# Circular building adaptability in multi-residential buildings – the status quo and a conceptual design framework



Citation for the original published paper (version of record):
Ollár, A. (2024). Circular building adaptability in multi-residential buildings – the status quo and a conceptual
design framework. International Journal of Building Pathology and Adaptation, 42(7): 1-17.
http://dx.doi.org/10.1108/IJBPA-08-2023-0110

# Circular building adaptability in multi-residential buildings – the status quo and a conceptual design framework



Anita Ollár
*Department of Architecture and Civil Engineering, Chalmers University of Technology, Gothenburg, Sweden*

Received 8 August 2023
Revised 13 November 2023
6 December 2023
15 January 2024
Accepted 17 January 2024

## Abstract

**Purpose** – There is a renowned interest in adaptability as an important principle for achieving circularity in the built environment. Circular building adaptability (CBA) could enable long-term building utilisation and flexible use of space with limited material flows. This paper identifies and analyses design strategies facilitating CBA to propose a framework for enhancing the implementation of the concept.

**Design/methodology/approach** – Interviews were conducted with professionals experienced in circular building design to explore the questions "How do currently applied design strategies enable CBA?" and "How can CBA be implemented through a conceptual design framework?". The interviews encircled multi-residential building examples to identify currently applied circular design strategies. The interviews were analysed through qualitative content analysis using CBA determinants as a coding framework.

**Findings** – The results show that all ten CBA determinants are supported by design strategies applied in current circular building design. However, some determinants are more supported than others, and design strategies are often employed without explicitly considering adaptability. The design strategies that enable adaptability offer long-term solutions requiring large-scale modifications rather than facilitating low-impact adaptation by dwelling occupants. The proposed conceptual design framework could aid architects in resolving these issues and implementing CBA in their circular building design.

**Originality/value** – This paper's contribution to CBA is threefold. It demonstrates design strategies facilitating CBA, proposes a conceptual design framework to apply the concept and identifies the need for a more comprehensive application of available adaptability strategies.

**Keywords** Circular building adaptability, Circular building design, Multi-residential building, Design framework

**Paper type** Research paper

## 1. Introduction

During their useful service life, multi-residential buildings (MBs) are exposed to changes due to economic, technical, environmental, or social factors (Schmidt and Austin, 2016). Various design strategies have been identified to support building adaptation facilitating these



Special thanks are due to the study participants who devoted their time and expertise to answering the interview questions. I would also like to express my appreciation to Paula Femenías and Janneke van der Leer for their feedback on previous versions of the manuscript and for Lina Zachrisson for her outstanding work transcribing the interviews.

*Funding:* This paper was carried out within the Circular Kitchen 2.0 project founded by Formas – A Swedish Research Council for Sustainable Development (project number: 202102454) and Västra Götalands Regionen (project number: 20232029).

changes (Schmidt and Austin, 2016). Furthermore, the literature demonstrates the benefits of design for adaptability such as reduced environmental impact (Bourke and Kyle, 2019; Chen *et al.*, 2021), decreased material flows and renovation costs (Kendall, 1999; Pinder *et al.*, 2013; Slaughter, 2001), extended lifespan of buildings (Schmidt and Austin, 2016) and increased user-control over their home environment (Braide, 2019; Plaut and Plaut, 2010; Schneider and Till, 2007).

Despite the available design strategies and apparent advantages of adaptability, successful implementation of adaptable housing design is rare (Tarpio *et al.*, 2021). This is due to barriers, such as the lack of economic incentives (Schmidt and Austin, 2016), technical solutions (Cellucci and Sivo, 2014), practical guidelines and design tools (Askar *et al.*, 2022), and regulatory support (Giorgi *et al.*, 2022). The renowned interest in adaptability as an important principle for achieving circularity in the built environment (Askar *et al.*, 2021) might facilitate opportunities to overcome the barriers.

Both adaptability and circularity entail a dynamic use of buildings and aim to preserve and prolong buildings' usefulness (Hamida *et al.*, 2022). By comparing the two concepts, Hamida *et al.* (2022) point out that circular building design (CBD) relies on adaptability-driven solutions and the determinants of circularity and adaptability overlap. They formulate the term circular building adaptability (CBA), which is defined as "the capacity to contextually and physically alter the built environment and sustain its usefulness while keeping the building asset in a closed-reversible value chain" (Hamida *et al.*, 2022, p. 61). As concluding recommendations of their study, Hamida *et al.* (2022) highlight the need for a better understanding of how CBA could be enabled by design strategies, and "a practical and evidence-based framework" (Hamida *et al.*, 2022, p. 64) for the implementation of the concept. Additionally, Hamida *et al.* (2023) explored design strategies of CBA in adaptive reuse and concluded (similarly to previous research on adaptability in general) that the original design of a building plays a significant role in enabling adaptability in future alterations. Therefore, to address these gaps in CBA research, this paper's objectives are to (1) identify and analyse strategies that could enable CBA and (2) outline a conceptual design framework for the concept's practical application. The aim is not to expand the already comprehensive collection of adaptability strategies but to put this collection in contrast with the scope of currently applied strategies in CBD and to potentially enhance the implementation of CBA.

## 2. Theoretical background

### *2.1 Circular building design*

The concept of circularity (a set of re-introducing loops for resource retention (Ellen MacArthur Foundation, 2015) is seen as a potential tool for addressing issues resulting from the linear processes of the built environment (Hossain and Thomas Ng, 2019; Pomponi and Moncaster, 2017). These linear processes are responsible for a significant environmental impact (Ness and Xing, 2017) and contribute to the premature obsolescence of still-functioning building products and components (Arora *et al.*, 2020). To mitigate these impacts and achieve circularity, circular design plays a central role (European Commission, 2020). As a result, in recent years CBD has gained traction both in academia and practice.

Pomponi and Moncaster (2017, p. 771) define a circular building as "a building that is designed, planned, built, operated, maintained, and deconstructed in a manner consistent with CE principles". Expanding on this definition, circularity in the building context involves prioritising adaptability, maintenance, and repair over replacement during the functional lifespan of a building and retrieving, reusing, or recycling still functioning building elements and materials at the end of a building's service life (Cheshire, 2021).

Design tools, frameworks and assessment methods have been developed to support CBD (Askar *et al.*, 2022). These tools and frameworks often emphasise the importance of design for adaptability to achieve circularity (Askar *et al.*, 2021). For instance, in a review of existing circular design approaches, van Stijn and Gruis (2019) define design for upgradeability and adaptability as one of the eight design principles facilitating CBD (the other principles being design for material and energy reduction, design for attachment, design for durability and reliability, design for standardisation and compatibility, design for ease of maintenance and repair, design for dis- and reassembly, and design for technical and biological cycles). Despite the recognised importance of design for adaptability in achieving circularity in the built environment, current practices focus primarily on end-of-life scenarios and have shortcomings regarding systematically increasing the functional lifespan of buildings through adaptable building design (Askar *et al.*, 2022).

### *2.2 Circular building adaptability*

Based on an extensive literature review comparing and synthesising the concepts of adaptability and circularity, Hamida *et al.* (2022) identified ten determinants of CBA (Table 1). These determinants safeguard the long lifespan of buildings, diminish waste production, and reduce the environmental impact of buildings (Hamida *et al.*, 2022). In a subsequent study, Hamida *et al.* (2023) further investigated how CBA and its determinants were applied in adaptive reuse. They used a qualitative approach to investigate five buildings in a multiple-case study. Their results showed that the influencing factors for applying adaptability-related strategies were organisational (collaboration and partnerships, motivation and capability, conservative sector), economic (viability, feasibility), knowledge-based (expertise, technologies, warranties), regulatory (legal and legislative support), and building design-related (building characteristics).

In relation to building characteristics, Hamida *et al.* (2023) identified design strategies applied in the original building design which facilitated CBA during their adaptation. These strategies included overcapacity, modularity, standardisation, design for disassembly, flexible infrastructure systems, open floorplan concept, shared facilities, using recyclable or reused products, retrieving still functional products and materials, repairing and retaining building components, implementing renewable energy systems, installing energy-efficient

| CBA determinant | Definition |
|---|---|
| Configuration flexibility | Changing the space layout without additional material flows |
| Product dismantlability | Demounting building components without damage or waste and enabling their reuse |
| Asset multi-usability | Using building assets for multiple purposes (e.g. multi-purpose spaces, shared facilities) |
| Design regularity | Designing buildings and their spatial configurations following regular patterns (e.g. modularity, standardised components) |
| Functional convertibility | Changing the primary function of the building (or a part of it) |
| Material reversibility | (Re)Using building materials as long and as effectively as possible in a reversible value chain |
| Building maintainability | Prolonging the usefulness of buildings and sustaining their performance |
| Resource recovery | Regenerating and reducing the resources consumed in the building (e.g. renewable energy techniques, natural ventilation, and lighting) |
| Volume scalability | Expanding or shrinking buildings or building units |
| Asset refit-ability | Refitting building assets to adjust them to improved requirements |

**Source(s):** Hamida *et al.* (2022)

**Table 1.**
Overview of CBA determinants and their definitions

alternatives, and strategically placed infrastructure cores. Hamida *et al.* (2023) concluded that while all CBA determinants were supported by some of these design strategies, in none of the cases (individually) were all determinants applied in a holistic and systematic way. The most supported CBA determinants were configuration flexibility, product dismantlability, and material reversibility. At the same time, the least addressed determinants were functional convertibility and building maintainability. Furthermore, they observed that the original design decisions restricted the implementation of some CBA determinants, such as design regularity or volume scalability. Based on the previous literature, this paper builds on and contributes to CBA research by continuing to collect data on the application of CBA strategies and proposing a conceptual design framework.

### *2.3 Multi-residential buildings*

In this paper, MBs are understood as buildings containing at least three housing units for residential purposes (Boverket, 2024). In the past decades, MBs have been produced in an increasing number to house the expanding urban population (Housing Europe, 2021). However, MBs are often designed without the direct involvement of the end-users, and design decisions are often guided by economic consideration rather than evidence-based end-user needs (Ollár *et al.*, 2020). Furthermore, “the large majority of multi-family housing is designed with no or one single - type of - occupant/occupancy in mind” (Geldermans *et al.*, 2019, p. 5). This, in turn, can lead to a low adaptive capacity (Geldermans *et al.*, 2019) and a potential dissatisfaction with the spatial design of dwellings, triggering extensive alterations (Femenias and Geromel, 2019). This could be mitigated by incorporating adaptability features in the original building design.

Design for adaptability in connection to housing has been long researched. In modern architecture, Schneider and Till (2007) traced the development of adaptable housing back to the 1920s and highlighted that the discourse about the necessity of adaptability in housing had several peak moments over time. During these peak moments, various attempts were made to develop adaptable residential buildings. However, adaptability has not evolved into an integrated part of housing design (Schneider and Till, 2007). Taking advantage of the renowned interest in adaptability for circularity (Askar *et al.*, 2021) has a promising potential to support the implementation of the concept.

Concerning adaptability in CBD, there is a lack of explorations in the context of MBs. For instance, the study of Hamida *et al.* (2023) – specifically focussing on CBA in adaptive reuse – included three office buildings (which were converted into a short-stay residential building, a care centre, and a student housing), a commercial building complex (used as a bank before and as a school after its transformation), and a vacant gym (that was reutilised as an office building). Furthermore, despite adaptability’s relevance and importance in MB design, adaptability tools and frameworks mostly focus on commercial and office buildings which are easier and less costly to adapt (Askar *et al.*, 2022). Hence, previous research on the subject needs to be complemented with studies investigating CBA in MBs. Therefore, this paper further advances the research on CBA by focussing on MBs to expand the investigated building typologies.

## 3. Materials and method

The research design was based on the study’s goal to define research questions and select methodological procedures that guide the material collection, analysis, and interpretation (following the guidelines of Flick, 2018). Based on the two objectives (outlined in section 1), two research questions were formulated: How do currently applied design strategies enable CBA in CBD? and How can CBA be implemented through a conceptual design framework?. A qualitative research approach was selected to investigate these questions. Such an approach allowed to gain insight into how a specific concept (CBA) is applied in a certain field (CBD) and explore the reasonings behind the connected processes (design choices).

Based on the dual objectives of this paper, the research design consists of two steps mirroring the two research questions (Figure 1). In Step 1, a Snapshot study (Flick, 2018) was carried out to explore processes related to the present and describe the status quo of CBA. The selected data collection method – fitting to conduct a Snapshot study – was interviews, which were then analysed through qualitative content analysis (Flick, 2018). The findings of the analysis guided the development of the conceptual design framework in Step 2. The following sub-sections give further detail of the material collection, analysis, and interpretation.

### *3.1 Data collection*

The empirical material was collected between September 2022 and April 2023. Six semi-structured interviews were conducted online with six companies experienced in CBD (Table 2). In each interview, one representative of each company participated in answering the questions. The selection of the potential interview subjects followed a purposive sampling through the following criteria:

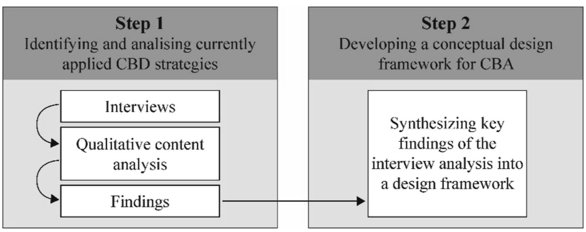
(1) Building typology: The company's portfolio contained MB(s).

(2) Design approach: The MB(s) were designed with CBD strategies. The building examples did not have to cover all CBD strategies (as identified by van Stijn and Gruis, 2019). However, the examples had to demonstrate the application of several CBD strategies in combination.

(3) Geographical location: The companies and examples were to be located in Europe. This criterion was meant to help understand design choices made for similar social, cultural, technical, economic, and climatic contexts.

The interviewees were identified through an online search and in previous literature. Additionally, interviewee C was identified as a recommendation from interviewee B. To date, only a few built examples are available due to the complexity that CBD entails (Cambier *et al.*, 2021), and amongst the examples, the representation of MBs was found to be low. Therefore, some interviewees were approached even if their circular building project was in the conceptual phase. The search was conducted in English, which limited the identification of companies with projects reported on in other languages. As a result, five companies were contacted in the Netherlands and one in Denmark. The high representation of Dutch examples was probably due to the country's high incentive to transition to circularity (Kanters, 2020; Ping Tserng *et al.*, 2021).

In each interview, the participants gave verbal consent for recording the conversation. The recorded material was treated according to GDPR and was subjected to anonymisation




**Source(s):** Author's own work

**Figure 1.** Steps of research design

**Table 2.** Overview of the participants of the interviews, the discussed building examples, and their locations

| Interviewee | Company's profile | Interview participant | Building examples | Location |
|---|---|---|---|---|
| A | design, development, and realisation of construction and infrastructure projects, including maintenance, renovation, and transformation | project manager, real estate developer, and business administrator | Stackable dwelling unit | The Netherlands |
| B | architectural design, product development, and digital production focussing on new circular solutions for housing | architect, researcher | Stackable dwelling unit | The Netherlands |
| C | design and development of circular buildings with a particular focus on adaptability | architect, real estate developer | MBs from the company's portfolio | The Netherlands |
| D | CBD for the private and public sector | project leader and technical designer for building details and innovation | MBs from the company's portfolio | The Netherlands |
| E | developing modular and circular housing systems for MBs | architect | Stackable dwelling unit | The Netherlands |
| F | architectural design of buildings and cities with a focus on sustainable and circular solutions for liveable homes | architect and CEO of an architectural office | Stackable dwelling unit | Denmark |

**Source(s):** The author's own work

to prevent the identification of the participants. Beyond the participants' names and professional backgrounds, no other personal data was collected. The duration of the interviews ranged between 30 and 65 min, depending on the elaborateness of the interviewees' answers. The interview questions focused on three themes: (1) the professional background and CBD experience of the interviewees, (2) applied CBD strategies in their MB projects, and (3) the design choices with a focus on how and why adaptability was enabled (or not).

MB examples of the companies' portfolios guided the discussion. The aim was to discover strategies that the interviewees applied in CBD (rather than using the building examples as case studies). Additionally, as mentioned earlier, some of the building examples were in a conceptual phase; hence, a thorough documentation analysis was not possible. The interviews were used to identify the applied CBD strategies and to explore why they were chosen. Four interviews (A, B, E, F) discussed one specific building example since those were the only examples developed with CBD strategies in the companies' portfolios. In interviews C and D, multiple building examples were brought up to exemplify the applied CBD strategies; in these two interviews, the companies' portfolios had a broader representation of circular MBs.

### *3.2 Interview analysis, interpretation and the development of a conceptual design framework*

The interviews were transcribed and analysed through qualitative content analysis (Flick, 2018) in NVivo. The CBA determinants (Hamida *et al.*, 2022) were used as a coding framework to analyse the empirical material. The determinants served as predefined codes to classify the design strategies mentioned by the interview participants. Additional codes were created in case new themes relevant to understanding the application of the design strategies emerged.

The analysis of the interviews provided a collection of design strategies enabling CBA and gave an insight into how CBD principles are considered and applied in MBs.

In the following step, a conceptual design framework was developed to enable a systematic implementation of CBA. It has been stressed in previous literature that a systems approach is critical to achieving successful CBD (Bocken *et al.*, 2016; Geldermans, 2016; Pomponi and Moncaster, 2017). In a systems approach, buildings are considered as a combination of all parts, much the same as the shearing layers concept (Brand, 1994) considers buildings as a combination of six layers: site (the lot the building sits on), skin (façade elements), structure (foundation and load-bearing parts), services (infrastructures – ventilation, heating, electrical wires, etc.), space plan (floorplan setting) and stuff (furnishings). Geldermans (2016) developed an inventory matrix that supports designers in applying circular design principles to each of the six shearing layers of buildings (Table 3). In the matrix, the sheering layers are further dissected into subcategories and parts (components, products and materials). While using the matrix, a holistic application of circular design principles is ensured by considering the principles in connection to all layers and parts and in combination across them. In this paper, Geldermans' (2016) inventory matrix served as an inspiration for proposing a design framework for CBA (described in section 4.2).

## 4. Findings

Five of the six interviewees revealed that design for adaptability was not a priority in their circular MB projects. The strategies identified in the interviews were often applied because the architects wanted to enable other CBD principles (for instance, design for disassembly) and not because they intended to facilitate adaptability. Design for adaptability was perceived as less critical than other circular design principles since it presumably had a less immediate or measurable impact on reducing resource use. However, interviewee C emphasised that a genuinely circular building must be adaptable both in the short and long term.

### *4.1 The design strategies' contribution to CBA and their possible application to the shearing layers*

The interviewees mentioned various circular design strategies applied in their projects that had the potential to support CBA. Table 4 summarises the design strategies and the enabled

| Shearing layer | Subcategory (Sc) | Part * | Bio-cascades | Bio-feedstock | Maintenance | Redistribution | Refurbishment | Remanufacturing | Recycling |
|---|---|---|---|---|---|---|---|---|---|
| Stuff | Sc-n | Part-n | | | | | | | |
| Setting (or Space plan) | Sc-n | Part-n | | | | | | | |
| Service system | Sc-n | Part-n | | | | | | | |
| Structure | Sc-n | Part-n | | | | | | | |
| Skin | Sc-n | Part-n | | | | | | | |
| Site | Sc-n | Part-n | | | | | | | |

**Note(s):** *component, product, material, etc
**Source(s):** Geldermans (2016)

**Table 3.** Geldermans' (2016) inventory matrix

| Design strategies | Named by | Adaptability features |
|---|---|---|
| Open building concept | C, D, F | Flexible position of the partition walls<br>Various floorplan solutions and room connections |
| Pre-cut openings in structural walls | C, F | Opening and closing entrance doors |
| Over-capacity | C, F | Various floorplan solutions<br>Multiple functions for dwelling units and buildings<br>Scalable dwelling and room sizes<br>Space for adapting to future requirements |
| Demountable building components | A, B, D, E, F | Dismantling, relocating and re-assembling buildings<br>Changing the physical composition of buildings<br>Separatable components enabling future reconfiguration and maintenance of the space<br>Scalable building and dwelling sizes |
| Prefabricated building components | A, C, E, D | Standardised measurements contributing to regular patterns in spatial design |
| Stackable building components | A, B, E, F | Regular patterns on the dwelling and building scale<br>Scalable building sizes |
| Modular, standardised building components | A, B, D, E, F | Regular patterns on the dwelling and building scale<br>Scalable building sizes |
| Scenario planning | A, B, C, E | Various floorplan solutions |
| Combined room functions | A | Multiple functional uses of space |
| Universal ceiling height | C, D | Regular dimensions for floor heights<br>Different building functions (e.g. housing, offices) |
| General room sizes | A, B | Regular dimensions for rooms<br>Interchangeable room functions |
| Sliding walls | A | Various floorplan solutions<br>Scalable room sizes |
| Centralised location of infrastructure systems (infrastructure core) | A, B, C, F | Multiple locations for infrastructure-dependent dwelling units (e.g. kitchen, bathroom) |
| Increased floor thickness for infrastructure systems | C | Multiple locations for infrastructure-dependent dwelling units (e.g. kitchen, bathroom) |
| Removable covers or panels in the walls and floors | C, F | Access to infrastructure installations to maintain, repair, or modify |
| Partition walls free from infrastructure installations | C | Possibility to move partition walls without adjusting infrastructure systems |
| Combined product function | A | Efficient space utilisation |
| Reversible connections | B, D, E, F | Dismantling, relocating and re-assembling buildings<br>Separatable components and materials that enable future reconfiguration of the space |
| Renewable energy systems | B, C, F | Resilient and reduced resource use |
| Aligning material measurements with building units and components | B | Regular patterns on the dwelling and building scale |
| Durable materials for ease of maintenance, reuse and recycling | A, B, C, D, E, F | Adjustable interior finishings<br>Choices for the end-users to personalise their space |

**Source(s):** The author's own work

**Table 4.**
The design strategies identified in the interviews and their adaptability features

adaptability features, and Table 5 shows the design strategies' contribution to the CBA determinants.

The Open Building concept (main structure with flexible infill) was mentioned as a strategy to enable different floorplan variations in the building and the dwellings. The Open

| Design Strategy | Configuration flexibility | Product dismantlability | Asset multi-usability | Design regularity | Functional convertibility | Material reversibility | Building maintainability | Resource recovery | Volume scalability | Asset refit-ability |
|---|---|---|---|---|---|---|---|---|---|---|
| | CBA determinants | | | | | | | | | |
| Open building concept | x | | | | x | | | | | |
| Over-capacity | x | | | | x | | | | x | x |
| Demountable building components | x | x | | x | | x | x | | x | |
| Prefabricated building components | | | | x | | | | | | |
| Stackable building components | | | | x | | | | | x | |
| Modular, standardised building components | | | | x | | | | | x | |
| Scenario planning | x | | | | | | | | | |
| Combined room function | | | x | | | | | | | |
| Universal ceiling height | | | | x | x | | | | | |
| General room sizes | | | | x | x | | | | | |
| Centralised location of infrastructure systems (infrastructure core) | x | | | | x | | x | | | |
| Increased floor thickness for infrastructure systems | x | | | | x | | x | | | |
| Removable floor panels | | | | | | | | | | |
| Partition walls free from infrastructure installations | x | | | | | | | | | |
| Sliding walls | x | | | | | | | | | |
| Pre-cut openings in structural walls | x | | | | | | | | x | |
| Combined product function | | | x | | | | | | | |
| Reversible connections | x | x | | | | x | x | | | |
| Renewable energy systems | | | | | | | | x | | |
| Aligning material measurements with building units and components | | | | x | | | | | | |
| Durable materials for ease of maintenance, reuse, and recycling | | x | | | | x | x | | | |

**Source(s):** The author's own work

**Table 5.**
The identified design strategies' contribution to CBA determinants

Building concept allows configuration flexibility and functional convertibility. One of the interviewees pointed out that a carefully thought-through legal framework was needed to fully exploit the potential that the Open Building concept created (namely, the possibility of filling the space with various layouts and dwelling sizes). They gave an example that showed that if the building were divided into the smallest dwelling units, it would have consisted of 48 dwellings. Therefore, the design team ensured that there were 48 dwellings registered at the administrative and legislative bodies. This way, owners could combine or separate the dwelling units. The possibility of subdividing larger dwellings was further enabled by pre-cut openings in the structural walls, which served as future entrance doors.

The interviewees had a divided opinion about the over-capacity of structural systems or floor areas. Some of them thought that building only what was needed and used was necessary to achieve circularity. One of them remarked that, especially in small dwellings – used by one or two occupants – there was less urgency to partition the dwelling into private and public spaces, and resources could be spared by using a more open floorplan. Others argued that reasonable over-dimensioning of certain building parts could enable various floorplan solutions, multiple functions, scalable dwelling and room sizes, and a good margin to adapt to future requirements. However, one of the participants explained that only the investors' special incentive for creating adaptable dwellings enabled the financial support to incorporate reasonably over-dimensioned building components.

Demountable building components were raised in each interview as a crucial circular design strategy. With the help of this strategy, the components could be easily maintained, demounted, replaced, relocated, or reassembled. Furthermore, changing the physical composition of buildings or the floorplan configuration of the dwellings is also achievable. The interviewees added that demountable building components follow a certain design regularity, further enabling horizontal and vertical scalability.

Several interviewees favoured prefabricated building components. The examples included prefabricated functional components (such as kitchens or bathrooms) and complete dwelling units. Although this strategy sped up the onsite construction process, the transportation to the site enforced some dimensional restrictions. The allowed width and height of objects transported on public roads often defined the measurements of the prefabricated building components. As a result, the standardised measurements of the components contributed to regular patterns in spatial design.

Various floorplan alternatives could be achieved within the same dwelling through scenario planning. In one of the example projects, the architects created 24 different floorplan variations for the dwellings, but the new owners could create their own floorplan solution, too. The interviewee explained that all the new owners chose their own floorplan design, and none of the architects' original floorplan variations were realised. This demonstrated the importance of end-user involvement in the design of their homes, and that scenario planning alone was not sufficient to provide for the end-users' spatial needs.

Multiple functions were combined in one room in the dwelling units to enable asset multi-usability and reduce unnecessary space and connected resource use. This was achieved by merging the functions of the entrance hall and the living room or the functions of the living room and the kitchen. It must be cautioned that although this design strategy reduced the unnecessary use of resources, it might have consequences on the functional and spatial experience of the dwellings. CBD is meant to contribute to a sustainable built environment, so it must consider not only environmental or economic but social aspects too. Reduced floor areas might lead to rooms that do not fulfil their functional purposes, and dwelling occupants would be unable to utilise the rooms according to their functional needs.

Four interview participants described that their companies developed stackable and/or modular building components. Instead of delivering floorplan designs and hiring a contractor to build the buildings, they developed prefabricated dwelling units that could be delivered as single houses or stacked to form terraced houses or MBs. Although this strategy supports design regularity and volume scalability, it has been cautioned that the exterior representation of the building should not result in a repetitive pattern. This was prevented by providing various façade finishings and different ways to stack the units.

Two interviewees reflected on the differences in building regulations connected to different building functions. They remarked that functional convertibility (e.g. from housing to office function or vice versa) was only possible if a building fulfils all requirements connected to different occupational functions. For example, a universal ceiling height of four metres would support both residential and commercial functions. However, such an increase in the volume of the rooms would lead to an increased demand for heating, cooling, natural daylight, or ventilation. Implementing design strategies supporting resource recovery could mitigate the impact of the increased resource demand.

Reconfiguring floorplans of dwellings required that all room functions had several possible locations within the dwelling. This could be enabled by general room sizes, which would, for example, facilitate a functional switch between a bedroom and a living room. Sliding walls also provided the ability to change floorplan configurations without additional waste. However, the infrastructure-dependent units were one of the most significant constraints in reconfiguring floorplans. The interviewees mentioned two strategies in connection to the infrastructure systems. One strategy focused on establishing a central infrastructure core in the dwelling where the kitchen and the bathroom were located. This strategy enabled partial adaptability of floorplans since the infrastructure-dependent units would always be in the same location. The other strategy established a central shaft within the building and supplied the dwellings through wires and ducts running in the floors. Two additional design strategies facilitated this: increased floor thickness and removable covers and panels in the floors. Since the infrastructure systems avoided walls, it was easier to reconfigure the floorplans or subdivide dwellings by removing, relocating, or adding walls. The accessible infrastructure systems further enabled ease of maintenance.

In a compact dwelling design example, the kitchen and the bathroom had a shared sink. The interviewee argued that the space of the dwelling could be used more efficiently by combining product functions (asset multi-usability). While the kitchen sink is usually used for food preparation and cleaning kitchenware, the bathroom sink is used for personal hygiene. Thus, it would be worth investigating whether these two functions could be merged without any hygiene risks.

Renewable energy systems were mentioned as a strategy to enable resilient and reduced energy use in buildings. The examples included solar panels, heat exchangers, and rainwater collection. These systems contributed to resource recovery and facilitated easy adaptation to future changes in available energy sources.

To reconfigure the spaces of the dwellings or the building, it was vital to prioritise reversible connections over chemical ones. Such connections facilitated dismantling, replacing, relocating, and re-assembling different parts and layers of buildings. Four interview participants emphasised that they prioritised "dry" connections so that the building components could be part of a circular value chain, as it was possible to disassemble them in the future.

Concerning material choices, the interviewees mentioned several circular design strategies. For example, aligning the measurements of materials (e.g. sheet materials and tiles) and building components influenced the overall dimensions of dwellings and buildings and the amount of waste produced during construction. Additionally, choosing durable materials that were easy to maintain, reuse, and recycle had a direct impact on the lifespan of the building.

The above-described strategies ranged from overall design concepts to product-specific solutions. These strategies were often simultaneously applicable to several shearing layers. For instance, over-capacity could be applied to all shearing layers to enable a capacity to accommodate future adjustments or prefabricating building components would influence the design and dimensions of the space plan, service, structure, and skin of a building. Table 6 provides an overview of the possible application of the identified design strategies to the shearing layers.

### *4.2 Conceptual design framework for CBA*

The analysis of the interviews showed that the applied strategies had the potential to enable multiple CBA determinants and contributed to the design of multiple shearing layers

Table 6.
The identified design strategies' possible application to the shearing layers

| Design strategy | Shearing layers Stuff | Space plan | Service | Structure | Skin | Site |
|---|---|---|---|---|---|---|
| Open building concept | | x | x | x | x | |
| Over-capacity | x | x | x | x | x | x |
| Demountable building components | x | x | x | x | x | |
| Prefabricated building components | | x | x | x | x | |
| Stackable building components | | | x | x | x | |
| Modular, standardised building components | x | x | x | x | x | |
| Scenario planning | x | x | x | | x | |
| Combined room function | | x | x | x | | |
| Universal ceiling height | | x | x | x | x | |
| General room sizes | | x | x | x | | |
| Centralised location of infrastructure systems (infrastructure core) | | x | x | x | | |
| Increased floor thickness for infrastructure systems | | | x | x | x | |
| Removable floor panels | | | x | x | | |
| Partition walls free from infrastructure installations | | x | x | | | |
| Sliding walls | | x | | x | | |
| Pre-cut openings in structural walls | | | | x | | |
| Combined product function | x | | | | | |
| Reversible connections | x | x | x | x | x | |
| Renewable energy systems | x | x | x | x | x | x |
| Aligning material measurements with building units and components | x | x | x | x | x | |
| Durable materials for ease of maintenance, reuse and recycling | x | x | x | x | x | |

**Source(s):** The author's own work

simultaneously. Choosing to apply a certain design strategy impacts the adaptability potential of a building and informs design choices regarding the building characteristics connected to each shearing layer. Based on these observations and inspired by Geldermans' (2016) inventory matrix a conceptual design framework was developed (exemplified in Table 7). The framework consists of three main parts: a library of design strategies enabling CBA, the CBA determinants and the building dissected into its parts. Designers could select strategies informed by the building context, identify CBA determinants supported by the chosen strategies, and define design choices connected to the applicable shearing layers and their parts.

Designing a building is never a linear process; some decisions are made parallel, or some design choices are reconsidered, which influences other design choices that need to be reviewed. Architects move between scales, building parts, etc. and follow an iterative process. The proposed design framework is meant to be used similarly. The starting point can be any of the three main parts. For instance, one could first select a shearing layer and then outline applicable CBA determinants. This could lead to design strategies that would inform the design choices connected to the shearing layer's parts. It is important to reiterate this process to align the design choices amongst the parts within and across shearing layers. The framework could also be used as a documentation or analytical tool to trace design decisions and assess whether all CBA determinants across all shearing layers are comprehensively facilitated. This can reveal whether the adaptability potential of a building and its shearing layers has been fully achieved or whether there is a need for further enhancement.

| Design strategy | Configuration flexibility | Product dismantlability | Asset multi-usability | Design regularity | Functional convertibility | Material reversibility | Building maintainability | Resource recovery | Volume scalability | Asset refit-ability | Building<br>Shearing layer | Subcategory (Sc) | Part * |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Open building concept | | | | | | | | | | | Stuff | Sc-n | Part-n |
| | x | | | | x | | | | | | Space plan | Sc-n | Part-n |
| | x | | | | x | | | | | | Service system | Sc-n | Part-n |
| | x | | | | x | | | | | | Structure | Load-bearing columns placed in a grid | Recycled concrete<br>Dismantlable metal joints<br>Part-n |
| | | | | | | | | | | | | Sn-n | Part-n |
| | x | | | | x | | | | | | Skin | Sc-n | Part-n |
| | | | | | | | | | | | Site | Sc-n | Part-n |

**Note(s):** *component, product, material, etc
**Source(s):** The author's own work

**Table 7.** Exemplifying the use of the conceptual design framework

The use of the CBA framework is demonstrated in Table 7 by taking the example of the Open building concept and using solutions mentioned in the interviews. The Open building concept enables configuration flexibility and functional convertibility and influences the design of parts of the space plan, service systems, structure, and skin. These shearing layers could be further dissected into subcategories. For example, the structure could be defined by a frame construction consisting of a column system between slabs. The columns' material choice could be aligned with other design strategies (such as aligning material measurements with building units and components and durable materials for ease of maintenance, reuse, and recycling). For instance, the columns could be made of recycled concrete (mentioned by interviewee E). The connection between the columns and slabs could be dismantlable metal joints (as shown in an example by interviewee F) that would also support the design strategy of demountable building components.

## 5. Concluding discussion

This paper identifies and analyses design strategies that enable CBA and proposes a systematic approach to implementing the concept. The key findings of the study can be summarised as follows:

(1) The design strategies often facilitated multiple CBA determinants and could be applied on several shearing layers simultaneously.

(2) All ten CBA determinants were supported by design strategies applied in current CBD. However, some of the determinants were more supported than others.

(3) The selection process of design strategies for CBD lacked the explicit consideration of design for adaptability.

(4) The design strategies that enabled adaptability offered long-term solutions requiring large-scale modifications rather than facilitating low-impact adaptation by dwelling occupants.

(5) The design strategies were not applied in a systematic way, resulting in partial adaptability in each discussed building example.

The results showed that the ten CBA determinants were supported by strategies already applied today in MB design. The strategies enabled mainly configuration flexibility, design regularity, functional convertibility, and building maintainability. Hamida *et al.* (2023) found that functional convertibility and building maintainability were the least-enabled determinants in adaptive reuse projects. This was due to the limitations of the original building design. Hence, implementing strategies supporting these two determinants in the original design of buildings is crucial to enable a holistic application of CBA.

Similarly, as in adaptive reuse (Hamida *et al.*, 2023), asset multi-functionality, asset refit-ability and resource recovery were rather underrepresented in newly designed buildings. Enabling asset multi-functionality and asset refit-ability by creating opportunities to use resources and spaces for different purposes simultaneously was generally not facilitated in the examples. Additionally, resource recovery was enabled only by using renewable energy sources, and design strategies that allow natural ventilation or daylight were not mentioned. Further research could explore how additional design strategies could enable these less-addressed CBA determinants.

The most often mentioned strategies were the demountable building components, pre-fabrication, and applying reversible connection. This shows that in current CBD, a significant emphasis is put on solutions that facilitate dis- and reassembly. This can enable ease of maintenance during the building's functional lifespan and effortless retrieval of building components at the end-of-life of a building. Hamida *et al.* (2023) found that repairing and retaining building components and retrieving still functional products and materials were often used strategies in adaptive reuse. Therefore, implementing design strategies in the original building design that increase the success rate of repairing, retrieving, and recirculating products and materials would be highly advantageous for future adaptation.

The identified design strategies were mostly used because they contribute to other circular design principles (e.g. design for disassembly) rather than because of the explicit consideration of CBA. This was due to certain influencing factors. The interviews revealed that economic incentives and regulatory support were the two most important factors enabling CBA. This observation aligned with previous research identifying barriers to implementing adaptability in housing design (Hamida *et al.*, 2023; Tarpio *et al.*, 2021). Hopefully, upcoming economic and regulatory frameworks supporting circularity will encourage the construction of more adaptable buildings.

Considering the adaptability features of the MB examples, most of the design strategies enabled long-term adaptability, requiring significant alterations and possibilities for end-users to adapt their dwelling to their needs were restricted to specific options for finishings of walls, floors, or inbuilt furniture. This is in line with the literature that showed that possibilities for floorplan alterations in MBs are still limited (Geldermans *et al.*, 2019). Previous research shows that the dwelling occupants frequently alter two shearing layers: space plan and stuff (Femenias and Geromel, 2019; Ollár *et al.*, 2022a, b). Therefore, CBD should incorporate strategies for dwelling occupants that enable low-impact alterations of these two shearing layers to reduce the resource flows from such alterations. Additionally, even though in some of the examples the end-users had the option to choose from floorplan variations before the building assembly, future alterations would require extensive construction work to reconfigure the interior spaces. This reinforces the need for appropriate technical solutions (as indicated by Cellucci and Sivo, 2014).

The MB examples discussed with the interviewees usually applied only a few design strategies. They did not follow a systematic approach to enable adaptability holistically in the building, as also observed by Hamida *et al.* (2023). The ownership form of the dwelling units further influenced the extent of adaptability features in the examples containing both rental and owner-occupied dwellings. In rental dwellings, the building owners' interest was to limit the potential alterations the end-users could perform to prevent damage to building components. While in owner-occupied dwellings, the end-users (owners) had the chance to be in control of their spaces and alter them according to their needs. These preconditions resulted in applying different design strategies and creating different levels of adaptability for rental and owner-occupied dwellings. This difference would be worth exploring in future research.

The design strategies' potential to support multiple CBA determinants and shearing layers simultaneously served as a base to develop the proposed conceptual design framework. Although the starting point of the investigation was MB examples, the design framework could be applied to other building typologies, too. The framework could assist architects in applying adaptability strategies on different shearing layers while comprehensively facilitating all CBA determinants. In its current conceptual form, the framework foremost intends to show a principal logic necessary for the systematic consideration of CBA. The framework needs to be further developed to create a user-friendly tool to help designers navigate the complexity of CBA. Further work could advance the development of the framework by including other adaptability strategies (e.g. Schmidt and Austin, 2016) with the evaluation of their contribution to CBA determinants and shearing layers. Furthermore, testing, iterating, and validating the framework with architects while applying it in design scenarios is essential. This would ensure a framework formulation that aids the design process of architects rather than further complicating it.

In conclusion, this paper's contribution is threefold. First, it demonstrates that there are already applied design strategies facilitating CBA. Second, it proposes a conceptual design framework to implement CBA. Third, it identifies a need for implementing strategies that can address some of the unresolved challenges (e.g. possibilities for the end-users to quickly adapt the space of the dwelling units, multifunctional spaces and products, design strategies supporting resource recovery). A next step in the developing research field of CBA is evaluating the theoretical work in actual design scenarios with the involvement of practitioners.

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**Corresponding author**
Anita Ollár can be contacted at: ollar@chalmers.se