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# Taxonomy supporting design strategies for reuse of building parts in timber-based construction



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## Abstract

**Purpose** – The reuse of timber building parts, when designing new buildings, has become a topic of increasing discussion as a proposed circular solution in support of sustainable development goals. Designers face the difficulty of identifying and applying different design strategies for reuse due to multiple definitions, which are used interchangeably. The purpose of this study is to propose a taxonomy to define the relationships between various concepts and practices that comprise the relevant strategies for reuse, notably design for disassembly (DfD) and design for adaptability (DfA).

**Design/methodology/approach** – Literature reviews were conducted based on research publications over the previous 12 years and located through the Web of Science and Scopus.

**Findings** – A taxonomy for the design process grounded on two strategies for reuse is presented: DfD and DfA. Based on previous work, the taxonomy aims to build a vocabulary of definitions in DfD and DfA to support other researchers and practitioners working in the field.

**Research limitations/implications** – The research is limited to the design phase of timber-based buildings. It does not take into account the other phases of the construction process, neither other kind of construction methods.

**Practical implications** – The application of the taxonomy can facilitate communication between different actors and provide a way for building product manufacturers to demonstrate their reuse credentials, enabling them to produce and promote compliant products and thereby support design for reuse strategies.

**Social implications** – This paper could contribute to a closer collaboration of all stakeholders involved in the building process since the very early phases of the conceptual design.

**Originality/value** – This paper contributes a comprehensive taxonomy to support the deployment of circular reuse strategies and assist designers and other stakeholders from the earliest of phases in the building's life cycle. The proposed definition framework provided by the taxonomy resolves the longstanding lack of a supporting vocabulary for reuse and can be used as a reference for researchers and practitioners working with the DfD and DfA.


**Keywords** Reuse, Timber, Building parts, Design for disassembly, Design for adaptability

**Paper type** Research paper

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## 1. Introduction

*Sustainability*, *change* and the *circular economy* (CE) are recurrent keywords leading the debate about proposed solutions to the scarcity of natural resources and the carbon footprint created by buildings. While change alone cannot be considered an innovation, modifying the way that buildings are designed and constructed to meet sustainable development goals (UN, 2015) could constitute a form of innovation. The reuse of building parts after deconstructing a building cannot on its own be considered an innovation as it has roots in Roman times (Bröchner, 2022); however, the means by which modern buildings might be designed and constructed could qualify as innovation if it supports sustainable development goals. Today, the reuse of timber building parts, when designing new buildings, has become a topic of increasing discussion as a proposed circular solution in support of sustainable development. Timber is a sustainable building material and can be easily deconstructed when properly designed and assembled (Ilgın *et al.*, 2022). Given the difficulty of identifying and applying various circular strategies, due primarily to the interchangeable use of many terms in the literature related to design and reuse, a taxonomy is proposed. The taxonomy, based on the framework of a common vocabulary, is intended to be used when designing with reusable or reused timber building parts and defining the scope of work.

## 2. Reuse in timber design

### *2.1 Circular economy in context of sustainable development*

There is a common understanding supported by multiple studies conducted over the last decade that the construction industry, more than others, has a large impact on the environment (Svatoš-Ražnjević, 2022; Fatourou-Sipsi and Symeonidou, 2021; Finch *et al.*, 2021; Crawford and Cadorel, 2017). Global material use is expected to more than double by 2060 and the estimates of materials used in the construction industry are expected to increase by one third followed by an increase in carbon emissions (UNEP, 2020). Between 2018 and 2040, global energy consumption is also expected to increase by 28%, with 36% of total energy attributable to the construction industry. Reducing embodied energy and, consequently, carbon emissions is imperative and would increase operating efficiency in construction (Hens *et al.*, 2021). It seems, therefore, crucial to manage the existing building stock so that it aligns with sustainable development goals (Fatourou-Sipsi and Symeonidou, 2021) by adopting a different approach that takes into account climate change, lack of resources and evolving social needs (Ostrowska-Wawryniuk, 2021).

CE policies are inevitably aligned with sustainable development goals and are promoted by various agencies and governmental bodies and non-governmental organizations through legislation and guidelines (see, for example, EU, 2013; EU, 2014; UN, 2015; UN, 2018; UN, 2020; WRAP, 2020). The research community, industry and society are progressively recognizing the importance of CE (Minunno *et al.*, 2018). According to the EU Waste Framework Directive (EU, 2008), by the year 2020, all member states should have been able to reach the goal of preparing for reuse, recovery or recycling not less than 70% of construction and demolition waste (Whittaker *et al.*, 2021). In the context of CE, buildings can be preserved through regular maintenance, restoration and renovation activities instead of being demolished, which is the least preferred solution. Even though multiple initiatives have been conducted worldwide to promote circularity in the construction industry, the way buildings are designed and built, their unique features together with current construction practices and the lack of a circular supply chain (Minunno *et al.*, 2018) represent a huge barrier to the reuse of building parts.

### *2.2 Reuse strategy*

When applying the principles of CE to the construction industry, a recent study identified two approaches:

(1) utilization of the existing architectural stock as "upcycled separate modules"; and
(2) design for disassembly (DfD), defined as the possibility to incorporate architectural parts in new buildings (Fatourou-Sipsi and Symeonidou, 2021).

According to the authors, it is fundamental to focus on the future of the building, which is claimed to be the essence of circular design and which, in contrast with the linear economy (i.e. construction, use and disposal), encourages a cycle of material flows through recovery and reuse. Vermeulen *et al.* (2019) provided a reorganized concept of the 3Rs concept of waste hierarchies (i.e. *reduce, reuse, recycle*) to the 10Rs hierarchy (*Refuse, Reduce, Resell, Reuse, Repair, Refurbish, Remanufacture, Re-purpose, Recycle materials, Recover energy, Remine*). Among the 10Rs, the concept of *reuse* will be considered when:

- designing new buildings, where building parts are designed to be disassembled and reassembled after many years (i.e. design for reuse);
- designing new buildings using parts from an existing building (i.e. design with reuse); and
- converting the function of a building (i.e. design for adaptability, DfA).

*2.3 Design phase*

A building planned, constructed, operated, maintained and deconstructed consistently with CE principles, including optimizing the use of a building throughout its lifecycle and incorporating the end-of-life phase into its design, could be defined as a circular building design. As the name implies, the focus of circular design is to reduce the value loss of embedded material by maintaining its circulation in closed loops, which extends the material's life and improves resource productivity. As happens in nature, the material, its parts or its constituents at the end of their life become a resource, feeding new cycles of use within or even outside of the original application scope (Antonini *et al.*, 2010). The design phase offers an opportunity to adopt a variety of strategies for reuse that target different aspects of circularity.

The literature often provides DfD and modular design as viable solutions to increase reuse approaches in the construction industry (Fatourou-Sipsi and Symeonidou, 2021; Whittaker *et al.*, 2021; Klinge *et al.*, 2019b; Finch and Marriage, 2018; De Berardinis *et al.*, 2017). The earlier work of Brand (1995, p. 71) argues for the analysis of "reliability, life-cycle behaviour, environmental impact, user acceptance, compatibility with other materials and ease of disassembly." Brand also observed that buildings nowadays are not normally designed to be adaptable even though the way they are used changes regularly. It was, therefore, possible and considered necessary in the early 1990s to design buildings that "invite adaptation." Sadly, as Brand notes, buildings are made to last about 30 years, and this is confirmed to a certain extent by the duration of loans and payback periods for investors. Brand argued that too much of the budget to construct a building is spent on features to provide an aesthetically impressive facade, instead of being invested in the structure, maintenance activities and adaptation possibilities.

The need to switch from architecture based on image to architecture based on process is an integral part of this thinking. The term *responsive architecture* was coined by Negroponte (in Iommi, 2018, p. 1450) as the design of buildings able to satisfy changes brought about by energy use, function and aesthetics, paving the way to a sustainable building process. The focus of the present study is on the design phase to enable reuse in construction. Even though unproven at this time, an upcycling approach in the design process for future buildings could provide significant results toward sustainable development (Fatourou-Sipsi and Symeonidou, 2021). Importantly, the practice of *reversible design*, where buildings can be assembled, disassembled and reassembled over time, is crucial to improve reuse supply chains, while ensuring that a building part retains its value at the end of its first lifecycle (Kunic *et al.*, 2021; Viscuso, 2021; Klinge *et al.*, 2019b).

### *2.4 Timber-based buildings*

The use of timber as a sustainable resource in construction is gaining momentum. As argued by Ilgın *et al.* (2022), the embodied and consumed energy of a building in steel and concrete is, respectively, 12% and 20% more compared to timber-based buildings. In the same study, it was found that the use of timber frames in multistorey buildings could reduce embodied carbon by 48% in comparison with steel and by 19% compared to concrete as the principal structural material. Moreover, timber is renewable and lightweight, with good thermal properties and a low carbon footprint (Svatoš-Ražnjević, 2022; Hens *et al.*, 2021; Kunic *et al.*, 2021; Ostrowska-Wawryniuk, 2021; Bukauskas *et al.*, 2019; Stavric and Bogensperger., 2015; Daerga *et al.*, 2014; Leskovar and Premrov, 2012; Weinand, 2009). Additionally, timber provides an agreeable indoor microclimate and has positive effects on the occupants of the building, while reducing stress (Ostrowska-Wawryniuk, 2021; Tarin *et al.*, 2019; Leskovar and Premrov, 2012). It seems possible that timber, especially for taller buildings, is a viable choice that could potentially decrease the environmental impact of construction. Timber consumption in the construction industry has, in fact, increased over the past two decades as a valid choice to align with European climate policy and in the expectation of production of mass timber panels, which is estimated to double by 2025 in comparison with 2019 (ibid). Logistical and planning obstacles, acoustic and vibration disadvantages (Ilgın *et al.*, 2022), together with limitations represented by durability and sustainable forestry issues (Carvalho *et al.*, 2020), must however be considered. Nevertheless, technology is rapidly and impressively developing, opening up many possibilities. Most of the literature focuses on technical and structural solutions, while research from a design perspective is lacking (Svatoš-Ražnjević, 2022).

An important role in sustainable development can be played by the reusable features of timber building parts. Through modularization and prefabrication, and by means of DfD and adaptability using specific connectors, each part of a timber building has a high potential for reuse. A recent study showed that in timber-based buildings 65% of building materials are reusable and 35% are recyclable (Ilgın *et al.*, 2022). If properly designed and constructed, timber-based buildings allow for flexibility in structure and form, with new construction techniques under development to match the requirements of building codes, market regulation and climate change (Ilgın *et al.*, 2022). This would make a significant contribution to extending the lifecycle of buildings and would reduce their carbon footprint, which could be considered the core of a circular approach (Kunic *et al.*, 2021; Whittaker *et al.*, 2021; Klinge *et al.*, 2019b; Finch and Marriage, 2018).

## 3. Methodological considerations

### *3.1 Taxonomy for classifying and organizing knowledge*

Organizing and structuring information assists in understanding a field of study and can help to stimulate interest in, and the development of, both theory and practice. A taxonomy provides the means to organize and structure knowledge, enabling researchers to study the relationships among dimensions or concepts when describing, understanding and analyzing phenomena (Glass and Vessey, 1995; Wand *et al.*, 1995). These relationships are visualized, for example, through hierarchical structures (Prat *et al.*, 2015) and multi-layer structures encompassing abstract layers, dimensions and characteristics (Janssen *et al.*, 2020). McKnight and Chervany (2001) claimed that taxonomies can bring order to otherwise disorderly concepts. Taxonomy design has been adopted in various disciplines such as natural sciences, social sciences, organizational science and strategic management (Kundisch *et al.*, 2021).

A taxonomy can be developed using any of the following classifications:

- referring to both the system and process of organizing objects of interest and the arrangement of those objects according to a system (Nickerson *et al.*, 2013);
- spatial, temporal or spatio-temporal segmentation of the world (Bowker and Star, 1999);
- a three-level model that includes the conceptual (i.e. deducing taxonomical structure from a theoretical foundation), empirical (i.e. grouping inductively via statistical methods) and operational (i.e. mapping both conceptual and empirical levels) approach (Bailey, 1994);
- grouping objects of interest in a domain based on common characteristics according to similarities and differences (Rich, 1992); and
- a system that groups objects by applying specific decision rules (Doty and Glick, 1994).

The EU taxonomy for CE (EU, 2020) – Taxonomy Regulation (Art. 2) – defines CE as an economic system whereby the value of products, materials and other resources in the economy is maintained for as long as possible, enhancing their efficient use in production and consumption and thereby reducing the environmental impact from their use. This taxonomy covers the holistic picture of CE. Other related CE tools are taxonomy of the waste of production in construction (Bølviken, 2014); taxonomy for circular product design and business model strategies (Bocken *et al.*, 2016); taxonomy of CE business models (Urbinati *et al.*, 2017; Lüdeke-Freund *et al.*, 2019); taxonomy on material waste recovery scenarios (Crowther, 2018a); taxonomy of design strategies (Moreno *et al.*, 2017; den Hollander *et al.*, 2017) and taxonomy of CE indicators (Saidani *et al.*, 2019). There is no taxonomy on the adoption of reuse as a value-retention strategy in timber-based buildings during the conceptual stage of a building's design. Of equal concern is the absence of a common vocabulary for designing with reuse because there are too many interchangeable terminologies. Such a taxonomy is needed to better inform design teams and other stakeholders on an understanding of a reuse framework with a focus on timber during the conceptual stage, thereby avoiding confusion and inhibiting deployment. This proposed taxonomy will help stakeholders make better decisions within the broad framework of sustainable development.

### *3.2 Data collection and identification of meta-characteristics*

To design the taxonomy, literature reviews were undertaken once the study objectives had been defined. According to Kitchenham (2004), literature reviews have two phases, namely planning and undertaking the reviews. Planning includes the identification and development of a review protocol. The next step is determining search terms and inclusion-exclusion criteria for the reviews. There are three approaches from which the authors can choose their own approach as befits their research (Nickerson *et al.*, 2013):

(1) the inductive approach involves observing empirical cases, which are then analyzed to determine dimensions and characteristics in the taxonomy;

(2) the deductive approach derives from theory or conceptualization that identifies dimensions and characteristics by a logical process (also known as the conceptual approach); and

(3) the intuitive approach is essentially *ad hoc* where the researcher uses understanding of the objects that make sense for classification.

This study uses a deductive approach to identify recurrent patterns of design for reuse. However, the domain of knowledge relating to the concept of reuse is multi-dimensional involving a large number of sub-issues (e.g. CE, replication, reproduction, renovation, refurbishment, adaptation, disassembly and building layers).

*3.2.1 Literature selection.* The first step in conducting literature reviews is to identify relevant research studies, which starts with the definition of search terms (Kitchenham, 2004). Nickerson *et al.* (2013) stressed that the approach must be derived from the purpose and target users of the taxonomy. Despite the extensive literature on CE, there are gaps especially when it comes to the design phase. To create the taxonomy, the authors aim to address the following:

- defining various forms and terminologies of reuse;
- classifying building layers to enable reuse in timber-based building design;
- defining building parts; and
- adopting reuse design strategies for timber-based buildings during the conceptual stage.

Thus, literature reviews were chosen because they were the most appropriate approach. The reviews centered on the term *reuse* in research publications between 2010 and May 2022 located through the Web of Science (WoS) and Scopus. A list of keywords was generated consistent with previous studies. Papers that were not relevant to the research (e.g. off-topic field and environmental impact) and papers published in other languages than English were excluded. The authors located papers by searching for the keywords listed in Box 1.

**Box 1. Search terms**

adaptability, building component, buildings, change of function, circular economy, component(s), connectors, construction, deconstruction, design for adaptive reuse, design for deconstruction, design for disassembly, design for future adaptive reuse, design for use, design, element(s), handling process, life cycle, material reuse, module, new buildings, rehabilitation, renovation, renovations, retrofitting, reuse, timber, timber-based, shearing layers

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A total of 3,470 papers were retrieved from which 170 were selected for review. Relevant publications over the past ten years were selected and reviewed in-depth based on an iterative search procedure. Two main themes emerged: classification of the building; and circular reuse strategies. A limitation of the study is its dependency on the strict keyword search rule defined to retrieve English-language papers, which refer predominantly to timber-based buildings. In this case, all searches included the keyword *construction* or *building*. The next step was to create vocabulary and the terms that fall and relate to reuse in general and reuse in timber in particular. The literature reviews and follow-on workshops undertaken by the authors allowed the identification of each category and their sub-categories together with vocabulary for the taxonomy. The proposed taxonomy for the design process was developed as follows.

Classification of the building:

- building layers; and
- building parts.

Circular reuse strategies:

- adaptability; and
- deconstruction or disassembly.

## 4. Proposed taxonomy

### *4.1 Classification of the building*

To design the taxonomy, the *classification of the building* starts with identifying the building layers. Brand (1995, p. 20) describes a building as made of "several layers of longevity of built components," namely, site, structure, skin, services, space plan and stuff. Brand¨s model has been further developed by Zimmann *et al.* (2016) by adding the layer "system," and by Schmidt and Austin (2016) by adding the layers "social and surroundings." The proposed taxonomy incorporates timber-based layers which are skin, structure and space plan (from Brand model), while other layers are excluded because they do not apply to timber-based design. In Brand's view, when the way a building is used changes, "function melts form" by means of an inside-out design approach, which lets the building grow from the inside to express human needs. The architectural model inspired by Brand's layers has been used for multiple purposes: adaptive reuse (Guidetti and Robiglio, 2021); creating interior resilience during the COVID-19 pandemic (Karimah and Paramita, 2020); information flows and adaptive architecture (Urquhart *et al.*, 2019); and detecting discrepancies in leadership in energy and environmental design (LEED) assessments (Pushkar and Verbitsky, 2018). As for building parts, the difficulty of interpreting a correct description of a building part, whether it is a component or an element, is mostly ignored or underestimated by the literature. Evidently, words such as element, module and component, referring to a building, are used interchangeably in the literature and a clear definition of each is missing. A small exception is *component*, which is described as the merging of various materials (Bock and Linner, 2015), and *module* defined as a combination of "polyvalent industrialized components," with assembly and disassembly characteristics (De Berardinis *et al.*, 2017, p. 524). Remarkably, *element* is the most recurrent and connected, related or associated term (745 instances) compared with the terms *component* (228 instances) and *module* (457 instances).

In addressing this issue, the authors' deduction has resulted in the distinction of the terms according to the scale of the building part. An element or component is strictly related to the size of the building part at a different scale or level. For instance, a timber wall panel made of different components (e.g. frame, insulating layer and finishing) can be an individual element itself, but can also be a component when assembled with other building parts (e.g. walls, floor, ceiling and windows) to generate a volumetric unit (e.g. a room or a living unit) in a modular system. A volumetric unit is made of multiple components, but it is an element that together with more volumetric units forms a building.

To establish a common vocabulary, the use of the generic term *building part* is recommended. The type of connection used between building parts will determine whether or not it can be successfully deconstructed and reused. The use of reversible connectors facilitates the assembly and disassembly and increases the reusability of timber building parts (Al Shamaa and Saleh, 2021; Klinge, 2019a, Akinade *et al.*, 2017). In the case of timber-based buildings, these connections can be realized through carpentry connections that can be assembled, disassembled and reassembled several times without impacting the characteristics and performance of the timber elements in the different layers of the building (Klinge, 2019a). Two key criteria for designing connections that can be disassembled while maintaining the integrity of all elements are as follows:

(1) avoid interpenetration of connectors with components; and

(2) adopt dry-jointing techniques in preference to chemical jointing (Morgan and Stevenson, 2005).

*4.2 Circular reuse strategies*

The literature reviews identified two main circular reuse approaches: adaptability and disassembly (or deconstruction). Both approaches lack a consensus of definitions, due to the interchangeable use of the terms. The following section presents the various definitions of adaptability and disassembly, needed to establish a definition framework for the taxonomy.

"Adaptability-related terms" have been used differently according to a particular context where a level of adaptation applies (Askar *et al.*, 2021; Schmidt and Austin, 2016). Brand (1995) defined adaptability as changes that are not only possible in the building, but to the structures. Schneider and Till (2005, p. 157) described adaptability as being "capable of different social uses," while Schmidt *et al.* (2010, p. 235) offered a robust view of adaptability relating to buildings as "the capacity of a building to accommodate effectively the evolving demands of its context, thus maximizing value through life." Both Gosling *et al.* (2013) and Heidrich *et al.* (2017) claimed that the overall characteristic of adaptability is the ability to respond to change; for example, the ability to change to fit changed circumstances. In general, the concept of change is the most common thread that runs through definitions of adaptability in the literature, irrespective of building type or sector – use, physical layout and size (Pinder *et al.*, 2015; Gosling *et al.*, 2013) – thus maximizing its value through life (Schmidt and Austin, 2016, p. 45). In the context of buildings, change refers to the capacity to respond to varying needs such as economic considerations, user requirements, capabilities and changing lifestyles (Durmisevic, 2019). Additionally, confusion about the meaning of adaptability is made worse by the term "flexibility," often used as a synonym and in conflicting ways. Schneider and Till (2005, p. 157) describe adaptability as being "capable of different social uses" and flexibility as being "capable of different physical arrangements." In contrast, in the literature analysis performed by Hamida *et al.* (2022), it is argued that flexibility should be incorporated in the design of new buildings as well as in the adaptation of existing buildings (Kaya *et al.*, 2021b). Obviously, literature on adaptability shows that researchers either used different terms or the same terms with different meanings (van Ellen *et al.*, 2021). Brand's (1995) concept of "shearing layers" in buildings was among the first to capture how adaptability can be configured.

Deconstruction or selective deconstruction or selective, systematic dismantling, also known as construction in reverse, is a strategy which, unlike mechanical demolition, aims to maximize the recovery of building parts when taking apart a building for future relocation and reuse and, consequently, to minimize construction waste (Bertino, 2021; Forghani *et al.*, 2021; Marzouk and Elmaraghy, 2021; O'Grady *et al.*, 2021; Bukunova and Bukunov, 2020;

Jockwer *et al.*, 2020; Kibert, 2016; Rios *et al.*, 2015; Thomsen *et al.*, 2011). The term deconstruction has been associated with the removal of demountable building parts to claim their residual value for reuse (Cambier *et al.*, 2021; Akinade *et al.*, 2020) and to building disassembly for material, element or component reuse (Guerra and Leite, 2021; van den Berg *et al.*, 2021; Akinade *et al.*, 2015). Cambier *et al.* (2021) distinguish deconstruction from disassembly by the possibility to claim the value of a building part or to reuse it as is. Disassembly could be defined as the disconnection of building parts or material separation (O'Grady *et al.*, 2021) when reversing the assembly process (Arisya and Suryantini, 2021 and Ma *et al.*, 2016) to reuse building parts for the same or a different purpose after recovery. This is termed *recycling of products* (Ma *et al.*, 2016). The last statement is debatable; however, it is appropriate to use the current term disassembly instead of deconstruction, even if it implies a difference in the way a building is designed and assembled.

*4.3 Proposed taxonomy design*

From the literature reviews, two forms of design strategy for reuse were identified: DfD and DfA. The proposed taxonomy focuses on reuse when designing new buildings, where building parts are designed to be disassembled and reassembled; and when designing new buildings using parts from an existing building or converting the function of a building. Here, the choice of building parts, such as elements, components, modules and connectors does influence the design potential for reuse. Finally, to enhance the taxonomy, it is important also to understand how the building layers relate to building parts. This taxonomy starts with mapping DfD and DfA of building parts to building layers. The proposed taxonomy in Table 1 is offered as a tool for designers and other stakeholders when applying reuse approaches in timber building design.

As stated by Anastasiades *et al.* (2021), DfD and DfA could be considered as the same approach but on a different scale. In DfD, the micro-scale of the building part or even of the single material is the object; in DfA the whole building is the object on a meso-scale. It is, therefore, appropriate to use design for disassembly and adaptability (DfD/A) when referring to reuse strategies in design in general and, thereafter, to address each strategy according to the specific approach to align with sustainable development goals.

*4.3.1 Design for disassembly.* DfD was, in the past, known as design for deconstruction. This has been defined as the possibility to incorporate building parts (i.e. dismantled elements and connectors) in new buildings. As such, it could be named reversible construction, reversible building design or reversible architecture (Arisya and Suryantini, 2021; Dams *et al.*, 2021; Fatourou-Sipsi and Symeonidou, 2021; Viscuso, 2021; Akbarieh *et al.*, 2020; Klinge *et al.*, 2019a). Up to this point, both deconstruction and disassembly are listed as strategies, meaning that deconstruction refers to the selective, systematic dismantling of building parts belonging to a building neither designed nor built for disassembly; while on the other hand, a disassembly activity implies the total dismantling of each building part in a building conceived and constructed for future disassembly and reuse. DfD is, therefore, considered the most sustainable strategy to adopt when planning a new building.

Reducing the amount of construction waste and extending the life of building parts through reuse are the goals of DfD (Arisya and Suryantini, 2021; Paduart *et al.*, 2011; Crowther, 1999, as cited in Arrigoni *et al.*, 2018). Reuse of assembly units in DfD is enabled by means of modularity, standardization and digitally controlled fabrication and contributes to the achievement of sustainability goals (Anastasiades *et al.*, 2021; Arisya and Suryantini, 2021; Viscuso, 2021; Nußholz *et al.*, 2019, as cited in Dams *et al.*, 2021; Eckelman *et al.*, 2018; Minunno *et al.*, 2018; Hosey *et al.*, 2015).

**Table 1.** Proposed taxonomy of design strategies for reuse of building parts in timber-based construction: relationship between the reuse design strategies, the building layers (skin, structure and space plan) and the building parts

| Design for disassembly and adaptability | Timber-based reuse design strategies | Skin | Structure | Space plan |
|---|---|---|---|---|
| DFA | i. Flexibility/adjustability | | | Element – Component – Module |
| | ii. Generality/multifunctionality/versatility | | | Element – Component – Module |
| | iii. Elasticity/expandability/scalability | Element – Component – Module | Element – Component – Module | Element – Component – Module |
| | iv. Movability/relocate-ability | | | |
| | v. Dismantlability/removability* | Element – Component | Element – Component – Module | Element – Component – Module |
| | vi. Convertibility/transformability | | | Element – Component |
| | vii. Recyclability/reusability/disaggregatability* | Element – Component – Module | Element – Component – Module | Element – Component – Module |
| | viii. Refit-ability | Element – Component | Element – Component | Element – Component |
| | ix. Accessibility/availability | Element – Component – Module | Element – Component – Module | Element – Component – Module |
| | x. Modularity/regularity | Element – Component – Module | Element – Component – Module | Element – Component – Module |
| DFD | Deconstruction | Element – Component | Element – Component – Module | Element – Component – Module |
| | Disassembly* | Element – Component | Element – Component – Module | Element – Component – Module |

**Notes:** The design strategies linked to DfA are based on the study by Hamida *et al.* (2022); *Indicates that a building part must have a reversible connector to facilitate this reuse strategy
**Source:** Created by authors

Better knowledge on the part of stakeholders about appropriate design approaches and awareness of the residual value of building parts is among the scope of current protocols on DfD, as reported by Dams *et al.* (2021). ISO 20887:2021 provides the principles, as well as the guidelines and the requirements for DfD/A, together with a vocabulary and definitions to enable the reuse of building parts. However, the standard applies to construction in general while this study focuses specifically on timber-based buildings.

To assist designers, the following is proposed:

- *Skin layer*: in traditional timber-based buildings, a non-loadbearing framed wall at the element level could be deconstructed. The same procedure applies at the component level, i.e. to wall cladding, when deconstructed from a building not designed for disassembly; whereas, disassembly activities are possible when the building has been conceived and constructed for future dismantling. Accordingly, a single skin element, such as a front door, is likewise a component of the skin, as is a window frame because it is demountable and can be disassembled.
- *Structure layer*: a similar classification to the above could be applied to the structure layer, where a single beam element or a stud wall-frame section is meant to be deconstructed. Conversely, in a building designed for disassembly, each roof truss as an element or each component chord of the truss is separable and demountable, and therefore reusable.
- *Space plan layer*: a door on the element level can be deconstructed and when designed for disassembly, even the door frame could be demounted. It is possible to deconstruct a partition wall as a component of the space plan in a traditional timber-based buildings, although its reuse is not ensured. On the contrary, in a building designed for disassembly it is possible not only to remove but also to reposition a partition wall as a component of space layout.

A separate analysis is required for the module level because volumetric construction provides wall panels whose elements and components are built into each module with structural, insulating and enclosing features. Each module represents a self-contained component of the building while supporting the building as a whole when connecting to other module components (Arisya and Suryantini, 2021), making disassembly possible.

In addition, the partition walls defining the layout of the space are connected with reversible joints avoiding glue, chemical joints and nails, as all buildings designed for disassembly are required to facilitate both deconstruction and disassembly on each level and layer. To summarize, a deconstruction strategy could be described as a careful demolition to select and store building parts with reuse potential and disposal to landfill for those building parts that cannot be reused as is or after minor recovery processes. A disassembly strategy occurs for each and every building part in those buildings designed and built for this purpose.

*4.3.2 Design for adaptability.* DfA is deemed a suitable strategy for reuse in timber-based buildings. DfA relates to the future-proofing of a building and can be defined as design that allows for reconfiguration or conversion to reflect changes in the purpose or use of a building during its design life, minimizing the risk of demolition as a result of economic, societal or functional obsolescence (ISO, 2020; Ross *et al.*, 2016). DfA should proactively and reactively accommodate future changes, whether an existing or new building (Huuhka and Saarimaa, 2018; Conejos *et al.*, 2014). DfA covers design for flexibility, durability, change, deployability and adaptive reuse (Munaro *et al.*, 2022).

To perform DfA, factors that designers need to consider, as summarized by Hamida *et al.* (2022), are as follows:

- flexibility or adjustability, which refers to the possibility to adjust the spatial configuration of the building through minor interventions;
- generality, multifunctionality or versatility, which refers to the possibility of using the spaces in a building for different purposes without conducting any changes;
- elasticity, expandability or scalability, which relates to the possibility to increase the volume of the building, vertically or horizontally, or divide and merge building spaces;
- movability or relocate-ability, which relates to the possibility to easily change the location of building assets, or displace the building components;
- dismantlability (dismountable or deconstructable) or removability, which refers to the possibility of removing the physical objects easily and effectively;
- convertibility or transformability, which relates to the possibility to give the building a new function in light of physical, legal and economic constraints;
- recyclability, reusability or disaggregatability which relates to the possibility of facilitating reuse and recycling of building parts;
- refit-ability, which relates to the possibility to manipulate and improve the performance of components and systems;
- accessibility or availability, which relates to the capacity to access building components and systems for further reprocessing and changes; and
- modularity or regularity, which refers to the potential for increasing regularity in the building pattern.

A building is not a static object but rather a system of constructed layers with different lifespans, where different elements or layers have significantly different design lives (Crowther, 2018b). Therefore, a building's adaptability must be considered in relation to the required durability of a building over its lifespan (Graham, 2005). The use of a layer design approach facilitates building layout flexibility and retrofitting (Webster and Costello, 2005 in Dams *et al.*, 2021) and enables the recovery of building parts. Building layers need to be dismountable for adaptation, where elements can be replaced as required because of end-of-life (Geldermans and Jacobson, 2015). In contrast, adaptability can be configured when building changes occur in physical building layers during different lifespans (Geldermans and Jacobson, 2015). For timber-based buildings, adaptability can be expanded horizontally (if suitable adjacent land is available) or vertically (if planning regulations and foundation designs permit) (ISO, 2020) and enhanced by the replacement of current materials by future, contemporary higher performing materials as newer technologies emerge (Morgan and Stevenson, 2005).

As discussed earlier, it is important to integrate layers within a building in ways that allow parts to be removed or upgraded without affecting the performance of connected systems. To enhance adaptability in design, designers should pay attention to the key principle of independence of building parts. The more each feature is uncoupled from the others, the more adaptable a building becomes. It is especially important to uncouple those layers of a building that have significantly different lifespans (Russel and Moffatt, 2001). The composition of building layers, and the way in which they are constructed and associated, determines the physical flexibility or adaptability of a building (Graham, 2005) where design for loose fit instead of fixed fit is the better option (Russel and Moffatt, 2001). Graham explained the characteristic of a building design based on loose fit as the relationship between the integrity of the individual layers of the building, the independent arrangement of elements and the connection detailing between each layer. These determine the adaptability or flexibility of the building, because a loose-fit approach leaves more freedom of customization to accommodate user requirements (Schmidt and Austin, 2016). Additionally, designers need to consider the principle of designing for long life to intensify adaptability in the building layers.

To support designers, the following is proposed:

- *Skin layer*: design façades so they can be replaced and adapted (Jockwer *et al.*, 2020; Graham, 2005); make the building envelope independent of the structure; provide means for access to the exterior wall system from inside the building and from outside; and design a versatile envelope capable of accommodating changes to the interior space plan (e.g. a modular or panelized system where transparent and opaque units can be interchanged) (Russel and Moffatt, 2001).
- *Structure layer*: add sufficient height to the lower floor to enable a range of other uses (Russel and Moffatt, 2001); design the structure so that it is strong enough to cater for different building uses and loading scenarios (Graham, 2005); dimension structural frames to assist in the adaptation of the space plan to various types of building use and establish a structural grid that permits modular skin and space plan design (Graham, 2005; Rinke and Pacquée, 2022); and introduce repetition and combination of the same module in various rotations to create the structure of interior and exterior volumes, façades and the roof (Jockwer *et al.*, 2020).
- *Space plan layer*: go beyond minimum spatial areas and floor heights (Eguchi *et al.*, 2011; Russel and Moffatt, 2001); provide high adaptability due to removable interior walls (Jockwer *et al.*, 2020); design multifunctional spaces; install interior partitions that are demountable, reusable and recyclable; and use adaptable floor plans, including large grids, that can be subdivided (Russel and Moffatt, 2001).

Adaptability also applies to all connections and details. Different technical solutions can be found in practice that enables the removal and opening of connections, and hence the adaptation of elements and members in a structure (Jockwer *et al.*, 2020). Using mechanical connections as opposed to chemical ones (e.g. adhesives) will enable components to be separated more easily; the connections should also be simplified wherever possible.

There are similarities between the concepts of DfA and DfD, in that they are both concerned with how a building could be taken apart into its constituent components, although focusing on different points and events in a building's lifespan.

The taxonomy presents a classification of building parts and the means to understand the degree to which DfD is desirable or necessary or how other reuse strategies, such as DfA, could be implemented. For example, during the initial design of a development combining residential and commercial space, the client and the lead designer can discuss the degree of adaptability to be built-in to increase or reduce the proportion of offices to apartments, by changing the building layer of space plan using the design strategy of convertibility/transformability (see Table 1). Decisions on the structure and space plan could be made to maximize flexibility at the outset, as well as allow for subsequent refurbishment. Another example could be where the design brief for a new building stipulates the use of the taxonomy as a basis for determining the extent to which DfD and DfA should be incorporated. Evidence of this process could, in the future, prove valuable when seeking planning and building control approval. Additionally, the taxonomy could provide a way for building product manufacturers to demonstrate their reuse credentials, enabling them to produce and promote compliant products and thereby support design for reuse strategies.

## 5. Conclusions

The reuse of building parts as a strategy to achieve circularity in support of the UN's sustainable development goals is a critical matter, as demonstrated by several studies and projects. From these, timber has emerged as a preferable material for circular buildings. Nevertheless, how this will affect the design phase of the construction process has not been sufficiently discussed. One reason could be found in the difficulty of interpreting the meaning of multiple proposed strategies and the interchangeable use of terms referring to the building parts. By means of literature reviews, the study presented here has resulted in a taxonomy for reuse when designing timber buildings, after formulating the interrelationship between the separate building layers (skin, structure and space plan), building parts and different circular reuse strategies to assist designers and other stakeholders from the earliest of phases in the building's lifecycle. The main features of DfD/A are the link between the end-of-life and design phases by means of a deconstruction plan, together with the ability to disassemble each layer or part of a building easily through the use of reversible connectors.

Further studies are required to validate the taxonomy using verified cases within circular timber-based construction. Additionally, it seems appropriate to analyze the possibilities offered by computational design as enablers of design for reuse, explore how the role of the architect will be affected by this modified approach to design and how education should also change to meet industry's needs.

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