, and maintenance. This review aimed to study how the construction sector approaches the DfAD to achieve buildings' deconstruction. Through an integrative review, this study sought to propose a framework of the categorized studies to achieve buildings' deconstruction.

2. RESEARCH STRATEGY

The research strategy consists of an integrative literature review based on six stages, as summarized in Figure 1, inspired by 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 a 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). Figure 2 shows the processing of the review in the literature.

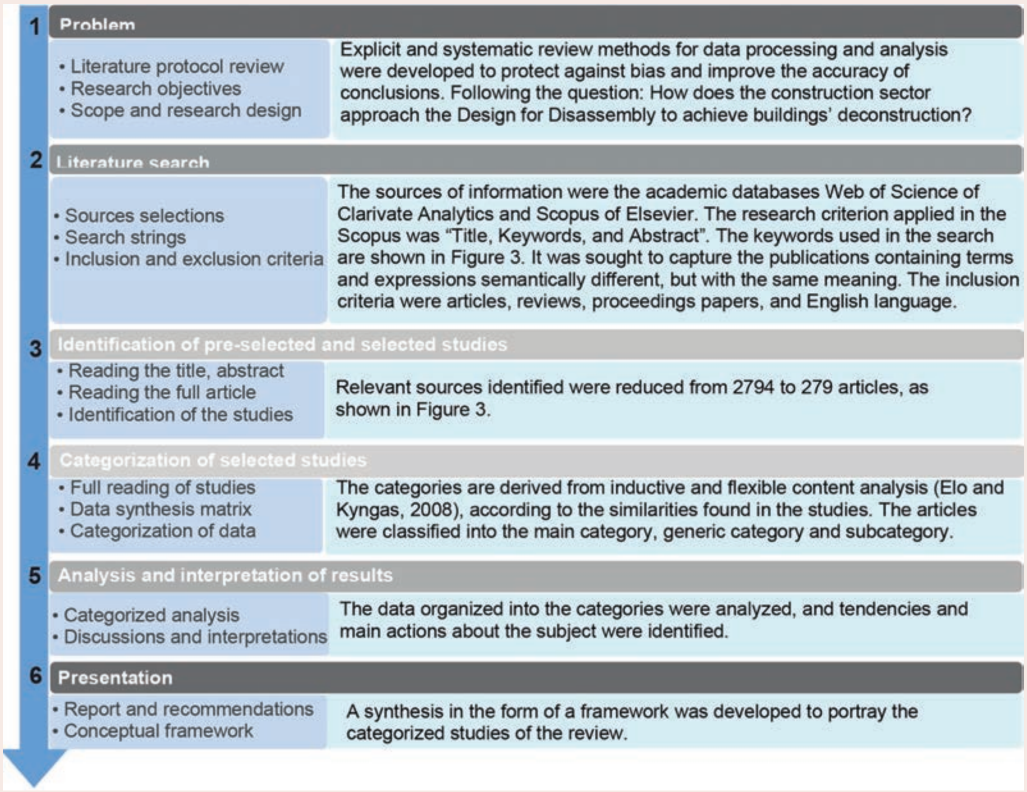

Figure 1. Stages, decisions, and processes of the integrative review.

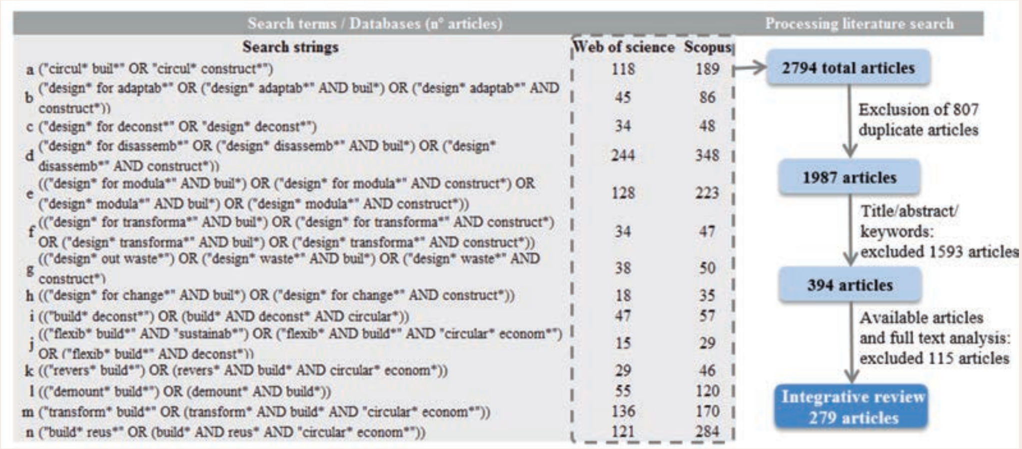

Figure 2. Processing the review in the scientific literature (review date: February 2020).

3. RESULTS AND ANALYSIS

The 279 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 1 indicates the categorization of the publications. The categories were described below.

Main category (No; %)	Subcategory (No; %)
Design and planning process (107; 38%)	Architectural values (3; 1.1%)
	Assembly/disassembly phase (5; 1.8%)
	Construction principles (52; 19.0%)
	Materials and connections (46; 16.5%)
Buildings' end-of-life (102; 37%)	2.1 Building stock potential (8; 2.9%)
	2.2 Construction and building renovation (23; 7.9%)
	2.3 Material/resource recovery assessment (32; 11.5%)
	2.4 Selective deconstruction (23; 8.2%)
	2.5 Waste management (16; 5.7%)
Circular assessments and strategic values (70; 25%)	3.1 Environmental and cost analysis (29; 10.4%)
	3.2 Pilots and case examples (24; 8.6%)
	3.3 Transition to circular buildings (17; 6.1%)

Table 1. Categorization of publications analyzed in the integrative review.

3.1 DESIGN AND PLANNING PROCESS

The category with the largest number of studies (107 articles) focused on the design phase of the building's life cycle and was subdivided into four subcategories. 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). In the subcategory "Architectural values", the minimization of waste in the design phase leads to rethinking the values and skills of professionals involved in building projects. Ajayi et al. (2016) recognized that proficiency in project tasks, design expertise, and knowledge related to construction are important skills to minimize CDW. 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.

"Assembly/disassembly phase" subcategory discussed strategic and planning methods for deconstruction projects, considering requirements such as time, resource program, and project costs (Hübner et al., 2017). 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. Charef et al. (2019) used Building Information Modeling (BIM) to manage the EOL assets and highlighted economic, political, sociological, and technological barriers regarding the deconstruction phase.

In the subcategory "Construction principles", 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 DfD is the key to the transformation capacity of buildings, evaluated in three dimensions: spatial, structural, and material dismantling (Durmisevic, 2019). 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. Industrialization creates new requirements for the design, prioritizing the performance of the construction and the needs of the production plan outside the construction site. Geraedts (2011) established a plan for projects with Industrial Flexible Demountable (IFD) methodology. 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.

In the "Materials and connections" 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. Youssef et al. (2019) showed a removable solution in masonry with dry joints, which allows reusing and recycling of materials. 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. Pongiglione et al. (2017) 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. Studies on the structural performance of concrete structures with reversible connections were evaluated in different systems (Sencu et al., 2019).

3.2 BUILDINGS' END-OF-LIFE

The 'Buildings' end-of-life' category represented 37% of the review and was subdivided into five subcategories. Different business opportunities in the EOL stage of buildings were explored, avoiding obsolescence, and ensuring the continued use of materials. The "Building stock potential" subcategory understands buildings as temporary stock of materials that need to track and communicating 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.

In the "Construction and building renovation" 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. 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 "Material/resource recovery assessment" subcategory, Nußholz et al. (2019), compared companies that produced building materials with secondary inputs to estimate the carbon savings potential. Brütting et al. (2019) presented a reduction of up to 63% in the environmental impact of reused structural 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. Van den Berg et al. (2020) concluded that an element would be recovered when an economic demand is identified; there are routines to dismantle it and; performance control until integration into a new building.

The subcategory "Selective deconstruction" 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. Volk et al. (2018) developed a systematic deconstruction process, based on a mobile sensor system.

In the "Waste management" 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. Osmani et al. (2008) revealed that CDWM is not a priority in the design process and those restrictions such as customers' lack of interest; perception to waste minimization; and training, act as a disincentive to the implementation of waste reduction strategies. A collaborative delivery process, with the early involvement of contractors, can improve the mitigation of waste and the proper coordination of the project between the areas involved (Ajayi and Oyedele, 2018).

3.3 CIRCULAR ASSESSMENTS AND STRATEGIC VALUES

The third category represented 25% of the publications and seeking to promote the circular vision, highlighting principles of CE and strategic tools for efficient choices of materials, components, and services that support a closed life cycle. In the "Environmental and cost analysis" subcategory the reduction in greenhouse gas (GHG) emissions and energy spending was analyzed using a building classification system (Aye and Hes, 2012), and in the recovery of wooden structures (Diyamandoglu and Fortuna, 2015). A demountable floor system has more environmental and economic benefits than conventional systems (Brambilla et al., 2019).

In the "Pilots and case examples" 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.

The "Transition to circular buildings" 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. Besides, Rios et al. (2015) reiterated the negative perception of the consumer regarding reusing materials, the time, and the cost of deconstruction. Pomponi and Moncaster (2017) highlighted the importance of interdisciplinary research and both individual and collective initiatives to promote economic models and implement circularity. Clapham et al. (2008) described the development of a Canadian National Standard for building disassembly and adaptability.

4. DISCUSSION

The categorization of the studies 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 DfAD. Although modular and prefabricated buildings show DfAD principles, they are not fully related to the method, as they are planned for easy transport, handling, and assembly, but not necessarily to be demountable and reused at the EOL.

The design is the most important phase in waste reduction. 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, 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; provide 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 sector to develop technologies and materials recovery capabilities, promoting networks of partners to access secondary materials.

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 materials reusing and recycling have on the life cycle of the buildings. The reuse of construction materials must overcome challenges related to insurance, warranty, quality, and performance of materials. In addition, 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.

Most studies focused on the reuse of steel components, as they are easier to deconstruct and reuse, than concrete and masonry structures. Besides, 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 taking into account 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 to regulate the management and distribution of EOL materials by creating markets and information exchange services for recovered products. Adaptive reuse of buildings is a subject that is gaining interest in the sector. However, economic and technical barriers, 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.

The third category corroborates the importance of the life cycle tools to predict and assess the environmental impacts of different EOL scenarios. There are challenges related to the lack of data and information for the construction, maintenance, retrofit, and reusing/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. The compatibility of LCA tools with BIM still needs to be further explored to allow an independent integration of other software and plug-ins.

Figure 3 presents a conceptual framework with the categorized studies of the review, related to the stage of the building life cycle. This framework is proposed to expand knowledge and the adoption of the DfAD concept in the sector. The approach emphasizes the 12 subcategories 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 waste 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.

Finally, 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. Besides, 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.

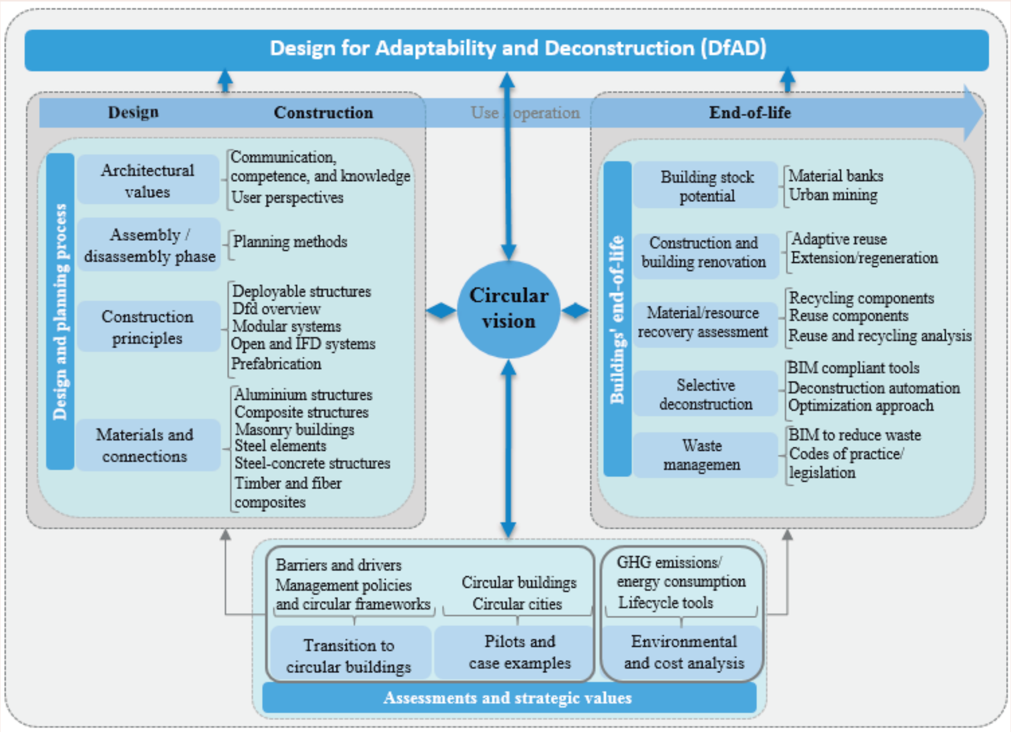

Figure 3. Conceptual framework of categorized studies for the implementation of DfAD in the construction sector throughout the building life cycle.

5. CONCLUSIONS

The study presented the state-of-the-art of DfAD methodology to reach buildings' deconstruction in the construction sector. The main contribution was a theoretical DfAD framework of the categorized studies in the sector. 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 framework can be used as guidance for academics to expand knowledge about the potential applications of the DfAD concept. Professionals in the implementation of CE in the construction sector can also use it. The sector's delay to changes, the lack of knowledge and clarification about DfAD, 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 sector will only be possible based on top-down mechanisms. Efficient legislation and public policies that promote the reuse and recycling of construction materials and components are required.

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. 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. Besides, to propose a system of guidelines for the deconstruction of buildings based on different stages of implementation of the ecodesign methods for deconstruction.

6. REFERENCES

Adams, K.T.; Osmani, M.; Thorpe, T.; Thornback, J. (2017). Circular economy in construction: current awareness, challenges and enablers. Proc. Inst. Civ. Eng. Waste Resour. Manag. 170, 15–24.

Ajayi, S.O.; Oyedele, L.O.; Kadiri, K.O.; Akinade, O.O.; Bilal, M.; Owolabi, H.A.; Alaka, H.A. (2016). Competency-based measures for designing out construction waste: task and contextual attributes. Eng. Constr. Archit. Manag. 23, 464–490.

Ajayi, S.O.; Oyedele, L.O. (2018). Critical design factors for minimising waste in construction projects: A structural equation modelling approach. Resour. Conserv. Recycl. 137, 302–313.

Akanbi, L.; Oyedele, L.; Omoteso, K.; Bilal, M.; Akinade, O.; Ajayi, A.; Delgado, J.; Owolabi, H.A. (2019). Disassembly and deconstruction analytics system (D-DAS) for construction in a circular economy. J. Clean. Prod. 223, 386–396.

Akinade, O.; Oyedele, L.; Bilal, M.; Ajayi, S.; Owolabi, H.A.; Alaka, H.A.; Bello, S.A. (2015). Waste minimisation through deconstruction: A BIM based Deconstructability Assessment Score (BIM-DAS). Resour. Conserv. Recycl. 105, 167–176.

Akinade, O.; Oyedele, L.; Ajayi, S.; Bilal, M.; Alaka, H.; Owolabi, H.; Bello, S.; Jaiyeoba, B.E.; Kadiri, K.O. (2017). Design for Deconstruction (DfD): Critical success factors for diverting end-of-life waste from landfills. Waste Manag. 60, 3–13.

Akinade, O.; Oyedele, L.; Oyedele, A.; Davila D. J.M.; Bilal, M.; Akanbi, L.; Ajayi, A.; Owolabi, H. (2019). Design for deconstruction using a circular economy approach: barriers and strategies for improvement. Prod. Plan. Control 1–12.

Aye, L.; Hes, D. (2012). Green building rating system scores for building reuse. J. Green Build. 7, 105–112.

Bertino, G.; Menconi, F.; Zraunig, A.; Terzidis, E.; Kisser, J. (2019). Innovative circular solutions and services for new buildings and refurbishments, in: Eco-Architecture VII: Harmonisation between Architecture and Nature. WIT Press, pp. 83–91.

Bilal, M.; Oyedele, L.O.; Akinade, O.O.; Ajayi, S.O.; Alaka, H.A.; Owolabi, H.A.; Qadir, J.; Pasha, M.; Bello, S.A. (2016). Big data architecture for construction waste analytics (CWA): A conceptual framework. J. Build. Eng. 6, 144–156.

Brambilla, G.; Lavagna, M.; Vasdravellis, G.; Castiglioni, C.A. (2019). Environmental benefits arising from demountable steel-concrete composite floor systems in buildings. Resour. Conserv. Recycl. 141, 133–142.

Brütting, J.; Desruelle, J.; Senatore, G.; Fivet, C. (2019). Design of Truss Structures Through Reuse. Structures 18, 128–137.

Cai, G.; Waldmann, D. (2019). A material and component bank to facilitate material recycling and component reuse for a sustainable construction: concept and preliminary study. Clean Technol. Environ. Policy 21, 2015–2032.

Charef, R.; Alaka, H.; Ganjian, E. (2019). A BIM-based theoretical framework for the integration of the asset End-of-Life phase. In: IOP Conference Series: Earth and Environmental Science. IOP Publishing, Brussels, p. 012067.

Clapham, M.; Foo, S.; Quadir, J. (2008). Development of a Canadian National Standard on Design for Disassembly and Adaptability for Buildings. J. ASTM Int. 5, 1–5.

Crowther, P. (2016). Morphological analysis of the city for achieving design for disassembly. In: 11 International Conference on Urban Regeneration and Sustainability (SC 2016). WIT Press, Rome, Italy, pp. 15–26.

Dahy, H. (2019). 'Materials as a Design Tool' Design Philosophy Applied in Three Innovative Research Pavilions Out of Sustainable Building Materials with Controlled End-Of-Life Scenarios. Buildings 9, 64.

Diyamandoglu, V.; Fortuna, L.M. (2015). Deconstruction of wood-framed houses: Material recovery and environmental impact. Resour. Conserv. Recycl. 100, 21–30.

Dorsthorst, B.J.H.; Kowalczyk, T. (2002). Design for recycling, in: Chini, A.R., Schultmann, F. (Eds.), Proceedings of the CIB Task Group 39 – Design for Deconstruction and Materials Reuse. Karlsruhe, Germany, pp. 70–80.

Durmisevic, E. (2019). Circular Economy in Construction Design Strategies for Reversible Buildings, 1st, The Netherlands.

Elo, S.; Kyngas, H. (2008). The qualitative content analysis process. J. Adv. Nurs. 62, 107–115.

Ellen MacArthur Foundation (EMF) (2015). Growth within: a Circular Economy Vision for a Competitive Europe. Ellen MacArthur Foundation. Available at: shorturl.at/yFPW5.

Eray, E.; Sanchez, B.; Haas, C. (2019). Usage of Interface Management System in Adaptive Reuse of Buildings. Buildings 9, 105.

Fragiacomo, M.; Lukaszewska, E. (2011). Development of prefabricated timber – concrete composite floor systems. Proc. Inst. Civ. Eng. - Struct. Build. 164, 117–129.

Feng, C.; Xiao, Y.; Willette, A.; Mcgee, W.; Kamat, V.R. (2015). Vision guided autonomous robotic assembly and as-built scanning on unstructured construction sites. Autom. Constr. 59, 128–138.

Geldermans, B.; Tenpierik, M.; Luscuere, P. (2019). Circular and flexible indoor partitioning-a design conceptualization of innovative materials and value chains. Buildings 9, 194.

Geraedts, R. (2011). Sucess and failure flexible building. Open House Int. 36, 54–62.

Heisel, F.; Rau-Oberhuber, S. (2020). Calculation and evaluation of circularity indicators for the built environment using the case studies of UMAR and Madaster. J. Clean. Prod. 243, 118482.

Höglmeier, K.; Weber-blaschke, G.; Richter, K. (2013). Potentials for cascading of recovered wood from building deconstruction—A case study for south-east Germany. Resour. Conserv. Recycl. 78, 81–91.

Hübner, F.; Volk, R.; Kühlen, A.; Schultmann, F. (2017). Review of project planning methods for deconstruction projects of buildings. Built Environ. Proj. Asset Manag. 7, 212–226.

Kanters, J. (2018). Design for Deconstruction in the Design Process: State of the Art. Buildings 8, 150.

Kibert, C.J. (2003). Deconstruction: the start of a sustainable materials strategy for the built environment. Ind. Environ. 84–88.

Maerckx, A.-L.; D'Otreppe, Y.; Scherrier, N. (2019). Building circular in Brussels: An overview through 14 inspiring projects, in: IOP Conference Series: Earth and Environmental Science. IOP Publishing, p. 012059.

Minunno, R.; O'Grady, T.; Morrison, G.M.; Gruner, R.L.; Colling, M. (2018). Strategies for Applying the Circular Economy to Prefabricated Buildings. Buildings 8, 1–14.

Munaro, M.R.; Tavares, S.F.; Bragança, L. (2020). Towards circular and more sustainable buildings: A systematic literature review on the circular economy in the built environment. Journal Clean. Prod. 260.

Mrkonjic, K. (2007). Environmental aspects of use of aluminium for prefabricated lightweight houses: Dymaxion house case study. J. Green Build. 2, 130–136.

Nordby, A.S.; Berge, B.; Hestnes, A.G. (2007). Salvageability of building materials. In: Conference on Sustainable Construction, Materials and Practices: Challenge of the Industry for the New Millennium, Portugal SB 2007. IOS Press, pp. 593–599.

Nußholz, J.L.K.; Rasmussen, F.N.; Milios, L. (2019). Circular building materials: Carbon saving potential and the role of business model innovation and public policy. Resour. Conserv. Recycl. 141, 308–316.

Osmani, M.; Glass, J.; Price, A.D.F. (2008). Architects' perspectives on construction waste reduction by design. Waste Manag. 28, 1147–1158. doi.org/10.1016/j.wasman.2007.05.011.

Pomponi, F.; Moncaster, A. (2017). Circular economy for the built environment: A research framework. J. Clean. Prod. 143, 710–718. doi.org/10.1016/j.jclepro.2016.12.055.

Pongiglione, M.; Calderini, C.; Guy, G.B. (2017). A new demountable seismic-resistant joint to improve industrial building reparability. Int. J. Disaster Resil. Built Environ. 8, 251–262.

Rios, F.C.; Chong, W.K.; Grau, D. (2015). Design for Disassembly and Deconstruction - Challenges and Opportunities. Procedia Eng. 118, 1296–1304.

Sanchez, B.; Esnaashary E. M.; Haas, C. (2019). A methodology to analyze the net environmental impacts and building's cost performance of an adaptive reuse project: a case study of the Waterloo County Courthouse renovations. Environ. Syst. Decis. 39, 419–438.

Sassi, P. (2008). Defining closed-loop material cycle construction. Build. Res. Inf. 36, 509–519.

Sencu, R.M.; Wang, Y.C.; Yang, J.; Lam, D. (2019). Performance evaluation of demountable shear connectors with collar step at ambient and elevated temperatures. Eng. Struct. 194, 94–105.

Thormark, C. (2001). Recycling Potential and Design for Disassembly in Buildings. Lund University, Lund Institute of Technology, Lund, Sweden.

Torraco, R.J. (2005). Writing Integrative Literature Reviews: Guidelines and Examples. Hum. Resour. Dev. Rev. 4, 356–367.

Tranfield, D.; Denyer, D.; Smart, P. (2003). Towards a Methodology for Developing Evidence-Informed Management Knowledge by Means of Systematic Review. Br. J. Manag. 14, 207–222.

van Den Berg, M.; Voordijk, H.; Adriaanse, A. (2020). Recovering building elements for reuse (or not) - Ethnographic insights into selective demolition practices. J. Clean. Prod.

Vardopoulos, I. (2019). Critical sustainable development factors in the adaptive reuse of urban industrial buildings. A fuzzy DEMATEL approach. Sustain. Cities Soc. 50, 101684.

Volk, R.; Luu, T.H.; Mueller-roemer, J.S.; Sevilmis, N.; Schultmann, F. (2018). Deconstruction project planning of existing buildings based on automated acquisition and reconstruction of building information. Autom. Constr. 91, 226–245.

Youssef, H.; Erler, M.; Jäger, W. (2019). Dry laying of masonry to build demountable, highly energy-efficient prototype houses. Mauerwerk 23, 265–275.

Whittemore, R.; Knafl, K. (2005). The integrative review: updated methodology. J. Adv. Nurs. 52, 546–553.

World Economic Forum (WEF) (2014). Towards the Circular Economy: Accelerating the scale-up across global supply chains, World Economic Forum. Geneva.

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