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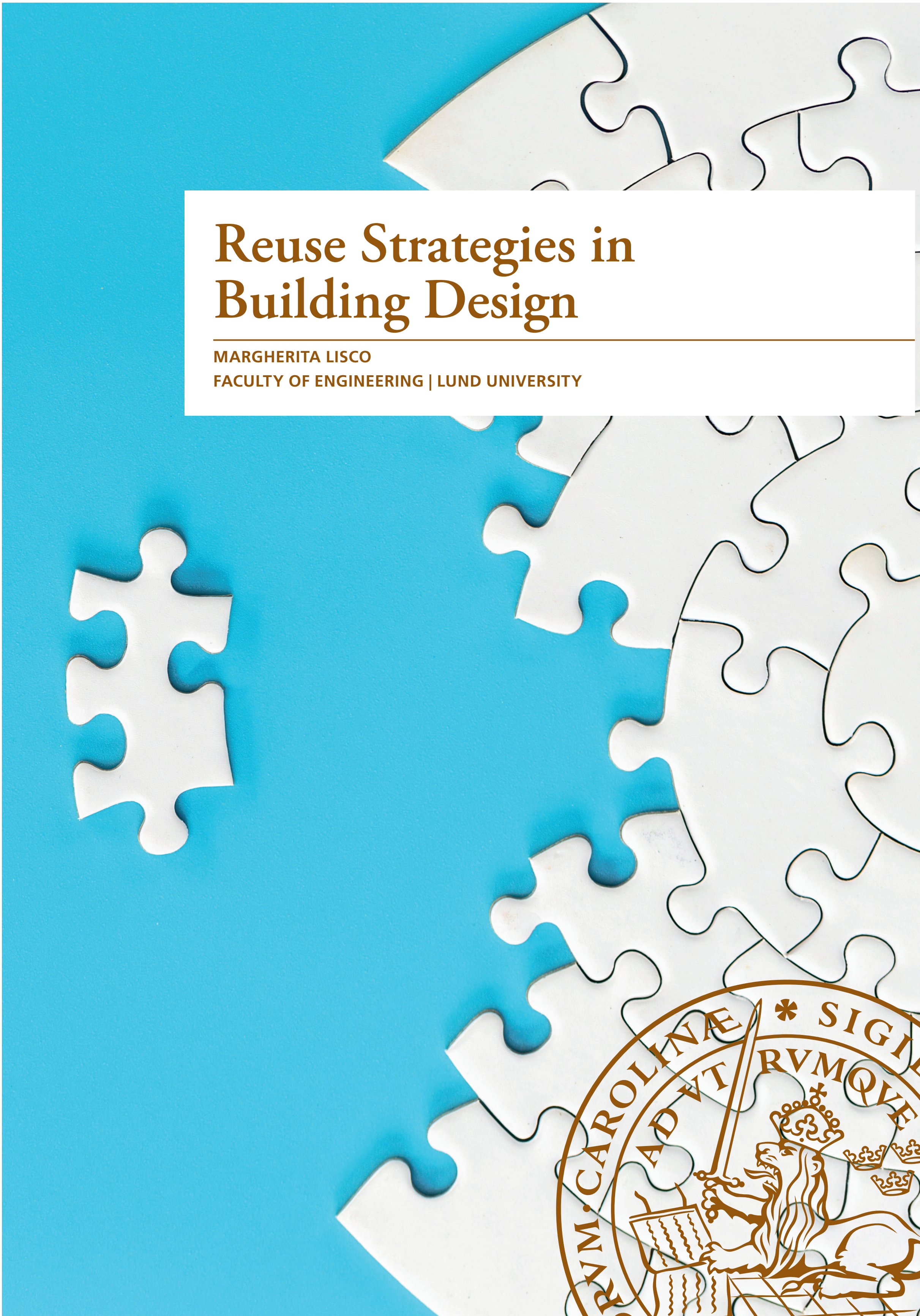

Reuse Strategies in Building Design

MARGHERITA LISCO
FACULTY OF ENGINEERING | LUND UNIVERSITY

Reuse Strategies in Building Design

Margherita Lisco

DOCTORAL DISSERTATION

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Abstract:

The building sector, as a major consumer of energy and resources, has been slow to adopt sustainability and digitalization compared to other sectors. This dissertation investigates how digital tools, particularly computational design (CD), can support the reuse of building parts within a circular economy framework, through design for disassembly and reuse-centred design (RCD) strategies. The research highlights the growing importance of layer-based design, industrialized construction and reversible connectors in enhancing the adaptability and longevity of buildings. However, significant technical and cultural challenges hinder the widespread adoption of reuse strategies, including the constraint of designing by availability, lack of classification systems, competency gaps and resistance to new workflows.

The research employs a mixed-methods approach to identify key challenges and opportunities in implementing RCD with CD tools. The findings indicate that while CD can optimize reuse strategies, automate building parts selection and facilitate design iteration, its integration into architectural practice remains underexplored. The research identifies emerging roles, such as data miners, augmented architects and circular material specialists, necessary to bridge the gap between traditional building practices and a digitally driven, circular construction model. Furthermore, the lack of structured data management, including material passports and digital inventories, remains a barrier to the adoption of reuse strategies.

The research highlights several soft aspects influencing the adoption of CD in RCD. These include the balance between increased design speed and long-term quality, the trade-offs between automation and creativity and the evolving aesthetic considerations in reuse-based architecture. While computational tools enable rapid prototyping and building parts selection, there is a risk of standardized, homogeneous design outcomes. Yet, CD can enhance craftsmanship, particularly in the detailing of joinery and connections, adding value to architectural design while supporting circular principles. By first addressing the challenges of reuse in design, then exploring the implications of adopting CD to support RCD and finally examining how to integrate CD methodologies into RCD strategies, this research contributes to sustainable development goals by promoting a transition from a linear to a circular construction model. The implications extend to education, professional training and sector practices, emphasizing the need for interdisciplinary collaboration and digital infrastructure to enable the transition. The findings provide a foundation for further discussion on how policy innovations and AI-driven design solutions can accelerate the adoption of RCD strategies in the building sector.

This research underscores the transformative potential of integrating RCD with CD to mainstream sustainable building practices, emphasizing the need for technical innovation, data management and interdisciplinary training to overcome existing barriers and realize a resilient, resource-efficient and circular building sector.

Key words: Reuse, Design, Circular economy, Digitalization, Computational design

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To my mother,
and in loving memory of my father
and my cats, Sissi and Frisella.

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“The science of today is the technology of tomorrow”.

Edward Teller (1908-2003)

Acknowledgements

Undertaking a PhD is a long journey, and although it is deeply enriching, it is not without its challenges. It is a continuous learning process that can be compared to the path a child follows in learning to walk. At first, the child crawls, then gradually learns different techniques to maintain balance, until finally feels confident enough to take their first independent steps. Reaching this milestone brings an indescribable sense of satisfaction, marking the moment a student is ready to walk independently as a researcher. Yet, just as a child who has learned to walk and run can occasionally stumble, so will the young researcher also encounter obstacles and setbacks. These challenges must be faced by standing up again and persevering because learning never truly ends, just as stumbling and falling are part of life, even in adulthood.

My PhD journey has encompassed all of this and would not have been possible without the people who supported me along the way. Professionally, I achieved milestones I once thought unreachable, especially given my initial total lack of academic writing skills. Privately, during these years, I got married, had a child and mourned the loss of two beloved family pets. It is fair to say that, both professionally and personally, I am no longer the same person who began this journey. For all of this, I am deeply grateful to my main supervisor Anne Landin, and my co-supervisors, Radhlinah Aulin and Henrik Szentes. Words cannot adequately express my gratitude to Brian Atkin, who taught far more than just how to conduct research and whom I am proud to call my mentor.

I am also profoundly thankful to my colleagues at the Division of Construction Management for their support, advice and the many moments of laughter. First and foremost, Francesca, who listened to my daily frustrations (and my singing) and shared both concerns and successes with me along the way. I wish to thank Anne for being such a supportive manager, always offering kind words. She was the first to suggest that I pursue an academic career, and I will remain forever grateful to her for believing in me and for her trust. A special thanks goes to Radhlinah (Linah) – not only a colleague, but also a true friend. Her door was always open, her phone always on, and she often worked overtime just to support me. I would also like to thank Rikard, who provided both suggestions and endless laughter and for being my office neighbour for almost one year now; Carlos, for his advices and for being my singing partner; Urban, who helped me choose the title of this thesis and for his feedback; Agnes, my first roommate, for encouraging me when we met; Stefan, for assisting me with the Swedish translation and for the many conversations, especially during the final months and Henrik Norinder, for his kind words and for checking on me on a regular base in the last period. My heartfelt thanks go to Kolbrun, always ready to solve any bureaucratic or organizational issue with her unique skill and efficiency and to Tim Nordin for helping me with the cover of the dissertation. To

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The truth is that, had my mother Catia and my brother Fabio not moved into my home during the last months, I would have been overwhelmed by the stress of daily life and unable to concentrate on my dissertation fully. For this, I am infinitely grateful to them. I must also thank Thomas, my loving and patient husband, who not only endured my emotional highs and lows, but also accepted living with three and a half Italians under the same roof for such a long time. Last but not least, I am deeply grateful to Fabio, my almost six years old little whirlwind, who, with his constant requests for cuddles and playtime, kept me grounded and helped me see things from the correct perspective, reminding me, as I have been told that, after all, it is just a PhD.

Margherita Lisco

Helsingborg, April 2025

Abstract

The building sector, as a major consumer of energy and resources, has been slow to adopt sustainability and digitalization compared to other sectors. This dissertation investigates how digital tools, particularly computational design (CD), can support the reuse of building parts within a circular economy framework, through design for disassembly and reuse-centred design (RCD) strategies. The research highlights the growing importance of layer-based design, industrialized construction and reversible connectors in enhancing the adaptability and longevity of buildings. However, significant technical and cultural challenges hinder the widespread adoption of reuse strategies, including the constraint of designing by availability, lack of classification systems, competency gaps and resistance to new workflows.

The research employs a mixed-methods approach to identify key challenges and opportunities in implementing RCD with CD tools. The findings indicate that while CD can optimize reuse strategies, automate building parts selection and facilitate design iteration, its integration into architectural practice remains underexplored. The research identifies emerging roles, such as data miners, augmented architects and circular material specialists, necessary to bridge the gap between traditional building practices and a digitally driven, circular construction model. Furthermore, the lack of structured data management, including material passports and digital inventories, remains a barrier to the adoption of reuse strategies.

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By first addressing the challenges of reuse in design, then exploring the implications of adopting CD to support RCD and finally examining how to integrate CD methodologies into RCD strategies, this research contributes to sustainable development goals by promoting a transition from a linear to a circular construction model. The implications extend to education, professional training and sector practices, emphasizing the need for interdisciplinary collaboration and digital infrastructure to enable the transition. The findings provide a foundation for further discussion on how policy innovations and AI-driven design solutions can accelerate the adoption of RCD strategies in the building sector.

This research concludes that CD has the potential to act as a catalyst for circularity in architecture, as long as the sector embraces new skills, collaborative processes and data-driven decision-making to optimize reuse at scale.

Populärvetenskaplig sammanfattning

Byggsektorn, som förbrukar en stor andel av energi och resurser i samhället, har jämfört med andra industrier varit långsam med att ta till sig aspekter av hållbarhet och digitalisering. Denna avhandling undersöker hur beräkningsdesign (CD) kopplat till cirkulär ekonomi kan stödja återanvändning av byggnadsdelar, särskilt genom projekteringsstrategier för demonterbarhet och återanvändning (RCD). Forskningen som genförts i denna avhandling belyser den växande betydelsen av vybaserad design, industrialiserat byggande och reversibla kopplingar för att öka byggnaders anpassningsförmåga och livslängd. Dock utgör betydande tekniska och kulturella utmaningar hinder för en bredare tillämpning av återanvändningsstrategier, inklusive avsaknaden av standardiserade klassificeringssystem, kompetensbrister och motstånd mot nya arbetsflöden.

En forskningsdesign med blandade angreppssätt har använts för att identifiera centrala utmaningar och möjligheter vid implementeringen av RCD med CD-verktyg. Resultaten visar att CD kan optimera återanvändningsstrategier, automatisera urvalet av byggnadsdelar och underlätta iterativ design, men att dess integration i arkitektonisk praxis fortfarande är outforskat. Studien identifierar framväxande yrkesroller, såsom digitalt förstärkt arkitektur och specialister på cirkulära material, som är nödvändiga för att överbrygga klyftan mellan traditionella byggmetoder och en digital och cirkulär byggmodell. Dessutom utgör bristen på strukturerad datahantering, inklusive byggvarukataloger och digital inventering, ett fortsatt hinder för implementeringen av återanvändning.

Vidare lyfts det fram flera mjuka faktorer som påverkar användningen av CD inom RCD. Dessa inkluderar balansen mellan minskad tid i projekteringen och långsiktig kvalitet, avvägningen mellan automatisering och kreativitet samt de föränderliga estetiska övervägandena inom återanvändningsbaserad arkitektur. Även om digitala verktyg möjliggör snabb prototypframställning och urval av byggnadsdelar, finns en risk för standardiserade och homogena designresultat. Samtidigt kan CD förstärka hantverksskickligheten, särskilt vid detaljerad utformning av fogar och kopplingar, vilket tillför värde till arkitektonisk design samtidigt som cirkulära principer understöds.

Genom att integrera CD-metoder i projekteringsstrategier för återanvändning bidrar denna forskning till hållbara utvecklingsmål genom att främja en övergång från en linjär till en cirkulär byggprocess. Implikationerna sträcker sig till utbildning, yrkesutbildning och industripraxis och understryker behovet av tvärvetenskapligt samarbete och digital infrastruktur för att möjliggöra omställningen. Resultaten lägger grunden för vidare diskussion om hur policyinnovationer och AI-drivna designlösningar kan påskynda införandet av principer för återandvändning inom byggsektorn.

Denna forskning drar slutsatsen att CD har potential att fungera som en katalysator för cirkularitet inom arkitektur, så länge sektorn omfamnar nya färdigheter, samarbetsprocesser och datadrivet beslutsfattande för att optimera återbruk i stor skala.

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List of abbreviations

AEC	Architecture, Engineering and Construction
AI	Artificial Intelligence
CD	Computational Design
CE	Circular Economy
DfA	Design for Adaptability
DfD	Design for Disassembly
DfR	Design for Reuse
DwR	Design with Reuse
RCD	Reuse-Centred Design

1 Introduction

Background

Bringing two parallel lines to converge at a definite point would seem to contradict the laws of geometry. Yet, in the real world, it is not uncommon for two distinct paths that initially lead in the same direction to merge at some point into a broader route that ultimately reaches the destination. The paths of sustainable development and technological advancement are two such examples that have been shaped by continual research over the last few decades. Looking back before reaching the destination helps in recognizing the valuable insights gained from past experiences, while looking sideways across the paths entails examining supporting features. The ultimate destination is the continued habitability of the planet, arising from the convergence of sustainable development and technological advancement paths.

The world, though, is facing multiple challenges, including climate change, geopolitical conflicts, economic instability and social inequalities. Environmental concerns, such as global warming and biodiversity loss, pose significant risks to ecosystems and human well-being. In many fields, there is increasing knowledge of what is causing climate change and of the need to act by means of sustainable solutions. One viable solution is circular economy (CE) to address sustainability challenges (Çetin et al., 2021; Geissdoerfer et al., 2017) with its related principles gaining importance among policymakers, academics and practitioners.

Similarly, digital transformation is affecting many aspects of everyday life, mostly positively but sometimes negatively. At the same time, the fourth industrial revolution (Schwab, 2024; Hossain & Nadeem, 2019) could drive the integration of advanced technologies and CE principles to reshape production and business models for sustainable outcomes (Ramakrishna et al., 2020). These advances offer major societal benefits; however, the fourth industrial revolution also brings challenges such as changes in the labour market, skill shortages and disruptive business models (Ramakrishna et al., 2017), as well as ethical concerns about artificial intelligence (AI). Once the underlying challenges have been tackled, digital technologies can then contribute solutions that address climate change and support CE principles (Keles et al., 2025).

The building sector is not immune to these challenges and changes, causing real-estate owners, investors, designers and constructors, among others, to re-examine their business strategies, policies and practices. Since the building sector is responsible for a significant proportion of energy and resource consumption, it has a vital role to play in reforming practices to contribute actively to the goals of sustainable development (Bruyninckx et al., 2024). So far, the building sector could be regarded as having adopted a passive, even reactive, stance where tangible actions toward sustainable development are far from standard practice (UNEP, 2020).

The discourses on sustainability challenges and digital transformation have been ongoing for decades. Even so, a significant gap remains between increasing awareness, expanding knowledge and theoretical advancements on the one hand and practical applications, industry progress and real-world projects on the other hand.

Unsurprisingly, sustainability and digitalization are topics currently occupying the minds of those in public offices, as well as business leaders and academics, all working toward the application of CE principles; in this sense aiming to retain and enhance the value of building parts from existing structures for future reintegration into new construction or renovation projects.

1.1 Problem statement

Various studies have claimed that the building sector is widely regarded as a major contributor to energy and resource utilization and the one with the lowest level of digitalization (e.g. Sawhney & Knight, 2024; Hossain & Nadeem, 2019; Huang et al., 2018). Consequently, it seems that the sector should invest greater effort into implementing further changes to contribute to sustainable development shortly. Unfortunately, the sector, with or without cause, has a reputation for being conservative, making it challenging to change established approaches and embrace digital tools and sustainability principles that would transform the building process (Ostapska et al., 2024; Munaro & Tavares, 2023; Dams et al., 2021; Munaro et al., 2021; Pomponi & Moncaster, 2017).

One step towards a sustainable built environment is to apply CE strategies to the building process, as this seems to be a viable solution and is even encouraged by the European Commission, through, for instance, *Fit for 55* (COM, 2021). Among the 11 circular *R strategies* identified by Johansen and Rönnbäck (2021) (i.e. *refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose, recycle, recover* and *resilience*), this research focuses primarily on *reuse*. Reuse can play a crucial role in waste prevention by prolonging the lifespan of products or components, thereby delaying or eliminating the need for the manufacture of new building parts.

When adopting reuse strategies in designing a building, three possible scenarios open up: (i) convert the function of an existing building, i.e. design for adaptability (DfA); (ii) design new buildings using parts from existing buildings, i.e. design with reuse (DwR); and (iii) design new buildings, where parts are designed to be disassembled and reassembled at the end of use, i.e. design for reuse (DfR) (Lisco & Aulin, 2024) or design for disassembly (DfD). These three design approaches can be identified as reuse-centred design (RCD), and notably, timber-based and industrialized construction seem to fit the purpose (Psilovikos, 2023; Jussila et al., 2022; Day et al., 2019).

Implementing reuse as a strategy in the building process, however, presents numerous challenges to be overcome (Giorgi et al., 2022; Rakhshan et al., 2020; Hart et al., 2019). The challenge of designing by availability, i.e. the difficulty of designing with a limited set of reused/reusable building parts, is defined as a technical challenge (Rakhshan et al., 2020) and is the main subject examined in this dissertation.

Additionally, digital approaches, particularly computational tools, could support designers in transitioning to a circular building process (Bekkering et al., 2021) and help to address this challenge. The argument for a digital built environment is in line with current guidelines, for example, *Europe's Digital Decade: digital targets for 2030* (European Commission, 2021) and seems essential to enable the CE (Çetin et al., 2021). Digitalizing reuse design practices requires a classification system for building parts (Lisco & Aulin, 2024; Sajjadian, 2024). The application of computational design (CD) is of particular interest in the context of the reuse of building parts (Heisel & McGranahan, 2024). This transition, however, also entails the emergence of new professional roles and, consequently, a need to update educational frameworks. The solution remains underexplored, although studies abound. Most tend to explore the potential of CD – seen as a process where information is processed algorithmically (Menges & Ahlquist, 2011, p. 11) – to optimize the design, generate free-form elements and achieve efficiency in terms of energy and daylight (Casini, 2022). Some studies investigate the reusability of structural elements, materials (Bertin et al., 2020; Hradil et al., 2014) or waste (Buyukmihci & Yazici, 2023).

Notably, the application of CD to enable reuse strategies is restricted to the structural elements of a building (see, for example, Çetin et al., 2021) or to match materials and product supply with design demands (Heisel & McGranahan, 2024; Heisel & Becker, 2020; Lokhandwala, 2018). There appear to be no studies combining the two perspectives of a CD approach and a reuse design approach that includes the building stock[1] considered as a storage of structural and non-structural parts, in the design of a new building.

[1] total amount of buildings in a country or region.

1.2 Aim and research questions

This research aims to critically examine the challenges and opportunities associated with reuse strategies in building design and to propose actions to improve their efficiency and feasibility.

This is achieved by, first, investigating the barriers to implementing reuse-centred design (RCD) strategies; second, examining the impact of computational design (CD) on both the building design process and the role of the designer in relation to RCD; third, exploring how to implement design for disassembly (DfD) in new building projects; and last, investigating the implications for education and training in the building sector.

The research questions that have guided the research are as follows.

1. What are the challenges facing the implementation of RCD?
2. How can CD applied to RCD affect building design and the designer's role?
3. How can CD facilitate the adoption of DfD in new building projects?
4. What are the implications of integrating CD and RCD for education and training in the building sector?

1.3 List of publications

1.3.1 Appended papers

This doctoral dissertation is based on the following papers, referred to by their Roman numerals in the text. The papers are appended at the end of the dissertation.

Paper I – Lisco, M., Martinez, C. and Persson, U. (2021). Challenges facing components reuse in industrialized housing: A literature review. *Environmental Science & Sustainable Development*, *6*(2), 73-82.

Paper II – Lisco, M. and Aulin, R. (2023). Taxonomy supporting design strategies for reuse of building parts in timber-based construction. *Construction Innovation*, *24*(1), 221-241.

Paper III – Vergani, F., Lisco, M. and Sundling, R. (2024, August). Circular economy competencies in Swedish architecture and civil engineering education. In *IOP Conference Series: Earth and Environmental Science* (Vol. 1389, No. 1, p. 012006). IOP Publishing.

Paper IV – Lisco, M. and Szentes, H. Exploring the combined impact of Generative Design and Reuse-Centred Design. Under second review process at *Engineering, Construction and Architectural Management.*

Paper V – Lisco, M. Design by availability: a computational approach to facilitate Design for Disassembly. Manuscript.

1.3.2 Other publications:

Smart Built Environment – "Systematic exchange of information for circular business models". (2021). Report from work package B – KTH and LTH.

Licentiate Thesis – Lisco, M. (2022). Reversible architecture. Reuse of timber building parts in circular design.

1.4 Contribution of the publications

In this section, a detailed overview of the distribution of responsibilities and contributions for each paper is provided. This breakdown is crucial for understanding the collaborative efforts that went into each and ensures transparency regarding each contributor's role. This not only acknowledges individual efforts but also emphasizes the collaborative nature of the work.

Paper I

		Design of the work	**Data collection**	**Data analysis**	**Drafting the article**	**Critical revision of the article**	**Final editing**
1	Margherita Lisco	x	x	x	x	x	x
2	Urban Persson	x			partly		
3	Carlos Martinez	x			partly		

Specifically, the main subject and related aspects have been outlined by the first-named author. The second author contributed to some parts of the introduction and the theoretical framework section. The third author created the figure featured in the discussion.

Paper II

		Design of the work	**Data collection**	**Data analysis**	**Drafting the article**	**Critical revision of the article**	**Final editing**
1	Margherita Lisco	x	x	x	x	x	x
2	Radhlinah Aulin		x	x	x	x	

The distribution of work was largely balanced, with the second author primarily concentrating on the methods section and the topic of DfA.

Paper III

		Design of the work	Data collection	Data analysis	Drafting the article	Critical revision of the article	Final editing
1	Francesca Vergani	x	x	x	x	x	x
2	Margherita Lisco	x	x	x	x	x	
3	Rikard Sundling			x	x	x	

The workload was evenly shared between the first and second authors, with the first author also taking the lead in drafting the introduction section of the paper. The third author contributed partly to the method section and was responsible for creating the tables included in the results section.

Paper IV

		Design of the work	Data collection	Data analysis	Drafting the article	Critical revision of the article	Final editing
1	Margherita Lisco	x	x	x	x	x	x
2	Henrik Szentes		x	x	x	x	

Both authors played a significant role in the overall process leading to the completion of the paper. However, the second author primarily focused on addressing the organizational tensions and paradoxes within the theory and discussion sections, as well as contributing to the section on methods.

Paper V

Sole author: Margherita Lisco

1.5 Limitations

Although the context is CE in the building sector, this dissertation focuses on reuse strategies only since reuse plays an important role in transforming the linear building process into one that is circular. While no special attention has been given to the other *Rs* strategies (Johansen & Rönnbäck, 2021). Furthermore, emphasis is placed solely on the building's design phase. The early research phase, which led to a licentiate thesis, looked exclusively into timber-based building. The rationale behind this choice is that timber-based buildings are more suitable for deconstruction and reuse and that timber has features which align with sustainable development, as discussed later in the related section in Chapter 2. The objective of this subsequent research was expanded to encompass buildings regardless of their material composition. Analysing the use of digital tools to enhance RCD has meant examining the role of CD to facilitate the reuse of building parts in new building projects. The impact of AI in a computational approach and other design optimization functions provided by CD have not been studied, as the technology has not yet achieved a level of integration significant enough for analysis.

1.6 Structure of the dissertation

This dissertation represents a framework that integrates the individual contributions of each appended paper, highlighting their interconnections and significance in enhancing the understanding of the subject. Through this approach, it seeks to offer a thorough exploration of the subject, inviting readers to engage with the complexities and implications of the research findings. Following this introductory chapter, the dissertation is structured into five additional chapters.

Chapter 2 presents the theoretical framework regarding RCD. After an overview of sustainable development and the fundamental principles of CE, the chapter delves into the principles and strategies that facilitate RCD and concludes by examining the role of digitalization in the circular design process.

In Chapter 3, the research methodology and a description of the research process and approach employed for conducting this research are presented. Additionally, this chapter describes the data collection techniques employed across the five studies that formed the research.

Chapter 4 introduces the main findings of the appended papers, using a thematic approach to draw them out from the studies, with a cross-thematic analysis then used to present them.

The findings are discussed in Chapter 5 with the purpose of addressing the research question while examining the findings in light of the theoretical framework.

In the final chapter, significant conclusions drawn from both theoretical and empirical findings are presented. This chapter also discusses the main contributions of the research and offers suggestions for future studies.

2 Reuse-centred design (RCD)

In this chapter, the theoretical framework is discussed and organized into 5 sessions: i) *sustainable development and circular economy*, ii) *RCD principles and strategies*, iii) *digitalization in design*, iv) *design as a process and a product* and v) *emerging roles and education*. The concepts described in this chapter are summarized and illustrated in Figure 1.

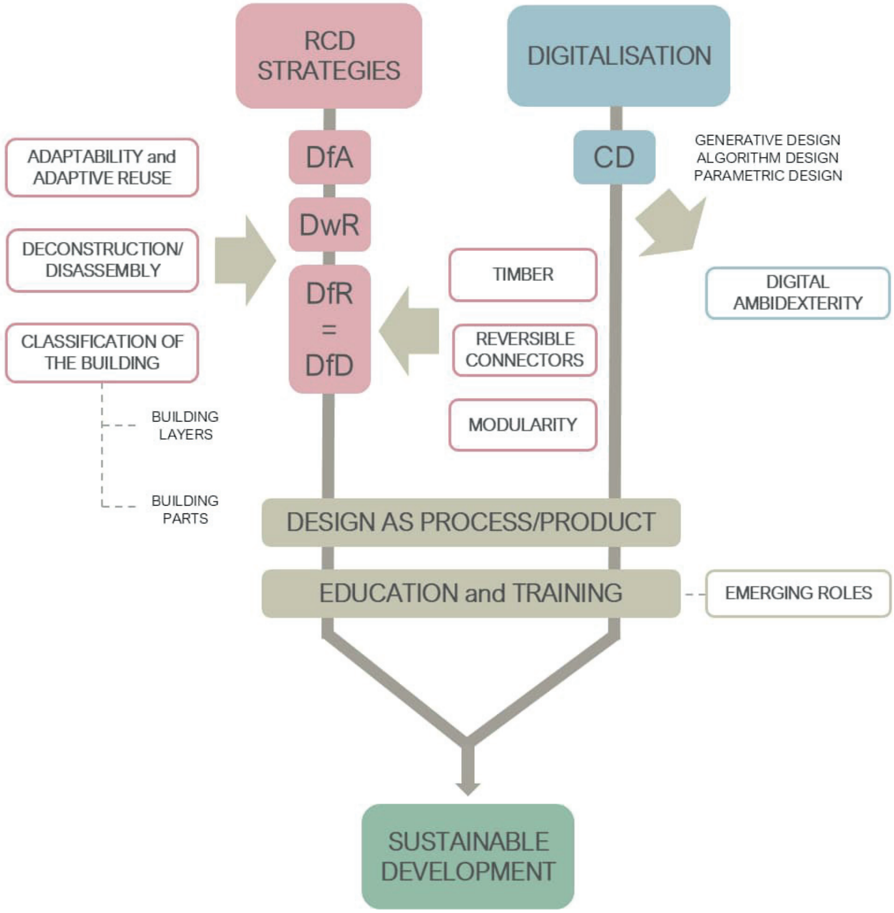

Figure 1. Outline of the theoretical framework supporting the research.

2.1 Sustainable development and circular economy

Defining sustainability uniquely is a complex task. The original definition from the *Brundtland Report* (Brundtland, 1987) is considered insufficient and has been integrated into "*300 different definitions of sustainability [and] sustainable development*", covering economic, social and environmental considerations (Dixit and Chaudhary 2020). The word sustainability has been replaced over time (Hajian & Jangchi Kashani, 2021) by sustainable development since the introduction of the sustainable development goals in 2015, as presented in *Agenda 2030* (UN, 2015). Consequently, climate change, the energy crisis and the shortage of raw materials have made sustainable development one of the most important topics on politicians' tables. Integrating environmental, social and economic concerns into every aspect of decision making is key to sustainable development (Emas, 2015), which could be considered as a mindset rather than a specific term (Daugelaite et al., 2021).

Among other human activities that have a significant impact on the environment, the building sector accounts for 35% of global energy consumption, contributing 38% of carbon emissions and generating 36–40% of waste while utilizing approximately half of all materials extracted from global resources (UNEP, 2020). This is an outcome of the traditional linear economy process based on take–make–use–dispose (Eberhardt et al., 2020) and needs to be addressed.

As argued by Zanni et al. (2021), emissions from buildings should be reduced by 60% by the end of 2030 to reach carbon neutrality by 2050. Furthermore, it is claimed that the existing European building stock will account for 85% of the expected stock in 2050. In Sweden, for example, between 2024 and 2033, there is a need for approximately 523,000 new buildings, although the annual figure is lower than in 2021 (Boverket, 2025). Implementing sustainable construction would enhance energy efficiency and, overall, decrease the environmental impact of building development.

The increasing discussion on CE principles as the pathway toward a sustainable built environment reflects the growing focus on environmental sustainability and resource efficiency. Although the literature provides more than 200 definitions of CE (Kirchherr et al., 2023), reducing environmental impact by increasing a product's value and efficiently using non-renewable sources can be considered the basis of CE principles. These principles have been summarized into six action areas, namely the ReSOLVe framework (*regenerate, share, optimize, loop, virtualize, exchange*) (Ellen MacArthur Foundation, 2015). According to this model, producing a new item (or building) should not require the consumption of non-renewable resources. International initiatives have been launched to promote a circular built environment to enhance and prolong the value of materials and products (UNEP, 2020). In Europe, developers, designers and other actors are encouraged to embrace CE strategies to promote sustainable development (European Union, 2024; European Commission, 2020; James & Mitchell, 2021).

Implementing CE strategies in the building sector appears crucial for fostering a sustainable, resource-efficient and resilient future, by considering the buildings as storage facilities enabling the harvesting and reuse of building parts (Kanters, 2020; Gorgolewski, 2008). These strategies align with global initiatives to tackle environmental issues, promote economic growth and improve the social and environmental performance of the built environment. Life cycle analysis (LCA), adaptive reuse, design for disassembly (DfD) and reuse of building parts can help preserve natural materials, extend building lifespans, thereby stimulating economic growth and supporting the continual circulation of resources (Munaro et al., 2021; Gerhardsson et al., 2020; Nußholz et al., 2019; Pomponi & Moncaster, 2017). Six key dimensions can affect the transition to the circular economy: governmental, economic, environmental, behavioural, societal and technological (Pomponi & Moncaster, 2017). Closing the loop of the traditional linear building construction process requires reimagining the built environment through new designs, business models, and collaborations among various resource management actors. Nevertheless, the sector faces a series of challenges as it transitions from a linear to a circular building process. This is discussed in the following sections.

2.2 Reuse-centred design principles and strategies

Among the 11 *Rs* noted in the introduction, *reuse* and *recycle* are the most common practices. Reuse, however, should be prioritized over recycle as a strategy because recycling demands significant energy (Anastasiades et al., 2021; Iacovidou & Purnell, 2016). Directly reusing a building part involves minimal modification (Minunno et al., 2018) and as a practice is supported by the CE approach. In the context of design, the implementation of reuse can be achieved in three distinct ways (Lisco & Aulin, 2024).

1. The complete reuse of an existing building for a different purpose, commonly referred to as Design for Adaptability (DfA) or adaptive reuse.
2. The selective incorporation of parts from an older building into a new building project, known as Design with Reuse (DwR).
3. The design of the whole building with features for easy disassembly to facilitate future reuse is termed Design for Reuse (DfR) or DfD.

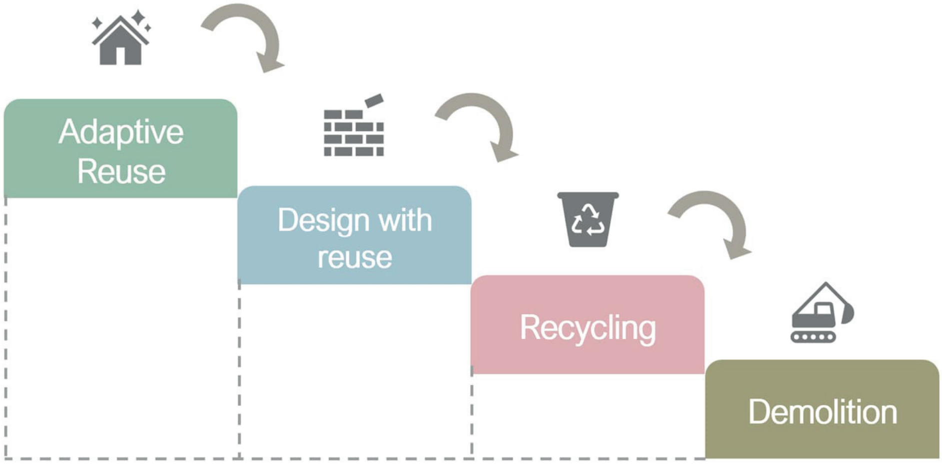

Figure 2. Conventional hierarchy of CE strategies related to reuse.

As illustrated in Figure 2, the highest level of reusability is whole-building reuse, also known as adaptive reuse or DfA. This strategy bypasses the need for reprocessing building parts or engaging in extensive deconstruction efforts. However, merely repurposing existing buildings for new uses is not always the most appropriate strategy. Adaptive reuse might be not feasible if, for example, the deteriorated state of the load-bearing structure makes the building not suitable for the purpose. Hence, it seems unrealistic to assume that new buildings will no longer be needed. Utilizing existing buildings as a material bank (Kanters, 2020) for a new building represents a relatively common practice and is defined as DwR (Lisco & Aulin, 2024). Incorporating existing structures and building parts decreases the need for new materials and resources. In cases where building parts are no longer fit for reuse, recycling should be prioritized as an intermediate strategy before considering demolition as a last resort. On the other hand, DfR (Lisco & Aulin, 2024) represents a step forward in promoting circularity because it requires new buildings to be conceived, designed and constructed for future disassembly; envisioned as banks of documented and demountable parts, thereby increasing the building stock (De Wolf et al., 2024; Anastasiades et al., 2021) from which to source building parts.

Adaptability and reuse are by no means novel concepts (Bertino et al., 2021; Duckworth & Wilson, 2020; Jacks, 2008). Yet, they have seen a recent resurgence in the building sector, with deconstruction and disassembly being essential practices for enabling their application. Additionally, it is necessary to classify building parts systematically to facilitate the easy replacement or reuse of single parts when necessary. The following sections introduce these principles.

2.2.1 Adaptability and adaptive reuse

Towards the end-of-life of buildings, their operational and commercial performance declines until they no longer meet the expectations of owners and users. Economic, legislative and technical reasons or a combination of them might necessitate a change in the building (Gosling et al., 2013). At this stage, there are two options to consider: either adapt and reuse the building or demolish it. By adapting buildings, owners not only prolong the building's lifespan but also create significant environmental, social and economic advantages, positioning adaptation as a sustainable alternative to demolition and new construction (Sanchez et al., 2020; Shahi et al., 2020). Building adaptability encompasses both in-use and across-use modifications, ranging from minor adjustments to major alterations, and can be achieved through passive and active solutions that primarily consider the physical characteristics and spatial configuration of the buildings (Hamida et al., 2023).

According to Tarpio et al. (2022), two key principles characterize adaptability in design: first, spatial solutions that allow for various uses without necessitating changes to the space; and second, solutions that alter the space, enabling it to adapt to a new use. The terms linked to these principles are often used interchangeably due to their overlapping scopes and the confusion that arises regarding their correct application (Lisco & Aulin, 2024). Adaptive reuse interventions can be classed into several categories, including those needed to meet the physical requirements of new functions, those aimed at restoring the building's integrity and efforts to enhance overall sustainability (Andreucci & Karagözler, 2024). Shahi et al. (2020) provide a categorization of building adaptation: adaptive reuse – which consists of *material reuse* and *conversion* – and refurbishment – which includes *rehabilitation, renovation*, and *retrofitting*. Each category is further divided into subcategories and classified according to their structural features, as presented in Table 1.

Table 1. Author's adaptation from Shahi et al. (2020).

Building adaptation			
		Structural	**Non-structural**
Adaptive Reuse	Material Reuse	✓	✓
	Conversion	✓	✓
Refurbishment	Rehabilitation	✓	
	Renovation	✓	✓
	Retrofitting		✓

To help address climate change, adaptive reuse strategies should represent the first choice at a building's end of life, as it preserves its structure and addresses social, economic and environmental issues (Langston et al., 2008; Bullen, 2007). Due to the significant environmental impact of the building sector, failing to optimize the useful life of buildings can lead to underutilization of their remaining lifecycle potential, resulting in wasted embedded resources (Conejos et al., 2014; Douglas, 2006). Nevertheless, implementing adaptive reuse strategies is not always feasible, as an example, retrofitting existing buildings typically requires removing materials and increasing embodied energy through modifications and new construction (Hosey et al., 2015) and as such, it is not ideal as a strategy. Therefore, other valuable alternatives should be considered.

2.2.2 Deconstruction or disassembly

The strategy to maximize the recovery of building parts during the deconstruction process for potential reuse, thus minimizing construction waste, introduces many related terms, such as *deconstruction*, *selective deconstruction*, *selective/systematic dismantling*, *construction in reverse* (Forghani et al., 2023; Bertino et al., 2021; Bukunova & Bukunov, 2020; Jockwer et al., 2020; Kibert, 2016; Thomsen et al., 2011) and *progressive or selective demolition* (Marzouk & Elmaraghy 2021; Rios et al. 2015 and Xu & Lu 2019). Demolition is, however, a linear process (Marzouk & Elmaraghy, 2021) rather than a circular strategy. In fact it employs a conventional method for dismantling a building, whether manually, mechanically or using hydraulic equipment and involves disposing of the resulting waste in landfills (O. Akinade et al., 2020; O. O. Akinade et al., 2015).

Building deconstruction is, instead, a strategy to prevent demolition from being the main method for disposing of building parts at their end of life (Bukunova & Bukunov, 2020). Consequently, deconstruction, as a term, has recently been preferred over demolition (Marzouk & Elmaraghy, 2021), since adopting deconstruction methods enhance the opportunities for reusing building parts (Van Den Berg et al., 2021). Nevertheless, deconstruction is cost-competitive only if reusable parts sufficiently mitigate supply uncertainty and higher labour cost (Viscuso, 2021).

The removal of building parts, or building disassembly, to recover residual value for reuse has been referred to as deconstruction (Guerra & Leite, 2021; Van Den Berg et al., 2021; Akinade et al., 2020). Disassembly is also defined as the disconnection of building individual parts or material separation (O'Grady et al., 2021) when reversing the assembly process (Arisya & Suryantini, 2021). Cambier et al. (2021) distinguish between deconstruction and disassembly, based on the potential for reclaiming the value of a building part or reusing it in its current form.

O'Grady et al. (2021) distinguish between disassembly and deconstruction, noting that deconstruction entails the removal of structural elements with the intent of reconstruction, whereas disassembly refers to the end-of-life process of breaking down a building into reusable parts. Yet, in this dissertation, the term *disassembly* – rather than deconstruction – is deliberately used to describe the dismantling of both the structural system and individual building parts, emphasizing environmental benefits and highlighting a difference in the way a building is designed and constructed. Figure 3 offers a visual description of the difference between the two principles.

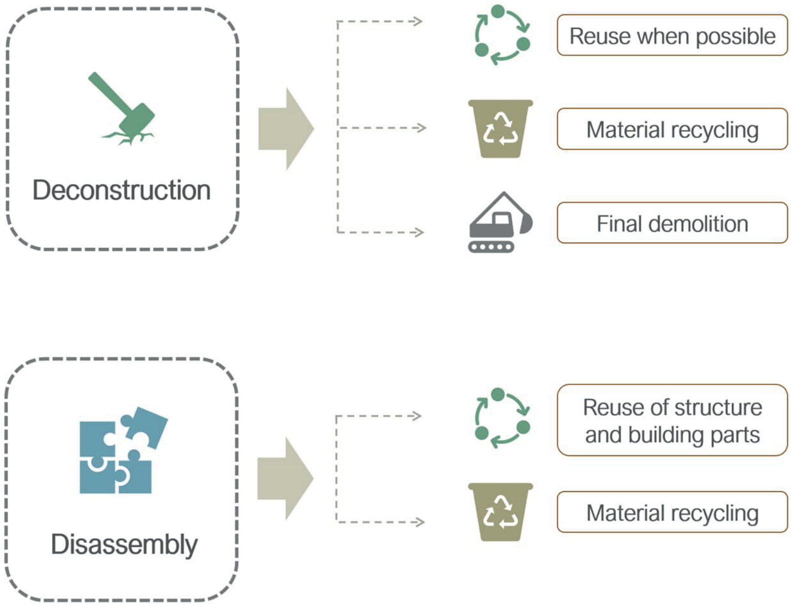

Figure 3. Conceptual differences between the principles of deconstruction and disassembly.

From the above, it becomes clear that disassembly might be the most suitable principle to apply to avoid demolition, which generates waste rather than reusable building parts. Buildings designed for disassembly can be almost entirely demounted and their parts reused, whereas deconstruction allows for reuse only to some extent, as illustrated in Figure 4.

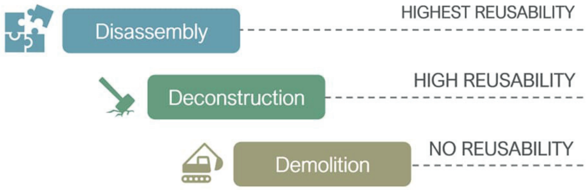

Figure 4. Reusability levels in relation to disassembly, deconstruction and demolition.

2.2.3 Classification of the building

To facilitate reuse strategies in building design, the literature emphasizes the importance of adopting Brand's model of six shearing layers of a building (Brand, 1995) and properly identifying each building part for future projects. This section outlines these concepts.

2.2.3.1 Building layers

Brand's model is built on previous work by Duffy (1990), according to whom a building is made of "*several layers of longevity of built components*": shell (structure), services, scenery (layout) and set (furniture).

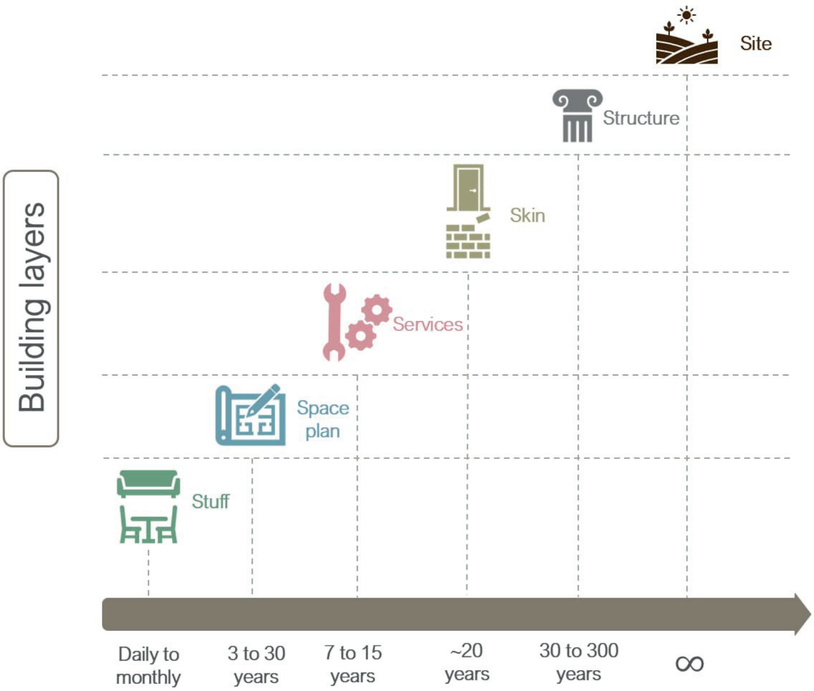

Figure 5. Author's illustrated interpretation of Brand's shearing layers model.

Brand added two more layers – *site* and *skin* – claiming that the basis of the design problem is time, as illustrated in Figure 5. According to Brand, when the way in which a building is used changes, "*function melts form*"; thus, an inside-out design approach allows the building to evolve from the inside to better express human needs.

The architectural model inspired by Brand's shearing layers could be used for multiple purposes: adaptive reuse (Guidetti & Robiglio, 2021); building interior resilience (Karimah & Paramita, 2020); temporary conversion during the Covid 19 pandemic (Shahi et al. 2020); information flows and adaptive architecture (Urquhart et al., 2019); and discrepancies in *LEED* (Leadership in Energy and Environmental Design) assessments (Pushkar & Verbitsky, 2018). By applying the building layers model, each part of a building can be repaired, replaced, removed or adapted independently without disrupting the entire structure. The layers of a building not only provide insight into its gradual transformation but also enable a different perspective when looking at architecture from being unique and long-lasting to dynamic and adaptable (Fatourou-Sipsi & Symeonidou, 2021; Karimah & Paramita, 2020). Pushkar and Shaviv (2013) provide a further classification in two systems: the building layers system – i.e. site, structure and skin – and the service layers system – i.e. services, space plan and stuff, claiming that their environmental burdens differ and thus require separate consideration. In 2016, Zimman et al. added the *system* layer to include more than just buildings in the classification of the built environment. The building layers could then be defined as follows:

- *system* – structures and services that support the building's functioning;
- *site* – building plot;
- *structure* – the skeleton (foundation and load-bearing system);
- *skin* – exterior walls, claddings, and glazing;
- *services* – pipes, wires, energy, and heating systems;
- *space plan* – internal fit-out with walls and floors; and
- *stuff* – furniture, lighting, and ICT (information and communication technology).

2.2.3.2 Building parts[1]

Durmisevic and Yeang (2009) introduced the classification of buildings into subsystems and components, each with a distinct lifespan. As for RCD principles, words such as *element*, *module* and *component*, in the context of a building, are used interchangeably in the literature: a clear, single definition of each is missing.

1 All constituents of a building – elements, components, modules or materials – can be referred to as building parts. The term element is used specifically in relation to structural components.

The challenge of accurately interpreting the description of a building part, whether classified as a component or an element, is often overlooked or undervalued in the literature. However, classifying the specific characteristics of building parts is crucial to offering guidance for designers and other stakeholders engaged in reuse strategies during the planning process. Further discussion on this matter can be found in Chapter 4.

2.2.4 Design for Adaptability (DfA)

Dams et al. (2021) describe DfA as a design approach that anticipates future reconfiguration or conversion of a building to accommodate the evolving needs of its occupants, whether due to changes in purpose or use. The primary aim is to keep demolition as the last option at the end of the building's life cycle. DfA should, therefore, be integrated into the conceptual phase of new projects, ensuring that architectural design, disassembly plan and building passports include inventories of reusable parts. Graham (2005) states five principles of DfA: i) start with the end in mind; ii) plan for change; iii) design for long life; iv) design for loose fit; and v) design for deconstruction. This approach could, in turn, enhance circularity in the building sector, particularly if high-quality, durable materials and modular demountable building parts are adopted.

2.2.5 Design for Disassembly (DfD)

Mattaraia et al. (2023) provided a historical overview of DfD, noting that the building sector borrowed the term from manufacturing, where publications on the topic date back to the 1960s. Design for assembly was the precursor to DFD and originated in the manufacturing industry during the 1970s, with early implementation methods emerging by the 1980s. Significant advancements and success with DfD were achieved by the early 1990s (Ostapska et al., 2024). Managing the end-of-life of products in the industry was the main driver of DfD (Guy & Ciarimboli, 2003). Lawson (1994) was the first to mention DfD in research publications within the Architecture, Engineering and Construction (AEC) sector, while the importance of linking the design with the end-of-life phase dates back to 2001 (Charef et al., 2019). By the late 1990s, numerous automobile and computer manufacturers had established programs for product retrieval and disassembly (Crowther, 1999). The practice of disassembling buildings, however, predates the related scientific literature. An ancient culture of using timber and dismountable wood joinery due to the risk of seismic activity abounds in Japanese vernacular architecture. As an example, for the past 1,300 years, the sacred inner space of the Ise Shrine has been carefully dismantled and reconstructed every 20 years, thereby preserving and transferring carpentry skills across generations (Guy & Ciarimboli, 2003). Furthermore, structures such as the Crystal Palace (1851) and the Eiffel

Tower (1889) are cited as examples of buildings conceived with future disassembly in mind. This was clearly demonstrated in the case of the Crystal Palace, which was re-erected in 1852-53 in a different part of London (Addis, 2006). Modern architecture offers examples of buildings where the articulation of connectors, materials and assembly methods is intentionally visible – as in DfD – though marked by notable shortcomings in aesthetics, occupant control and sustainability (Guy & Ciarimboli, 2003). Merrild (2024) argues that the knowledge embedded in pre-modern architecture has been lost during the modernist era and advocates for a renewed consideration of pre-modern architectural principles as a foundation for achieving a more sustainable built environment.

Various scholars have addressed transformation in the building sector, presenting a new design vision that considers the building's end-of-life from a circular perspective. This vision aims to facilitate the reusability of building parts and minimize construction and demolition waste (e.g. Charef et al., 2019; Osaily et al., 2019). According to Mattaraia et al. (2023), DfD involves the direct reuse of salvaged components from existing buildings. Several studies have highlighted key DfD principles, including detachability, independence, accessibility and adaptability (Vandervaeren et al., 2022; Debacker et al., 2015; Paduart, 2011). This approach paves the way for a new building sector centred around innovative design practices and creates a market for reusable, disassembled building parts.

Notably, the terms design for deconstruction and DfD are often used interchangeably in the literature. It can be argued that deconstruction refers to the dismantling of buildings to maximize reuse and recycling, whereas DfD facilitates this process through strategic planning and design aimed at achieving zero waste. Consequently, DfD is the preferred term used in this dissertation.

2.2.5.1 Link to building layers and reuse

The ability to integrate architectural components (such as disassembled elements and connectors) into new construction projects can also be referred to as reversible construction, reversible building design or reversible architecture (Arisya & Suryantini, 2021; Dams et al., 2021; Fatourou-Sipsi & Symeonidou, 2021; Viscuso, 2021; Akbarieh et al., 2020; Klinge et al., 2019a; Klinge et al., 2019b). Simple assembly and demountability are crucial aspects that facilitate reuse in building construction (Zanni et al., 2021). Conceiving a building as an aggregation of layers with varying life spans enables a design approach that organizes different parts based on similar longevity. This basic practice in life cycle thinking prompts designers to consider aspects such as construction, maintenance, deconstruction, reuse and eventual disposal of building parts beyond the life of the building (Graham, 2005). In designing for life expectancy, building layers should be demountable to allow for reuse, enabling parts to be replaced as needed (Dams et al., 2021). This can occur due to end-of-life considerations – for example, façades, which are expected to wear out before structural elements – or simply to incorporate a new and improved product. Flexibility and the possibility to recover or replace a building part easily are seen as crucial by Klinge et al. (2019a) and are the core of reversible architecture. In this way, building design plays a crucial role in a closed-loop system at the base of CE.

2.2.5.2 Timber

The CE aligns with the waste hierarchy concept, first proposed by the Dutch parliament in 1979 to prioritize waste management. Cascading, by prolonging the use of the same resource, is key to waste reduction. Timber, with the highest percentage of reuse potential in comparison to other materials, can eventually be incinerated to produce energy. Many governments, including Sweden, Austria and Germany, have banned wood waste in landfills, while others impose taxes to discourage it (Psilovikos 2023; Whittaker et al., 2021).

Timber has been a key construction material since ancient times, praised for its global availability, workability and ease of production. Timber is a natural and renewable resource with excellent thermal insulation, fostering a comfortable indoor environment and contributing to a lowering of occupant stress levels (Ostrowska-Wawryniuk, 2021; Kovarova, 2019; Leskovar & Premrov, 2011). Its local availability makes it a preferred material for construction, contributing significantly to sustainable development. For many structures, timber has become a viable alternative to steel and concrete, requiring less embodied energy and resulting in a smaller carbon footprint in line with European climate policy goals. For example, using timber frames can reduce embodied carbon by 48% compared to steel and 19% compared to concrete (Ilgin et al., 2022). Additionally, timber structures offer better reuse potential and lower carbon emissions than steel (Al-Obaidy et al. 2021). It is now gaining popularity as an eco-friendly alternative to concrete and steel, due to its carbon sink capabilities, indoor comfort and structural strength.

Engineered timber products enable efficient offsite prefabrication, reducing onsite construction time and waste. Recent innovations in prefabricated timber buildings have further modernized the sector, promoting timber's sustainability, flexibility and recyclability as essential for the future of industrialized building construction (Psilovikos 2023; Day et al., 2019).

Unlike other major building materials, timber parts can be reused without requiring breakdown and re-manufacturing; however, the time-consuming and labour-intensive process of reusing and recycling timber makes DfD crucial to enable CE (Psilovikos, 2023). Two key factors drive the sustainable use of timber in circular design for reuse: the implementation of modular design, standardization and prefabrication techniques (Chiletto et al., 2024; Svatoš-Ražnjević et al., 2022; Carvalho et al., 2020; Klinge et al., 2019b; Kovarova, 2019) and the use of reversible dry connectors (Klinge et al., 2019b) alongside the strategic separation of building parts based on their life spans, according to Brand (1995).

2.2.5.3 Reversible connectors

Connections are crucial in timber construction, enabling both structural integrity and disassembly for reuse (Morgan & Stevenson, 2005). Effective connectors ensure load transfer, stiffness and ductility while supporting circularity through ease of assembly, accessibility and cost efficiency (al Shamaa & Saleh, 2021; Chao & Chuang, 2021). Reducing the complexity of installation and redesigning fasteners can improve disassembly and reuse.

Timber construction commonly utilizes joinery or carpentry connections, mechanical connectors, fasteners and adhesives. To support reuse, connections should be designed so that disassembly does not damage the connected components. Sandin et al. (2022) classify disassembly into three categories: (i) separation causing minor damage; (ii) separation causing no damage; and (iii) separation causing extensive damage to components. Since nails and screws in reclaimed timber pose challenges, damage-free connection systems are essential (Nakajima & Futaki, 2001). Detachable systems maximize material reuse and reduce waste. Effective design principles include avoiding interpenetration of connectors and prioritizing dry jointing over adhesives (Morgan & Stevenson, 2005). Hradil et al. (2014) rank connectors for timber structures by their reusability: (i) screws; (ii) bolts and dowels; and (iii) nails, staples and carpentry joints.

An effective way to improve reusability is by utilizing reversible connections, not just at the component level but also within individual elements (Klinge, 2019a). Reversible connectors, such as carpentry joints, enable multiple reuse cycles without compromising integrity (Klinge, 2019a). These connectors enable both assembly and disassembly, significantly enhancing the potential for reusing timber structural elements (al Shamaa & Saleh, 2021; Akinade et al., 2017).

2.2.5.4 Modularity

Modularity as a concept has already been discussed in modern architecture (Arisya & Suryantini, 2021). Akinradewo et al (2023, p. 1) define the term *modular* as *"a method or process of construction in which individual modules are standing alone, waiting to be assembled to form larger structures"*. Conversely, *modular design* entails the use of three-dimensional construction modules that are fabricated off-site and then delivered to the construction site for complete building assembly, distinguishing it from the prefabrication of individual mechanical systems or wall assemblies (Akinradewo et al., 2023). This dissertation adopts the definition by Arisya and Suryantini (2021), who describe modules as standardized components used in modular construction. Accordingly, the adoption of modularity facilitates reuse and significantly reduces or even eliminates waste, thereby aligning it with the principles of sustainable architecture (Akinradewo et al., 2023). Additionally, modular construction, combined with off-site methods, offers significant advantages, including greater cost and time certainty, improved building performance, built-in potential for future deconstruction (Akinade et al., 2017).

Nevertheless, concerns have been raised regarding the aesthetic appeal of modular buildings – designed to consist of volumetric units, with limited flexibility (Feldmann et al., 2022). Notably, although cultural aspects and aesthetic expression are essential concepts of sustainable architecture, they are often underrepresented in sustainable building assessment frameworks (Grazuleviciute-Vileniske et al., 2021). One strategy to avoid aesthetic monotony is to reduce the scale of the module into submodules, thereby ensuring greater design flexibility, as demonstrated by the use of tatami modules in traditional Japanese architecture (Arisya & Suryantini, 2021). Volumetric modules tend to offer less flexibility compared to frame systems; however, this limitation could potentially be addressed through a hybrid approach. Integrating reversible connectors and adopting a layer-based design strategy might further enhance flexibility and component interchangeability.

2.3 Digitalization in design

While the fourth industrial revolution can lower costs and improve product quality, its innovative technologies remain largely underutilized in the building sector (Hossain & Nadeem, 2019). Yet, digital technologies hold great potential to transform the building sector by automating processes and fostering innovation while improving efficiency, safety and sustainability (Hossain & Nadeem, 2019; Zatsarinnaya et al., 2023). In this dissertation, it is argued that digitalization could play a key role in the transition from a linear design process to a circular one.

2.3.1 Computational Design paradigm

As noted by Erioli (2020), mastering new tools alone might not be enough to leverage the innovation flow without a shift from a theoretical to a design-oriented approach. Computation, which can be defined as information processing, aims to condense large amounts of data into manageable sets of operations. Since 2000, computation-based design has advanced globally, with CD, algorithmic design and generative design gaining popularity (Sajjadian, 2024). Moreover, Agkathidis (2015) noted that computational tools have transformed architectural design with innovative form-finding techniques known as parametric, generative or algorithmic design. These methods enable designers to explore new topologies and focus on *form finding* rather than merely *form making*. Nevertheless, techniques resembling generative form-finding approaches existed at the beginning of the twentieth century (Agkathidis, 2015). Although CD concepts have existed for nearly half a century, establishing a universally accepted definition remains a challenge (Belluomo, 2025).

A definition of the abovementioned terms is attempted by Caetano et al. (2020): Parametric design is *"a design process based on algorithmic parameters and rules to constrain them"*. Generative design is *"a design paradigm that employs algorithmic descriptions that are more autonomous than parametric design"*. Algorithmic design is *"a design paradigm that uses algorithms to generate models and, therefore, we also consider it generative"*. All three terms belong to the CD paradigm as illustrated in Figure 6. Online sources provide a different classification of the terms, defining CD or Algorithm Design as a process where *"a step-by-step algorithm is made in software like Dynamo, Grasshopper, C#, Python, etc. to define interrelated parameters"*. Parametric design is thereby what happens when the parameters set in the computational script work as the project's guiding principles, while generative design is interpreted as an extension of parametric design, that is able to generate several parametric iterations (Chebiyyam, 2025).

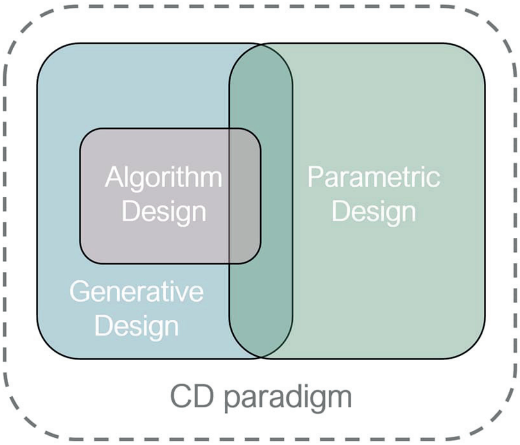

Figure 6. Conceptual representation of the terms' extension regarding the CD paradigm (after Caetano et al., 2020).

The increasing accessibility for designers of algorithms and scripting, along with the decreasing cost of digital fabrication, parametric tools, simulation software, optimization and generative algorithms are encouraging the development of generative design techniques (Agkathidis, 2015). As argued by Heisel & McGranahan (2024) computational tools support circularity by creating material passports that document material types and locations of building parts, and disassembly guidelines. If a digital database of reclaimed building parts were then available, it could maximize the reusability of building parts by assisting the designers in generating unexpected aggregations (Buyukmihci & Yazici, 2023; Moussavi et al., 2022; Lokhandwala, 2018).

Generative design and GenAI

Ambiguity also arises when discussing generative design and generative artificial intelligence (GenAI). While related, the two terms refer to fundamentally different approaches within the design and computational fields. GenAI, broadly understood as an artificial intelligence system capable of producing text, images or other forms of media, has rapidly gained prominence. It utilizes large datasets to learn underlying patterns and distributions, allowing it to generate content that reflects the style and features of its training data (Malmsten, 2024). In contrast, generative design employs algorithms to rapidly produce complex forms from minimal input, enabling the exploration and refinement of design solutions guided by specific mathematical constraints and rules (Regan-Alexander, 2023). The integration of GenAI and generative design offers architects and designers creative potential. By merging GenAI's content generation capabilities with the iterative, optimization-driven nature of generative design, rapid exploration of design alternatives and innovative solutions are possible (Malmsten, 2024).

2.3.2 Digital Ambidexterity

Applying CE principles for sustainable development by means of digital tools might be challenging. As discussed earlier, it requires a novel approach to the design process, new knowledge, new skills for the actors involved in the design phase and a holistic approach. It also requires pushing forward, exploring and testing solutions for a future where designing for disassembly and future reuse becomes the conventional practice. Meanwhile, it is crucial to continue with the steps taken so far when existing buildings are used as banks for other projects (DwR). The role of digitalization, particularly CD, has been claimed as crucial in the context of RCD (Buyukmihci & Yazici, 2023; Moussavi et al., 2022; Lokhandwala, 2018). This approach of exploiting current circular strategies – DwR, while exploring new strategies to implement in the future – DfR or DfD, is known in the literature as *ambidexterity* and is borrowed from organization theory, and it has been a significant topic in recent years (Chakma et al., 2024). The concept of ambidexterity is based on the premise that organizations must simultaneously strive for the complementary but also the contrasting objectives of exploration and exploitation (O'Reilly & Tushman, 2013; March, 1991; Duncan, 1976). Studies of the public sector (Magnusson et al., 2021) and management (Liu et al., 2023) introduced the term digital ambidexterity to describe a dynamic process that seeks to simultaneously exploit existing technologies and digital tools while exploring novel technologies and tools. One of the arguments of this dissertation is the need to streamline the adoption of DfR by promoting the adoption of CD tools as part of an exploratory phase, while reinforcing ongoing practices where CD is currently limited to matching the digital inventory of the building stock to a new building project (DwR).

2.4 Design as a process and product

It can be argued that over the course of the 20th century, designers' perspectives on the design process evolved, with an emphasis on structural form driven by specific functions rather than on referencing historical styles. Moreover, advances in technology gave rise to the expression *"function defies form"*, leading to the obsolescence of Louis Henry Sullivan's principle that *form follows function* (Bangre et al., 2024). The design process, with its complex nature involving "*uncertainty, uniqueness and conflict*" (Sheil et al., 2020), is primarily aimed at defining and shaping the building's architecture, as highlighted by Song et al. (2016). Traditional views of design often perceive it as a linear refinement process, where larger problems are addressed before smaller ones. However, this perception can limit innovation by neglecting how small-scale details can impact larger environmental and structural concerns (Sheil et al., 2020).

As digitalization becomes more prevalent in this field, it appears essential to re-evaluate conventional design methodologies. Incorporating computational concepts allows for a more dynamic design process, which can be structured as follows: input (rules of construction, site and apartment characteristics), computation (construction and assessment processes) and output (construction scripts and specifications) (Panait, 2012). Erioli (2020) notes that in traditional linear design, most decisions are made during the conceptual phase, resulting in a comprehensive, albeit rigid, prefiguration of the design. In contrast, a computational approach allows for decisions to be distributed throughout a nonlinear design process, fostering greater flexibility. To further enhance this approach, a holistic design process is advocated by Buccellato et al. (2016) to integrate generation, storage and interdisciplinary communication of data. Festino Panella (2023) emphasizes the role of the generative design in promptly finding effective solutions to mitigate risks, thereby ensuring long-term sustainability. This intangible aspect of the design process merges science and art, providing opportunities for faster, easier and more economic designs (Khakzand & Mozaffar, 2007; Panait, 2012).

A new design paradigm is emerging within architecture, wherein designers, users, the environment, materials and digital codes each have a role in shaping a new design process (Sheil et al., 2020). This transition suggests that the building is approaching a period of profound transformation, where data will redefine conventional approaches and performance-based decision-making. As noted by Sheil et al. (2020), this evolution will necessitate new skills and roles within the design process to strike a balance between optimal function and harmonious aesthetics.

Through digitally driven design processes, innovative architectural outputs are possible, characterized by their dynamic and unpredictable transformations (Kolarevic, 2001). Furthermore, the design process itself, by being inherently multiactor, multi-disciplinary and multi-faceted, involves collaboration among architects, consultants and specialists across various fields (Sariyildiz et al., 2000). This complexity necessitates a deep understanding of the various interrelated elements involved in the design process. It calls for a harmonious integration of functionality, economic feasibility, social relevance and technological advancement. Such a comprehensive approach enriches architectural practice and broadens the horizons of what can be achieved through design. In the building sector, however, it is not clear what data are required for reusing building parts effectively and how this, in turn, will affect the design process (Sajjadian, 2024) as well as the design outcome.

The design process generates outcomes that need to address a wide range of requirements, integrating functional, formal and technical dimensions. These encompass usability, economic viability, aesthetic quality, social implications, adherence to technical standards and mechanical functionalities (Sariyildiz et al., 2000). In this context, design transcends mere aesthetics; it emerges as a product that balances diverse criteria to create meaningful environments. Even though architectural expression and aesthetics have historically been central to the notion of architectural quality, design encompasses much more than aesthetic considerations; it is an integrated process requiring collaboration among various practitioners, including engineers and other specialists (Sajjadian, 2024).

In analysing architectural representation as a product of design, a tension emerges between the desire for verisimilitude – a realistic reflection of an object or space – and the necessity to retain certain degrees of indeterminacy (Picon, 2003). This dichotomy underscores the important distinction between the physical and virtual realms, as well as the contrasts between materiality and the digital landscape. As information and communication technology progresses, the design process has evolved to generate virtual objects that exhibit geometrical and morphological traits similar to their physical counterparts (Sariyildiz et al., 2000). This blending of the digital and the physical signifies a profound transformation in how architectural products are conceptualized and created, illuminating new pathways for exploration within the design discipline. The growing integration of digital technologies within design practices has redefined architectural language, a transformation represented by Schumaker's concept of *parametricism* (Schumacher, 2019). This new paradigm illustrates advancements in design capabilities brought about by digital tools and methodologies. Modern architectural drawings have become data-rich models utilized by construction firms to document projects and supply critical information for downstream applications (Sajjadian, 2024). The transformation of the design as a process and outcome contributes to the emergence of new roles.

2.5 Emerging roles and education

By 2030, SDG Target 4.7 aims for learners to acquire the knowledge and skills essential for advancing sustainable development (Global Education Monitoring Report Team, 2019). Josefsson & Thuvander (2020) stress the importance of offering education on circular practices to architects, contractors and policymakers to increase the practice of reuse. A lack of education on CE principles is indeed a significant barrier to circular building design (Cruz Rios et al., 2021). Ramakrishna et al. (2020) argue that universities play a key role in the emerging Industry 4.0–CE paradigm. Industry 4.0 centres on the digitalization of a product's value chain (Hossain & Nadeem, 2019) along with advancements in design and construction quality (Hook et al., 2016). In recent decades, computers have transformed nearly every profession around the world, and many tools in design and construction practices that are now aligning with sustainable development, are driving a transition from analog and intuition-based approaches toward data-driven methods in design (Bangre et al., 2024; Sajjadian, 2024). There is a compelling argument that digital literacy is essential to this transition (De Wolf et al., 2024; Sawhney & Knight, 2024).

Despite this, the sector continues to exhibit low productivity, constrained technological progress and limited mechanization and digitalization (Hossain & Nadeem, 2019). The environmental impact of the designer's role and the consequences of their work need to be considered (Hosey et al., 2015), as well as the role that education plays in this shift.

2.5.1 Augmented architect

Kołata & Zierke (2021, p. 1) state that "*the architectural profession combines science, engineering and art*", and is one in continuous transformation. By employing digital technologies to design, build and forecast the societal and cultural effects of their work, architects draw upon the fields of social science, earth science and philosophy – often without formal theoretical training (Muntanola, 2008). Furthermore, the advent of AI tools might increase the tasks of the architect or lead to a duality in the profession, distinguishing between roles centred on conceptual design and those focused on computational processes.

2.5.2 Education

While digitalization is transforming the building sector, there are concerns that the educational system is not keeping pace with this change (Schnabel, 2015). Technological and cultural advancements are driving innovation in architectural education, with digitalized design emerging as a key aspect (Schnabel, 2015).

Critics argue that these design approaches disconnect architecture from its context and users, reducing spatial quality and urban integration. Additionally, a fully computerized approach might diminish the role of physical modelling and drafting, risking the loss of material qualities and effects once central to architectural education (Agkathidis, 2015). Rather than categorically opposing digitalization without critical evaluation, it might be beneficial to revisit architectural education (Schnabel, 2015) and integrate AI applications in academic programs to educate the students of the future to take advantage of existing tools to perform some tasks better, while retaining control of the final outcome (Asfour, 2024).

2.6 Conclusion

The transition toward a circular and sustainable built environment demands a paradigm shift in how buildings are designed, constructed, used and eventually deconstructed. Integrating CE principles – such as reuse, adaptability and disassembly – into the building sector offers substantial environmental, economic and social benefits. Strategies like DfA, DfR (or DfD) and modular construction, particularly when using renewable materials like timber and supported by digital tools, can enable buildings to become resource banks rather than waste sources. Furthermore, CD present new opportunities to optimize RCD strategies and enhance decision-making in both current (exploitation) and future (exploration) projects. However, successfully embedding these practices into the building sector also requires structural changes in education, professional roles and policy, ensuring that all actors are qualified to contribute to a more circular and resilient built environment.

3 Research methodology

This chapter provides a comprehensive overview of the research design, process and related methodological considerations. By detailing the underlying methodological approach, this chapter aims to enhance the reader's understanding of the research foundation, guiding principles and the rationale behind methodological choices.

3.1 Philosophical framework

The philosophy of scientific research can be seen as a framework guiding the researcher's thinking, enabling the acquisition of new and reliable knowledge about the subject of study. Research philosophy is described as the formulation of research assumptions, along with the understanding of its knowledge and nature (Saunders et al., 2007). The collection of beliefs, assumptions and principles inherent in research philosophy usually guides the selection of the study's approach and methods. A framework of understanding that forms the foundation for theories and methods related to a specific subject is defined as paradigm (Fellows & Liu, 2022). This shapes how a researcher perceives and interprets the world, directly influencing the design, methods and execution of a research project. It ensures coherence between the researcher's perspective and the investigative process, guiding the choice of methods and analytical approaches. In other words, while philosophy can be seen as pertinent to the researcher's perspective on reality and the specific problem being investigated, the paradigm integrates the methodological approach conducted in the study. Both concepts encompass a framework of beliefs, theoretical assumptions and philosophical principles that guide the research approach.

In construction management, the problem investigated nearly always involves human experience and social interaction. Furthermore, various aspects related to the use of a building are usually examined from the perspective and perception of its occupants. Construction management research and social sciences share, indeed, a significant overlap, primarily due to their mutual focus on human behaviour, organizational dynamics and societal impacts (Volker, 2019; Brown & Phua, 2011; Harty, 2008). This overlap encourages the integration of theories and methods from both fields, leading to more holistic and effective approaches to address challenges within the building sector.

Given the exploratory nature of the aim and the research questions, a qualitative methodology has been used. The term qualitative refers to the characteristics and essence of the phenomenon being studied (Säfsten & Gustavsson, 2020). A qualitative approach is considered suited to under-researched areas to promote the growth of construction-specific knowledge (Fellows & Liu, 2022). The exploratory feature of this qualitative research is to gain understanding and gather data to allow theories to emerge. Indeed, qualitative research appears suitable for generating new theoretical concepts and interpreting the significance of a theory or phenomenon. As argued by Fellows and Liu (2022), construction research is still developing in terms of maturity and alignment with fieldwork contexts. Thus, conducting exploratory studies that employ qualitative methods seems appropriate for fostering construction-specific knowledge.

3.2 Research design

When a problem area is mostly unexplored, it often requires a greater degree of flexibility during the research process (Säfsten & Gustavsson, 2020). Therefore, a flexible design has been developed for this research, to provide insight into an issue, partly by developing a theoretical understanding of the problem. In flexible designs, data collection, analysis, theory development, refining research questions, adjusting samples and reassessing study goals often occur simultaneously as the study evolves (Robson & McCartan, 2016). As described by Robson and McCartan (2016), a good flexible design *inter alia*:

- utilizes various qualitative data collection methods, potentially including some quantitative data;
- adopts a flexible design approach, focusing on evolving designs, multiple realities, the researcher as a data collection instrument and participants' perspectives;
- draws on established research traditions, with the researcher reviewing and applying one or more inquiry methods;
- employs a rigorous methodology for data collection, analysis and reporting, with the researcher ensuring the accuracy of findings; and
- has clear and engaging writing, making the narrative and findings realistic and reflective of real-life complexities.

Flexible designs are inherently iterative and as such can adapt in response to how the research develops over time (Robson & McCartan, 2016), as it is discussed in the research process section.

3.3 Research process

Fellow and Liu (2022) liken the research to an information system where the aim and the objectives, as desired outputs, determine the rest of the system, i.e. data and information (the inputs) and test and analysis (the conversion process) in a defined environment. Additionally, it is argued that data consist of objective facts that exist independently of context, whereas information incorporates subjective elements, such as judgments. In other words, information is data that have been processed, structured and presented within a context to convey meaning (Fellows & Liu, 2022; Säfsten & Gustavsson, 2020).

According to Fellows & Liu (2022), in the field of construction management, research typically includes a blend of both pure and applied research, rather than being limited to a single classification. While pure (Fellows & Liu, 2022), or basic (Säfsten & Gustavsson, 2020), or academic (Robson & McCartan, 2016) research is primarily performed to enhance the body of knowledge, applied research focuses on addressing practical problems in the real world. Although contributing to theory is not its primary aim, it still serves as one of the outcomes of applied research.

This research belongs to the field of engineering science, which, rather than being merely applied science, focuses on advancing existing knowledge for practical applications (Meijers, 2009). In real world research, two types of problems normally occur: closed-ended problems – simple problems, easy to identify and to correctly solve – and open-ended problems – complex and difficult to identify, in which variables and relationships are difficult to detect (Fellows & Liu, 2022), and this research relates to the second type.

An overview of the process and the methodology along the whole research project is provided in Figure 7.

First, after identifying the problem area, two primary research topics were identified: sustainable development in the building sector and the digital tools that might facilitate it. An initial literature review, along with a comprehensive exploration of related issues, processes and actors through online sources, seminars, webinars and conferences, has fostered a wide-ranging understanding of the subject to be studied.

A pre-study was conducted, together with a researcher from Kungliga Tekniska Högskolan (KTH), in Stockholm, within the Swedish Smart Built Environment (SBE) program, for the project “Systematic exchange of information for circular business models”. The results from 42 interviews at a national and international level paved the way for the research design. The aim was to map existing processes, standards and tools to improve circularity in construction. Drawing on the results from a previous project, data from document analysis and interviews were thematically analyzed, with findings informing subsequent project phases. The author did not participate in the subsequent phases.

Once the purpose and research questions were provisionally defined, the first activity of the doctoral studies involved participating in an international conference on urban planning and architectural design for sustainable development. Study 1 was conducted, resulting in a conference paper (*Paper I*) focused on timber-based buildings. The aim was to identify key drivers and gaps in reuse, particularly within the context of industrialized timber construction.

In Study 2, the focus remained on timber-based buildings, extending beyond industrialized housing. The aim was to develop a taxonomy based on previous studies addressing overlapping definitions of circular design strategies, culminating in a journal article (*Paper II*). A deductive logic – which typically progresses from theory to empirical data (Robson & McCartan, 2016) – underpins Studies 1 and 2.

From the results of this first phase, which led to a licentiate thesis, the need emerged to: i) assess the integration of CE concepts in university programs (Study 3); ii) explore the implications of a new design approach – based on availability of reclaimed parts and assisted by a computational approach – as perceived by practitioners (Study 4) and iii) understand how CD can facilitate the adoption of DfD.

Although conducted concurrently, Studies 3 and 4 pursued different aims. After reviewing scientific literature and engaging with different stakeholders, it became evident that newly graduated students lack adequate training on CE principles. Study 3 aimed, therefore, to identify the extent to which CE concepts, strategies and tools are integrated into the programs of five Swedish higher education institutions (HEIs) within the Swedish Universities of the Built Environment network and resulted in a conference paper (*Paper III*).

The purpose of Study 4 was to explore implications and potential tensions of implementing CD for RCD, as perceived by designers in the building sector. This study resulted in a journal paper (*Paper IV*).

The last study tried to gain in-depth knowledge on strategies to facilitate the adoption of DfD by means of CD, through interviews with experts in CD and RCD. This study led to *Paper V*. Abductive reasoning has been adopted in Studies 3, 4, and 5 intended as a process that cycles between deduction and induction (Robson & McCartan, 2016).

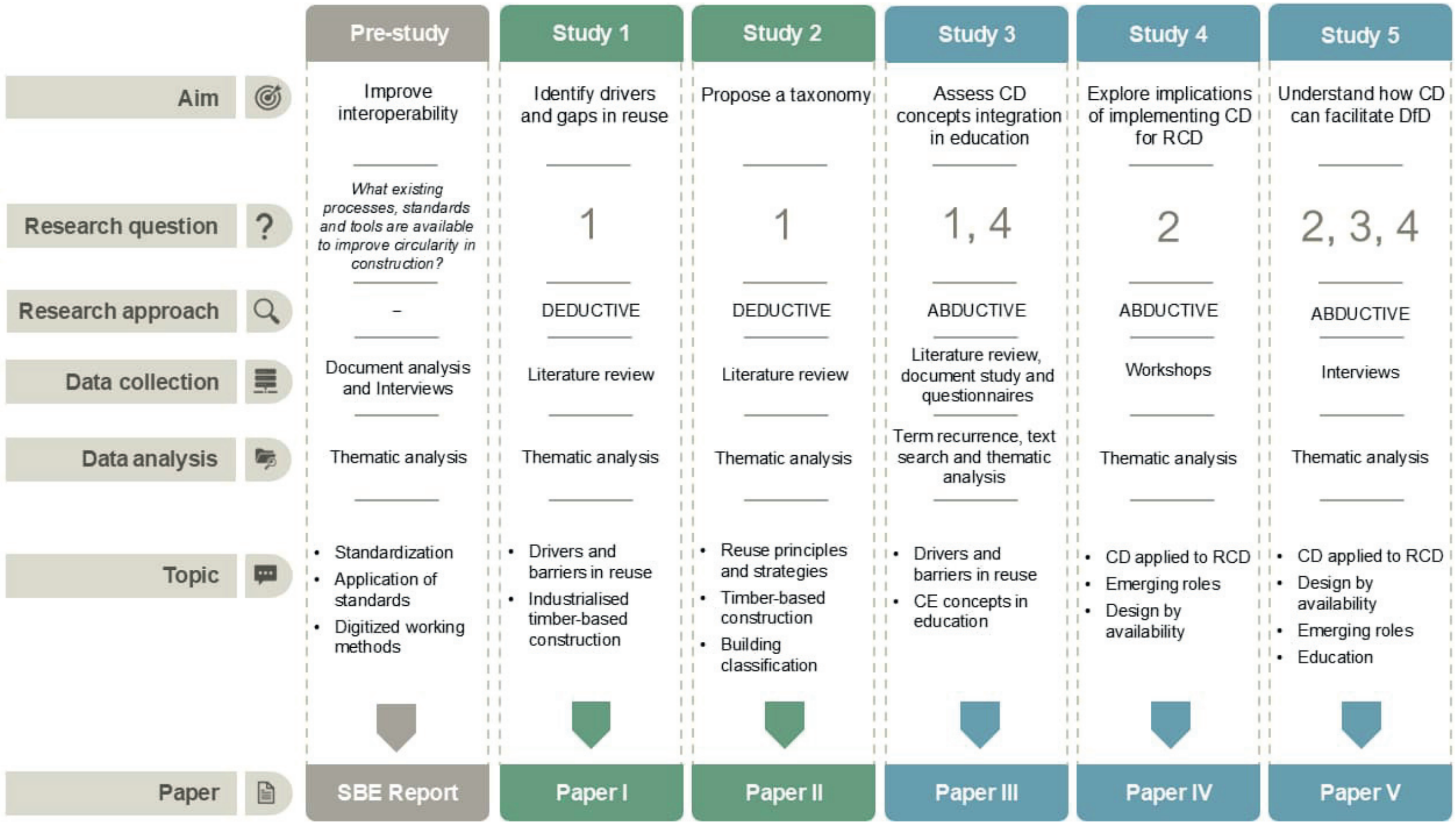

Figure 7. Outline of the research process.

3.4 Data collection methods

Due to the exploratory approach which underpins the whole research project and to enhance the rigour of the research (Robson & McCartan, 2016), a triangulation (Yin, 2018) of methods has been adopted, particularly in Study 3, to take advantage of the strengths of each method and to overcome the weaknesses in them (Fellows and Liu, 2021). The data collection methods and analysis are presented, discussed and an overview of the research process is provided in Figure 7 at the end of section 3.5.

3.4.1 Literature review

A literature review can be defined as the process of mapping and reviewing current and relevant literature (Säfsten & Gustavsson, 2020).

Robson and McCartan (2016) state that the purposes of the literature review include identifying gaps in knowledge and general patterns in previous research in the same area, defining a terminology or identifying differences in definitions used by researchers or practitioners and comparing studies with conflicting findings to further explore the discrepancies. Moreover, the literature should be reviewed critically to demonstrate that the researcher has used insights to study existing work in the field (Fellows & Liu, 2022).

This method has been employed in each study, given the distinct and well-defined topics addressed in each one. In the first three studies, it played a critical role by facilitating data collection, ensuring the accuracy and reliability of gathered information, and defining the appropriate analysis techniques to derive meaningful insights. In contrast, in the remaining two studies, it was utilized exclusively to develop a robust theoretical framework that guided the research design, provided conceptual clarity and supported the study’s overall structure and interpretation of findings.

For the first study, a comprehensive literature review was deemed suitable for initial investigation of the main topics to gain an understanding of the state of the art of CE principles and strategies, along with the challenges in the building sector. This study focused on the identification of drivers and barriers related to component reuse in industrialized housing. The keywords utilized for article retrieval included reuse, building components, building elements, construction and industrialized timber construction, covering the period from 2000 to 2021. Thereafter, for Studies 2 and 3, a structured literature review has been conducted by identifying suitable keywords, formulating inclusion and exclusion criteria, formulating a search strategy to perform searches, summarizing and reviewing the identified literature and extracting data (Säfsten & Gustavsson, 2020). Web of Science, Scopus and

Google Scholar search engines were selected to identify, evaluate and synthesize current research on sustainable development and the circular economy within the building sector, including all sub-topics related to the study.

For Study 2, which concerns reuse in timber-based buildings in general, a total of 3470 articles, published between 2010 and May 2022, in the Web of Science and Scopus were retrieved. Duplicates and articles that, upon closer examination, were not pertinent to the research (such as those focused on unrelated fields or environmental impacts) were excluded, along with papers published in languages other than English. The searched terms included *inter alia* adaptability, building component, deconstruction, design for adaptive reuse, design for deconstruction, design for disassembly and design for future adaptive reuse.

The CE competencies needed in the AEC sector were identified using a literature review, also in Study 3. Specifically, technical competencies include technical knowledge, skills, manufacturing methods, data, material specifications and other information used in the AEC sector and deemed relevant to the production of circular building parts and structures, as well as during construction, maintenance, repurposing and deconstruction activities.

3.4.2 Document study

Since the lack of knowledge about CE principles was the most recurrent finding across the studies, a triangulation method was employed in Study 3, which was largely descriptive in nature. The document study, also referred to as content analysis (Flick, 2018) consisted in collecting the course syllabi from the five universities listed in section 3.3. The aim was to examine whether each course syllabus incorporated any of the competencies identified from the literature.

Specifically, 31 relevant programs were examined: 20 five-year (300-credit) architecture and civil engineering programs and 11 bachelor's (180-credit) programs in real estate, construction management, civil engineering and technology management. Course lists were compiled, distinguishing compulsory and elective courses, with duplicates and non-relevant subjects (e.g. mathematics, languages) removed. Only compulsory bachelor-level courses were included in the study. 426 course syllabi were downloaded from the respective HEIs' websites between December 2023 and January 2024. This excluded the syllabi for nine new courses at LTU, which were not yet available.

3.4.3 Questionnaires

There are three ways of administering questionnaires – *self-completion, face-to-face-interview* and *telephone interview* (Robson & McCartan, 2016). The first kind of questionnaire was adopted in Study 3, with the intention of reaching a large sample with little effort and in a short time as discussed by Robson & McCartan. The questionnaires were sent out via e-mail to 19 relevant actors, both individuals and organizations interested in moving to a CE model in their practices. For this study, actors were selected from previous contacts with proven CE expertise, ensuring diverse professional roles to cover the entire value chain. Of the 11 respondents, three had limited experience with circular projects, while the rest were actively engaged in CE implementation. Their answers were matched to the list of competencies retrieved from the literature study.

3.4.4 Workshops

Rather than explaining a phenomenon, the goal of Study 4 was to explore how practitioners perceive the two ongoing transitions about generative design and RCD. Given the study's exploratory nature, workshops were chosen as the data collection method, deemed particularly valuable for investigating emerging domains, as noted by Ørngreen and Levinsen (2017). Empirical data were collected through four workshops held in Sweden, Finland, Denmark and Norway between August and November 2023. The sampling of the participants was determined after sending invitations via e-mail to practitioners in project firms, specifying the required experience and/or knowledge about generative design and RCD as a prerequisite to join the workshop session. In total, 55 registered, but only 31 attended, including 23 practicing architects, 5 other practitioners and 3 researchers. Participants were encouraged to share their perspectives and collaboratively develop emerging ideas and concepts, both to generate valuable insights and co-produce reliable research data (Thoring et al., 2020; Ørngreen & Levinsen, 2017; Shaw, 2006). Each workshop included four blocks with distinct goals and methods to promote discussion and document results. Active participation was essential throughout all four blocks of the activity. In the first two blocks, participants were organized into groups, each responsible for presenting their findings on a flipchart. In the third block, individual participants were asked to reflect on their insights, which they documented on sticky notes. The final block provided an opportunity for participants to share conclusions and any additional thoughts that had not been addressed during the sessions. Flipcharts and sticky notes were documented and saved to keep essential information intact (Baxter and Jack, 2008). The written data were digitalized using *Microsoft OneNote* to collect all data divided, first, by workshop and, second, by session. To ensure openness, sessions were unrecorded, and data remained anonymous.

3.4.5 Interviews

The qualitative approach was also adopted for Study 5. Fossey et al. (2002) suggest that this method is favoured for building knowledge in under-researched areas, making it a common choice in exploratory studies (Bullock, 2016; Stebbins, 2001). In Study 5 a one-on-one structured interview format has been selected as appropriate data gathering method, not only due to its status as the most frequently utilized data collection method in qualitative research (Sandelowski, 2002), but also for its effectiveness in gathering data that sheds light on the experiences and viewpoints of participants (Ryan et al., 2009; Andersson & Öhlén, 2005). The structured interview format was deemed essential to ensure all respondents provided consistent answers, which might facilitate comparison of responses, and to minimize bias arising from the interviewer's follow-up questions.

The interviewees were selected through networking, connections made at conferences and seminars and social media platforms like LinkedIn. Lastly, a snowball sampling method was also adopted (Patton, 1990). When respondents are chosen based on their expertise, the key informant method can be highly effective and efficient for gathering detailed or specialized knowledge that typical survey respondents are unlikely to provide (Kumar et al., 1993). A total of 8 key informants participated in the study, which is a strong number considering the limited pool of practitioners with expertise in both CD and RCD.

Teams was used as a platform to conduct and record the interview sessions, which, as well as Zoom, presents access, time and cost effectiveness as advantages when conducting qualitative studies (Archibald et al., 2019). Another advantage is the immediate availability of a transcript, ensuring accuracy in capturing what was said, along with eliminating the physical and mental fatigue often linked to traditional transcription (Matheson, 2007) and saving time (Gibson et al., 2005). An informed consent has been given to record each session.

3.5 Data analysis

3.5.1 Analysis of literature review

The data gathered from the literature review studies were analysed by the thematic content of the articles, based on the purpose of each study (Säfsten & Gustavsson, 2020).

A comprehensive search conducted for Study 1 yielded 136 articles based on the relevance of their titles, abstracts, and keywords. However, following a rigorous critical review assessing their methodological quality, relevance, and contribution to the study, only 30 articles were deemed highly significant and selected for inclusion in the final review. Those articles comprehensively outlined the key themes identified in the literature, effectively summarizing and synthesizing existing research. These themes served as the foundation for understanding the study's findings, providing valuable insights into the research landscape and contributing to the overall analysis.

After the planning phase to define and develop the review protocol for Study 2, a deductive approach was chosen for the performing phase to identify recurrent patterns of RCD. The deductive approach, also known as the conceptual approach, relies on theory to logically identify dimensions and characteristics (Nickerson et al., 2013). Relevant publications from the past ten years were selected and thoroughly reviewed using an iterative search process. The literature reviews and subsequent brainstorming sessions conducted by the authors facilitated the identification of each category and its subcategories, along with the vocabulary needed for the taxonomy. The term taxonomy originates from the Greek words "taxis" (order) and "nomos" (law) and describes a systematic approach with multiple levels and often a hierarchical structure. (Meredith, 1993). McKnight and Chervany (2001) argued that taxonomies can organize concepts that would otherwise be disorderly. Therefore, this analysis was adopted in this study aiming to establish the connections among the different concepts and practices that include the relevant reuse strategies. In the end, 170 articles were selected for the review. The subsequent step involved developing a vocabulary and terms related to reuse in general and specifically to timber reuse. The literature review, along with follow-up workshops conducted by the authors, led to the identification of various categories and their sub-categories, along with the corresponding vocabulary for the taxonomy. Ultimately, a taxonomy was created based on the relationship between reuse design strategies, building layers, and building components.

For Study 3, the competencies identified from the literature were initially categorized into technical, valorisation and transversal competencies. Subsequently, only the technical competencies were chosen and further organized into 13 distinct clusters of thematic areas. The selection of studies used for identifying technical competencies was based on relevant sources in the field.

3.5.2 Analysis of document study

The study of course syllabi for Study 3 was conducted in two phases. The first phase employed a quantitative approach using NVivo, while the second phase involved a qualitative analysis. In this phase, two researchers independently reviewed the syllabi in full to assess the extent to which the course content aligned with circular-related concepts.

The first phase of the quantitative analysis used a term recurrence approach in NVivo, analyzing 14,380 terms of five or more letters. However, this method proved insufficient for identifying all competencies due to language variations in the syllabi. To address this, a text search approach in NVivo was used for more effective categorization. In the second phase, two researchers independently conducted a qualitative analysis of the course syllabi, thoroughly reviewing them to assess the extent to which the course content aligned with circular-related concepts. The 13 clusters and technical competencies guided the identification of CE-related competencies in the syllabi. Courses were classified only if they clearly aligned with the mapped competencies and could belong to multiple clusters if covering multiple themes.

3.5.3 Analysis of interview and questionnaire responses

The answers to the open questions in the questionnaire were analysed adopting the same methodological approach applied to identify clusters of thematic areas from the literature, which was utilized to systematically categorize the competencies gathered from the questionnaire responses in Study 3. By employing this consistent strategy, a coherent framework for analysis across both the literature and participant feedback was ensured. This dual application facilitates a deeper understanding of the relationships and patterns that emerge from the competencies.

A multiple-step analysis of the key informant responses was conducted for Study 5: initial review, data organization, categorization, coding, thematic classification, thematic analysis, AI-assisted coding, coding review and topic identification. The adoption of qualitative analysis software, AI-assisted, was informed by the study's intrinsic focus on generating outcomes through the processing of input data.

3.5.4 Analysis of data from workshops

Some analysis was conducted during each workshop when the moderator categorized the participants' insights into two main themes: opportunities and threats, with a possibility for notes that fell somewhere in between. Subsequently, the digitalized data were analysed utilizing an inductive approach (Ryan & Bernard, 2003) and 12 themes were derived from empirical data through an iterative coding process (Fellows & Liu, 2022), aimed at uncovering conflicting perspectives that highlighted the tensions between distinct, logical, yet opposing viewpoints on related topics (Lewis, 2000).

3.6 Methodological limitations

A limitation of Studies 1 and 2 is their dependency on the strict keyword search rule defined to retrieve English-language papers referred predominantly to timber-based buildings. Additionally, for Study 1, specifically, industrialized buildings were considered. Consequently, significant findings from a range of literature on reuse strategies might have been missed.

Study 3 explored a variety of CE-related terms; however, courses addressing relevant CE issues under different terminology might have been overlooked. Additionally, while syllabi might cover pertinent topics, they often only provide brief summaries, sometimes lacking explicit details on learning outcomes. Consequently, 15 courses without sufficient content information were excluded. Moreover, the analysis faced challenges due to NVivo's limitations with prefixes, suffixes and compound words in Swedish, which may have resulted in missing relevant terms. Furthermore, this study's methodology did not aim to capture transversal and valorisation competencies or assess the skills students might gain through course participation, thus leaving these areas outside its scope.

Regarding Study 4, while workshops can effectively gather data from a large number of participants, it's acknowledged that they have limitations concerning the depth of insight and the time available for detailed exploration. Although the explorative approach using a convenience sample was suboptimal, the findings offer valuable insights into current thoughts and reactions among practitioners. Additionally, they underscore the necessity for further qualitative research with a larger and more diverse sample that includes all major design disciplines within the building sector.

Research interviewing is a process of generating knowledge (Brinkmann & Kvale, 2015). Even so, an interview study, as the one conducted for Study 5, comes with a series of limitations. First of all, it can be argued that interviews are inherently interpretative and meaning-making activities (Holstein & Gubrium, 1995). Additionally, qualitative coding is a human process that depends on the researcher's subjective interpretation of the data to categorize and extract meaning, which can introduce a degree of bias and limit the generalizability of the findings. Moreover, the snowball sampling, as a form of convenience sampling, is intrinsically limited and could also entail substantial bias (Fellows & Liu, 2022) On the other hand, it could reduce the risk of bias when the population is homogeneous with respect to the target characteristic (Naderifar et al., 2017). As Study 5 specifically targeted experts with proven experience in circular design and demonstrated expertise in CD, the risk of obtaining superficial and biased insights is interpreted as minimal. Hence, the key informants are considered representative of the target population. Lastly, some limitations of using AI tools for thematic analysis emerged. A potential concern with language models is their tendency to inherit biases from training data, which might lead to biased analysis results (Christou, 2024). Furthermore, the AI assistant initially included wording from the interviewer's questions when associating the excerpts with specific codes. It appears, therefore, that AI, while enhancing data processing efficiency, still requires human intervention to ensure accurate and meaningful analysis. Hence, its role is not to replace researchers but to enrich their analytical capabilities (Turobov et al., 2024).

3.7 Validity and reliability

Although trying to be objective and conduct research with rigorous precautions, it appears inevitable to not somehow influence the results (Popper, 1989). Research is normally conducted within specific contexts, and environmental variables can significantly influence the results. Moreover, an interpretivism approach introduces a risk of bias, which must be considered. Therefore, the researcher must make a conscious effort to maintain objectivity (Fellows & Liu, 2022). Subjectivity is also often seen as prone to bias and preconceived notions, leading to opinions rather than objective findings (Säfsten & Gustavsson, 2020). As argued by Patton (1990), it is essential to openly acknowledge the potential impact of the researcher's perspective and clearly describe how the study was conducted in relation to its outcomes. This requires carefully documenting the research process while demonstrating awareness of existing conditions. In this regard, the assumption that digitalization can enable circular strategies in design needed to be verified.

Validity and reliability are key scientific quality criteria that serve as indicators of the quality of the study. Validity refers to the degree to which the measurement accurately reflects the intended subject of study (internal validity) and the extent to which the findings apply across different contexts (external validity). Reliability, on the other hand, pertains to the consistency of the results of the study when repeated under the same conditions (Säfsten & Gustavsson, 2020). These two concepts are interdependent. When using measuring instruments such as questionnaires and structured interview guides to study abstract concepts, it is essential to ensure their validity, meaning they accurately measure what they are intended to assess (Leedy & Ormrod, 2015).

To enhance validity throughout the research process, a literature review was conducted prior to developing the research design. Additionally, a preliminary study with a broader objective was carried out to acquire essential background knowledge to conduct the study as rigorously as possible. Furthermore, a triangulation strategy has been adopted by utilizing multiple data sources as well as multiple data collection methods (Robson & McCartan, 2016). To enhance reliability, each study design was discussed and approved by the researchers involved, and data collection methods and analysis techniques were collected in a systematic manner for transparency and to facilitate replication. For inter-rater reliability, two researchers analysed the same data material in Studies 2, 3 and 4.

3.8 Conclusion

This chapter has outlined the philosophical grounding, research design and methodological approach adopted for this research, emphasizing the exploratory and qualitative nature of the investigation. The research adopts a flexible design to address complex and underexplored issues related to RCD and digitalization in the building sector. By integrating a diverse range of methods – including literature reviews, document study, questionnaires, workshops and interviews – this research adopts a triangulated approach to ensure methodological rigour, enhance validity and support insights. While certain limitations related to interpretation and sampling method or size have been acknowledged, the chosen methods are deemed appropriate for advancing knowledge in the emerging intersection of RCD principles and CD within the building sector.

4 Findings

The research findings are presented using a thematic approach rather than one based on the individual findings of each paper. After identifying the most relevant topics from each study and categorizing them into thematic areas, the findings are organized as follows: *strategies, challenges* (including technical and cultural challenges) and *soft aspects*. Additionally, a cross-cutting classification within these categories grouped the themes into *design parameters*, *data framework* and *human factors*. Figure 8 illustrates the relationships between these themes and their connections across different categories to guide the reader and form the foundation for the subsequent discussion chapter.

4.1 Design parameters

4.1.1 Key strategies for implementing reuse in design

Effective implementation of reuse in building design requires a combination of technical expertise, adaptable construction methods and classification systems. As noted in Study 3, the global goal for all learners under SDG target 4.7 is to acquire the knowledge and skills necessary to promote sustainable development by 2030 (Global Education Monitoring Report Team, 2019). Studies 3, 4, and 5 highlighted the deficiency in these competencies and skills among both practitioners and recent graduates. One fundamental strategy that emerged from the data is ensuring that practitioners develop the necessary technical competencies and skills to work with reclaimed building parts, optimize modular construction and integrate circular principles into the design process.

One of these principles involves discretizing the building into distinct layers (van Vliet et al., 2021; ISO, 2020; Guldager Jensen & Sommer, 2018) – one for each of its functions and each with different life spans and adaptability, as in Brand's model (1995). Applying this principle to RCD allows individual building parts to be repaired, replaced or upgraded without compromising the entire structure. As emphasized in Studies 2 and 5, a layer-based design can increase longevity, adaptability and ease of maintenance while minimizing material waste. This strategy, by making buildings not only adaptable but also inherently reusable, fosters resilience, prolongs building lifecycles and contributes to sustainable development.

Equally important is the focus on the design of details, for example, joinery. The findings support the theory that dry and reversible connectors – such as mechanical fastenings instead of glued or welded joints – enable easy disassembly, thus facilitating the reuse of building parts in future projects. Reversible connectors support design for disassembly and adaptability, ensuring that buildings can be systematically demounted and reconfigured over time rather than demolished. Notably, in the Netherlands, the leading country in DfD in AEC (Ostapska et al., 2024), there is a guideline for the reuse of steel that requires "*the details should be completely made out of virgin bolts*" when reusing structural elements, as mentioned by a Dutch key informant from Study 5. This reinforces the idea that connectors play a crucial role. Additionally, Studies 5 and partly Study 4 suggest that utilizing computational tools to map the connections between building parts can enable designers to rethink structural designs, facilitating more efficient reuse strategies. Lastly, the analysis from Study 5 identifies the importance of focusing on detailing in the early stage of a project, since the complexity of connections can significantly impact the overall design and its feasibility for disassembly. It is argued that CD tools can play a key role in this regard, especially in timber construction, as claimed by key informant 4 in Study 5:

> *"Computational design tools might allow you to investigate the detailing of these connections that are designed for disassembly and their impact on the sizing of the timber earlier on and, therefore, avoid redesigns later on and ultimately save on time and money for the clients."*

When exploring RCD strategies, the literature offers numerous terms and approaches used to identify each building part that often share overlapping definitions, leading to confusion within the field and representing a further barrier to the widespread adoption of CE principles. To streamline this process, a common vocabulary (Day et al., 2019) for univocally identifying building parts is essential. Standardized and commonly accepted terminology simplifies communication across disciplines and supports the development of digital inventories, which can improve building parts traceability. This, in turn, can optimize reuse opportunities and resource management. The literature often ignores or overlooks the challenges of accurately defining building parts, whether classified as components or elements. However, it is essential to identify these units along with their specific characteristics to guide designers and stakeholders involved in reuse strategies during the planning process. The study conducted for *Paper II*, aimed to determine whether a common vocabulary could assist designers in identifying and applying reuse design strategies in timber construction. It resulted in a proposed taxonomy based on clearly defined terms used to identify building layers and parts in timber construction, particularly when designing with reusable or reclaimed components.

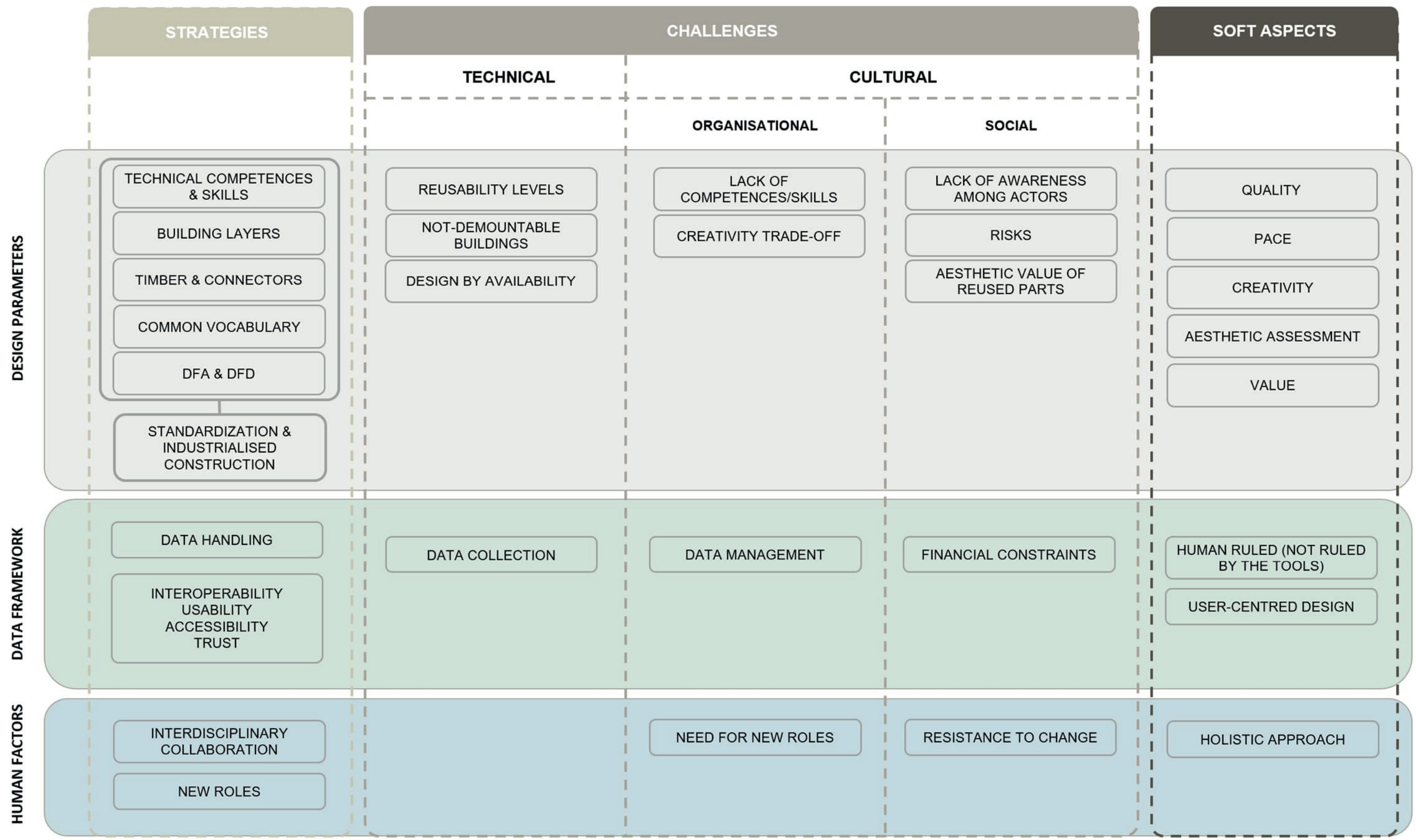

Figure 8. Overview of the findings presented using thematic analysis and colour coding.

Another contribution from Study 2 is the identification of two main forms of reuse strategies: Design for Adaptability (DfA) and Design for Disassembly (DfD). The first strategy, also referred to as adaptive reuse, should be prioritized as it involves repurposing and potentially transforming an existing structure, which often does not require new resources. While adaptive reuse was not the primary focus of this research, the principle of adaptability has been examined. Indeed, DfA also implies designing a structure and layout that can easily accommodate future modifications. In this sense, DfD inherently includes DfA as it promotes a flexible design and a forward-thinking approach to the future needs of users. The proposed taxonomy, presented in *Paper II*, focuses on reuse in two contexts: designing new buildings that allow for future disassembly and reassembly of building parts (DfR) and designing new buildings that incorporate building parts from existing structures or repurpose building functions (DwR and DfA) – which emerges as the most widely adopted strategy according to the findings from Studies 4 and 5. In this context, the selection of building parts – such as elements, components, modules and connectors – plays a significant role in influencing the design potential for reuse. This taxonomy for timber-based construction specifically examines the relationship between building parts and the building layers. The taxonomy begins by aligning DfD and DfA different strategies with corresponding building layers, drawing from Brand's (1995) model. It emphasizes the relevant building layers for timber-based buildings, specifically *skin*, *structure* and *space plan* while excluding *site*, *services* and *stuff,* which are not suitable for this framework. This approach ensures a comprehensive understanding of which strategy is suitable when designing for disassembly and adaptability, ultimately enhancing the reuse potential of building parts.

All these strategies call for greater standardization and industrialized construction methods. In this context, timber-based construction emerges as particularly well-suited to RCD due to its compatibility with industrialized building techniques. As retrieved from the literature and confirmed by informal meetings with practitioners, current buildings are not specifically designed and constructed for disassembly. Instead, they are designed with a vision for future disassembly and reuse, primarily employing timber as the main building material due to its inherent ease of disassembly. Moreover, timber, as discussed in Chapter 2, by being a renewable resource, reduces environmental impact and can enable a more adaptable and resource-efficient built environment.

4.1.2 Technical challenges for implementing reuse in design

The findings show that the transition toward an RCD approach in the building sector presents several technical challenges, particularly concerning the reusability of building parts, the limitations of existing building stock and the constraints of designing by availability. These factors create significant barriers that must be addressed to enable a circular approach to construction. Studies 1, 2, 4 and 5 have examined these challenges and their findings are presented below.

One of the primary challenges in reuse is the varying level of reusability of reclaimed building parts, as discussed in *Papers I, IV* and *V*. Structural elements such as beams, columns and façade systems have different degrees of wear and degradation, which must be carefully assessed before reuse. Exposure to environmental factors, mechanical stress and previous modifications might compromise the structural integrity of reclaimed components, making some of them unsuitable for reuse without extensive refurbishment or reinforcement. This variability in quality and performance makes it difficult to streamline the integration of reused building parts in new designs.

Another significant challenge is that while buildings are designed for long-term use, the functional needs of users often change more rapidly. As a result, the actual "use life cycle" of building parts tends to be shorter than their technical life span. Unfortunately, most existing buildings were not designed for disassembly (Kanters, 2018), relying on permanent construction methods such as welded steel joints and chemical adhesives, which hinder the reusability of the building parts (Marzouk & Elmaraghy 2021). Findings from Study 1 indicate that properly dismantling buildings to reuse its parts requires a specialized workforce which, in turn, demands significant time and financial investment, often resulting in demolition rather than systematic disassembly. Additionally, the lack of reversible connectors means that a significant portion of building parts and materials are damaged or rendered unusable during the deconstruction process. Moreover, the absence of deconstruction plans together with an uncertain supply of building parts further complicates the process.

Design by availability represents one of the technical challenges in RCD (Moussavi et al., 2022; Rakhshan et al., 2020). It implies that designers and engineers must work with a limited stock of reclaimed building parts from donor buildings rather than relying on a virtually limitless selection of new materials and standardized components. Unlike conventional design, where components are specified based on project needs, reuse requires adapting designs to what is available and accessible. This constraint introduces complexities in ensuring structural integrity, aesthetic coherence and functional performance, among others. Variations in dimensions, material properties and supply inconsistencies make it difficult to plan projects in advance without flexible and iterative design processes. Furthermore, without a comprehensive digital inventory that categorizes available reclaimed building parts, sourcing and integrating them remains a time-consuming and uncertain task.

4.1.3 Cultural challenges in RCD assisted by CD

The widespread adoption of RCD is not only hindered by technical barriers but also by cultural challenges when introducing a CD approach. These challenges, identified across Studies 3, 4 and 5, are categorized as organizational and social.

4.1.3.1 Organizational challenges

These challenges concern competency gaps and creativity issues when adopting a CD mindset for the development of circular design strategies, influencing both design methodologies and collaborative workflows. The implementation of reuse strategies is hindered, among others, by the lack of expertise in both reuse methodologies and CD tools. Many practitioners in the building sector have limited knowledge of RCD principles, making it difficult to integrate reclaimed building parts effectively into new designs. Similarly, the adoption of CD for optimizing reuse remains scarce due to a skills gap in coding and data-driven design methods. This lack of technical proficiency limits the ability to assess, categorize and integrate reused building parts efficiently in the design, slowing down the adoption of reuse-based workflows, as demonstrated by the findings from Studies 3 and 5. Addressing this challenge requires upskilling designers, engineers and construction practitioners through targeted education and training programs focused on RCD principles and computational methodologies.

One of the key obstacles in adopting CD tools for RCD is the tension between computational optimization and creative processes. While CD tools could enable more efficient reuse strategies by speeding up the process of categorizing and combining reused building parts, practitioners perceive the changes in the creative process in two contrasting ways. Some practitioners from Study 4 perceive this approach as restrictive, arguing that it limits the artistic and exploratory nature of conventional design workflows by *"[taking] away the fun and problem-solving parts"*. Nonetheless, this shift in workflow might also present new opportunities for creativity. A CD mindset could increase the level of reuse by efficiently finding and testing multiple aggregation options from a large inventory of existing building parts. Rather than limiting creativity, this approach might redefine it, allowing designers to explore solutions that might be overlooked or, as noted during a workshop in Denmark from Study 4, it could generate *"...possibilities that a human cannot imagine possible"*. Additionally, by automating repetitive tasks and optimizing building parts selection, CD frees up time for practitioners to focus on higher-level creative decisions. The data from the same study suggest that CD can democratize the creative process by engaging more team members in design exploration. This collaborative approach can spur new forms of creativity, particularly in interdisciplinary teams where engineers, architects and data specialists – *data miners*, work together to find innovative reuse solutions.

4.1.3.2 Social challenges

Social challenges when adopting computational-assisted RCD strategies include a lack of awareness about each strategy, financial risks associated with the adoption of reclaimed building parts and concerns over their aesthetic value and structural performance. Overcoming these barriers is crucial to fostering a circular mindset in the building sector.

A fundamental challenge arises from the lack of awareness among practitioners, clients and stakeholders regarding the importance of adopting DfD, as well as the necessary methodology for its implementation. Many architects, engineers and developers continue to follow linear construction practices, prioritizing short-term cost efficiency over long-term recovery and reuse of building parts. The absence of DfD principles in standard building regulations, guidelines and education curricula further reinforces the perception that reuse is an alternative approach rather than a mainstream strategy for a sustainable building sector. Without adequate knowledge and incentives, DfD principles – including industrialized construction, reversible connectors and classification of building parts – remain unexploited, limiting the potential for future reuse and circularity in the built environment. Raising awareness through education, policy integration and discussions in the building sector is essential to embed DfD as a standard practice rather than an exception.

The studies undertaken as part of this research have, to varying degrees, identified the perceived risks associated with reclaimed building parts. This presents another cultural barrier to their widespread adoption. One of the primary concerns is risk assessment, as reclaimed parts must meet safety, durability and performance standards comparable to new building parts. The uncertainty regarding the structural integrity and compliance of second-hand building parts often discourages designers and clients from considering reuse as a viable option. Additionally, financial risks play a significant role in decision-making. The responsibility for incorporating reclaimed building parts into new construction projects remains unclear, leading to uncertainty among developers, contractors and insurers. Questions such as who is accountable if a reused building part fails or how warranties and legal responsibilities are assigned remain largely unanswered. This lack of clarity creates scepticism among stakeholders, making it challenging to invest confidently in reuse strategies, especially in the absence of a supportive regulatory framework. Overcoming these concerns requires standardized testing procedures, certifications for reclaimed building parts and financial models that minimize risks associated with reuse investments. Government incentives, insurance policies and performance guarantees could help mitigate the financial burden and encourage wider adoption.

The perception that reused building parts are less aesthetically valuable than newly manufactured ones remains a significant challenge to address. Many designers and clients still associate reuse with imperfections, visible wear or outdated styles, seeing it as a compromise rather than an opportunity. The preference for pristine, uniform and mass-produced building parts often overshadows the aesthetic potential of reclaimed parts, limiting their integration into mainstream architecture. Even so, this potential could be reframed through design innovation, where visible signs of reuse – such as patina, texture variations, or other irregularities – are celebrated as part of a building's narrative and identity. Notably, Study 5 addressed this challenge, with key informants arguing that new building parts combinations, aligned with emerging construction techniques, will *"influence the design for a richer environment."* They also emphasized the importance of integrating historical design methods and *"old school craftsmanship"* with modern industrial processes.

4.1.4 Soft aspects in adopting RCD aided by CD

Beyond technical and cultural challenges, the integration of CD in RCD brings into view several soft aspects that influence the pace, quality, creativity, aesthetics and perceived value of building design. These factors, identified primarily in Studies 4 and 5, shape the way CD affects architectural outcomes, balancing efficiency with craftsmanship and redefining the role of design in circular construction.

4.1.4.1 Increased tempo vs. long-term quality

One of the key impacts of CD in RCD, discussed in Studies 4 and 5, is the acceleration of the design process. Computational tools allow for faster generation and iteration of design solutions and, henceforth, could optimize reuse strategies and reduce manual effort in the selection of building parts and their aggregation. This increased pace does, however, raise concerns about long-term quality. If speed becomes the primary driver, there is a risk that the focus on refinement, detailing and durability might be diminished. The challenge lies in ensuring that efficiency does not come at the cost of craftsmanship and resilience.

4.1.4.2 Tempo, time savings and creativity trade-offs

CD enhances time efficiency, allowing for rapid testing of several design alternatives, as confirmed by the key informants from Study 5. This can lead to significant time savings, especially when working with reclaimed building parts. Nevertheless, when tight deadlines are imposed, the increased tempo might limit opportunities for deep reflection and creative exploration, as the focus shifts toward quick decision-making and optimization rather than conceptual development. On the other hand, when schedules allow for flexibility, CD can free up more time for creative refinement by automating repetitive tasks, enabling designers to experiment with combination of building parts, aesthetic aspects and structural innovations. Thus, the relationship between CD, time savings and creativity is context-dependent – it can either restrict or enhance design freedom based on how it is implemented.

4.1.4.3 Aesthetic assessment of CD and RCD

While CD offers numerous options and alternatives to a design problem, when applied to RDC, it can sometimes detract from aesthetics, leading to *generic design* or *homogeneous design solutions*, as noted by some participants in Study 4. This concern aligns with observations about the impact of standardization as a consequence of adopting DfD. The increased emphasis on standardization, where possibilities for variation are limited, might result in a *cookie-cutter* or *boring* architecture characterized by repetitive design outputs. However, there is a counterpoint where a high level of standardization – particularly in industrialized construction – can facilitate DfD and adaptability, *"so we do not have to disassemble the whole building, but you can remove parts of the building and add new ones"*, as noted by a key informant in Study 5. This approach not only promotes CD as an aiding strategy in early design but also allows designers to create buildings that are easier to modify in response to future needs. As one participant in a workshop from Study 4 argued, this can lead to new aesthetics and new opportunities through the implementation of standardized systems. A statement confirmed by key informant 7 in Study 5, noted that "*…if the tools make new design solutions or things that were not often used before, they can have an influence on the aesthetic value of the design output"*.

4.1.4.4 Added value

Among the findings from Study 5, one of the most valuable aspects of applying CD to RCD is its potential to elevate craftsmanship, particularly in joinery and its connection detailing. Unlike conventional building design, which often prioritizes speed and cost efficiency over material expressiveness, an RCD approach places greater emphasis on how different building parts are assembled, connected and disassembled. A higher degree of precision in joinery design, allowing for dry, reversible connectors, not only facilitates disassembly and adaptability but also contributes to the architectural identity of the building and could be seen as an added value compared to traditional construction, where detailing and material articulation are often secondary concerns.

4.2 Data framework

Proper data management is a fundamental strategy for successfully implementing RCD, especially with a data-driven approach. Structured and reliable data handling is essential in a circular building sector, where building parts must be carefully catalogued and assessed before being reintegrated into new projects. This includes ensuring interoperability, usability, accessibility and trust in data while addressing the technical and cultural challenges associated with managing vast amounts of information on building parts.

4.2.1 Data handling and the strategic role of interoperability, usability, accessibility and trust in data

Studies 4 and 5, and partly Study 2, highlight the importance of properly handling data when adopting RCD strategies, particularly when applying digital tools. Findings from Study 5 revealed that for DfD and the CD approach to be scalable and efficient, data must be:

- interoperable, meaning it can be seamlessly exchanged across different platforms, including BIM, building parts databases and CD tools;
- usable, ensuring that data are structured in a way that allows designers, engineers and contractors to retrieve and apply it effectively in RCD;
- accessible, so that all stakeholders – whether designers, material suppliers, or construction teams – can easily access the necessary information at different project stages; and
- trustworthy, as inaccurate, outdated, or incomplete data can lead to poor selection of building parts, inefficiencies and potential design failures.

Establishing quality control mechanisms and standardized data frameworks is essential to ensure reliability.

4.2.2 The technical challenge of collecting and classifying data from existing buildings

One of the most pressing technical challenges in RCD implementation is data collection from existing buildings. Most older structures were not designed with disassembly or traceability of building parts in mind, meaning that even if a 3D model of a building exists, essential material properties, dimensions and conditions of building parts are often unknown or undocumented. Conducting manual assessments can be labour-intensive and costly, while digital scanning technologies and AI-driven building parts recognition are still developing. Data from the pre-study and from the literature review in *Paper I* suggest that new roles might be needed, as discussed in the section on human factors later in this chapter.

4.2.2.1 Risks of repetitive errors in data-driven design

As previously discussed, CD has the potential to optimize reuse by automating the matching process between building parts from a digital inventory and the constraints of a new project. However, if the input data are flawed, computational tools will replicate and amplify these errors, leading to designs that might be structurally unsound, inefficient or impractical to construct. For example, incorrect dimensions, material properties or connection details in the data pool can cause systematic failures in algorithm-generated designs. This highlights the critical need for accurate data validation and verification processes before computational tools are applied.

4.2.2.2 Data-driven architecture: the future of circular design

As the sector moves toward data-driven architecture, integrating digital material passports and AI-driven design automation will be crucial in optimizing RCD strategies. The use of machine learning for predictive modelling and digital twins for tracking building parts, for example, represents a significant transition toward a more innovative, circular built environment. For this transition to succeed, the underlying data infrastructure must be robust and scalable, ensuring that RCD strategies are not hindered by incomplete or inaccessible data.

There is a significant ongoing discourse surrounding the integration of AI and machine learning within the realm of CD. Key informants from Study 5 underscored a need to explore how AI can be strategically integrated into the design process. A recurring linked theme is the necessity for providing practitioners with advanced technical skills in coding and computational tools, such as *Grasshopper 3D* and *Python*. This training is seen as essential for designers to keep pace with technological advancements. As key informant 7 stated, *"[we are] quite eager. We really want to start using them because we will make the work better, easier [and with] higher quality, I guess, and we do not want to fall behind"*.

Despite the enthusiasm for AI, there are concerns about the current capabilities of computational designers in implementing these technologies effectively: *"It is time to implement the AI tools; so the question is, are the current computational designers good enough to create those kinds of solutions?* The importance of staying updated through conferences and courses on AI and CD is also emphasized in Study 5. This continuous learning is regarded as crucial for adapting to new software and methodologies that can enhance design practices. In summary, these findings indicate a clear trend towards embracing AI and machine learning in CD, alongside a recognition of the need for robust technical skills and ongoing education to navigate the challenges and opportunities presented by these technologies to enhance RCD.

4.2.3 Organizational challenges in data management

Findings from Studies 4 and 5 highlight that data management is not just a technical necessity; as stated by key informant 6 from Study 5, it is *"a big bone structure"* for reuse implementation, especially when integrated with CD tools. Proper handling of digital inventories, deconstruction data and classification of building parts allows for efficient decision-making in projects where reclaimed building parts are the primary source. Without a well-structured data framework, sourcing and integrating reused building parts could become chaotic, inefficient and prone to mismatches. Establishing standardized data collection methods (such as 3D scanning), classification systems and digital repositories (such as material passports and BIM-integrated databases) are essential to improve the reliability and usability of reclaimed building parts.

4.2.4 Cultural and financial barriers to computational design

Beyond technical challenges, cultural barriers play a significant role in limiting the adoption of computationally assisted reuse strategies in design. CD is often excluded from project budgets because many clients and developers do not fully understand its benefits. The initial investment in digital tools, data infrastructure and training is often seen as an unnecessary expense rather than a strategy to improve design efficiency. Moreover, as revealed from Studies 4 and 5, RCD strategies require the handling of massive amounts of data, from material properties and structural conditions to availability and location of each building part. If this information is poorly organized or difficult to retrieve, it cannot be effectively utilized in design processes. Developing structured, searchable digital repositories is crucial to making reused building parts a viable and scalable option in construction.

4.2.5 Soft aspects of data-driven architecture

Lastly, while CD can optimize RCD, the design outcome should be guided by human-defined rules and not be dictated by the tool itself. This is crucial in ensuring that DfD aided by CD remains a rule-based design process, where clear, logical principles set by the designers, shape decision-making rather than arbitrary algorithmic outputs, as mentioned in Study 5. At the same time, it should also be a user-centred design approach, meaning that human creativity, intuition and project-specific needs remain at the fore of the design process.

4.3 Human factors

4.3.1 Interdisciplinary collaboration and emerging roles

The successful implementation of DfD and CD requires a fundamental transition toward interdisciplinary collaboration. This, in turn, calls for expertise beyond traditional architectural and engineering roles, integrating knowledge from information science, materials science, computational modelling and digital fabrication. As a result, new emerging roles are probably going to shape the future of the built environment, requiring the sector to rethink its traditional structures and workflows.

To leverage DfD and apply CD tools, practitioners with specialized skills are needed to analyse, manage and optimize reuse processes. This requires the creation of new roles, as confirmed by Studies 3 and 4. They include the following.

- *Data miners* – experts responsible for collecting, structuring and interpreting data from existing buildings, ensuring that building parts inventories and digital repositories are accurate and usable for design and construction.
- *Augmented architects* – designers or AI agents equipped with computational expertise, who can integrate algorithmic modelling, generative design and digital fabrication into circular construction processes.
- *Circular material specialists* – people who assess the performance of reclaimed building parts, developing strategies for their classification, standardization and reintegration into new projects.

These new interdisciplinary roles are essential for bridging the gap between traditional construction practices and the digitally driven, circular future of the building sector.

4.3.2 Cultural barriers

Despite the growing need for these emerging roles, many organizations still operate within hierarchical, discipline-specific silos, where architects, engineers and contractors follow predefined roles that do not yet account for the integration of CD or circular strategies. One of the significant barriers to the adoption of new tools and workflows in design and project teams is the resistance from individuals who are accustomed to traditional methods. This resistance is often rooted in a lack of trust in new tools, as people might feel intimidated by unfamiliar technologies and prefer to rely on their established processes, even if they are less efficient. For instance, one key informant from Study 5 stated, "*the biggest barrier... is this resistance against new tools and new workflows and methods*" and elaborated on how some individuals perceive new tools as a "*black box*" leading to doubts about their effectiveness.

Additionally, another key informant from the same study highlighted the challenge of "selling" these new methodologies to team members who are not familiar with them, emphasizing the need to demonstrate the benefits of applying these tools in various projects, even in-house. This illustrates a common theme in the transition to a CD mindset: the necessity of fostering trust in and understanding of new methodologies to overcome such resistance. There is also a reluctance to invest in new expertise, as organizations often struggle to see the long-term value of digital and circular specialists. Many practitioners are unfamiliar with the role of data in design, making it difficult to justify hiring data experts or training architects to work with computational tools and building parts databases. This resistance slows down the adoption of interdisciplinary collaboration, delaying the transition to a digitally driven circular building sector.

4.3.3 A holistic approach to design

Both the literature and participants from Studies 4 and 5 emphasize the importance of an interdisciplinary, holistic approach to enable RCD. Particularly, DfD and CD should not be viewed as isolated technical solutions, but rather as part of a broader architectural and environmental philosophy that integrates:

- CE principles to maximize building longevity;
- digital tools to enhance efficiency and optimize reuse strategies;
- collaboration across disciplines to develop new workflows and expertise; and
- user-centred design that ensures buildings remain adaptable, functional and aesthetically valuable.

4.4 Conclusion

The findings underscore the necessity of implementing reuse strategies in building design through a combination of technical and cultural changes. Key strategies such as layer-based design, industrialized construction, reversible connectors and a common vocabulary are essential for facilitating DfD. Even so, technical challenges, including the reuse level of reclaimed building parts, the constraints of designing by availability and the lack of standardized data management, highlight the need for improved methodologies and digital tools to support reuse in practice. Cultural barriers, particularly the skills gap in both CD and DfD techniques and sector resistance to new workflows, further hinder the transition toward circular design. Addressing these challenges requires interdisciplinary collaboration, emerging roles specializing in data-driven reuse strategies and a fundamental change in the building sector toward recognizing the value of reused building parts. By embracing computational tools, digital inventories and, ultimately, AI-driven design solutions, the building sector could optimize RCD strategies and move toward a more resilient and circular future.

5 Discussion

The following discussion critically analyses the findings against the research questions and the theoretical framework that has guided the research. It is structured around the three main thematic areas identified in the findings: *design parameters*, *data framework* and *human factors*.

5.1 Design Parameters

5.1.1 Challenges facing the implementation of RCD

The findings from Studies 1 and 2, in line with Anastasiades et al. (2021), indicate that a lack of standardized construction methods and classification systems, poses a significant barrier to the implementation of RCD. Moreover, the construction techniques employed often make it difficult or even impossible to dismantle the existing building stock, as confirmed by Kanters (2018), when arguing that 99% of existing buildings are not designed for disassembly, and by Ostapska et al. (2024) who state that, overall, there is a lack of advanced technology for DfD. For this reason, combined with the varying reusability level of reclaimed building components – as highlighted in Studies 1, 2 and 5 – demolition is often favoured over deconstruction, which is typically labour-intensive and costly. This, in turn, can reduce the supply of reclaimed building parts for reuse, in line with Minunno et al. (2018). Despite these challenges, the extensive stock of building parts contained in existing buildings, coupled with the necessity of reusing them for resource efficiency, explains the sector's emphasis on repurposing resources through urban mining (Arora et al., 2020), supported by regulations (European Commission, 2020) policies (Prasad, n.d.) and guidelines (Miflin et al., 2017).

A central argument in this dissertation is the need to promote RCD by rethinking design approaches and encouraging the widespread implementation of DfD in new building projects. Yet, the practical and technical integration of DfD in new buildings appears still undervalued and rarely prioritized by those involved in the design phase, as confirmed by a recent study that identifies 151 DfD structures (Ostapska et al., 2024). Even if this rather precise figure is out by a significant percentage, it is still indicative of the limited adoption of this design strategy

(Bertino et al., 2021; Kanters, 2018). The insufficient implementation of DfD and the current focus on the existing building stock is further supported by the findings from Study 5, where all key informants were involved in projects requiring them to match parts from existing building inventories to new building projects. When DfD principles were part of the project, the limited experience of key informants was in temporary structures or exhibition artefacts. Nonetheless, it is crucial to acknowledge that deferring the integration of a design approach that prioritizes DfD in both current and future construction projects will unavoidably hinder its widespread adoption.

Designing with reusable building parts presents another significant challenge, requiring designers to adapt a design to an unpredictable stock rather than selecting building parts based on design intent (Josefsson & Thuvander, 2020; Moussavi et al., 2022). This constraint complicates the process further when planning for structural integrity and aesthetic coherence during the design process (Daugelaite et al., 2021; Grazuleviciute-Vileniske et al., 2021). As argued by Moussavi et al. (2022), a fundamental change in design methodology is necessary, where the availability of building parts dictates the outcome. Instead of defining geometries in advance, designers might need to work within the constraints of varied and uncertain features of building parts, making these characteristics the primary inputs while system geometry and topology emerge as the outputs. Notably, this aligns with the findings of Study 5, where key informant 7 emphasized that demountability principles should be integrated during the early phase of the design, rather than being incorporated after the design has been conceived, as is commonly the case. Relying on a finite set of elements could also be seen as a limitation to the creativity of the designer in the conceptual phase or as an added layer of complexity to the design, as noted by key informant 5 in Study 5. Nonetheless, this approach challenges the conventional linear nature of design processes and the pre-determinacy of design solutions (Moussavi et al., 2022). CD tools might help address this challenge by generating design outcomes that explore multiple solutions by combining the building parts in unexpected ways.

As illustrated in Figure 9, should DfD become seamlessly integrated into ongoing and future projects, the abovementioned challenge could be effectively resolved. Indeed, when disassembly is planned in the conceptual phase, the design outcome, by being demountable as well as digitally documented, serves as a built-in inventory in the way described by a key informant from Study 5. This would ensure that all building parts are embedded in a digital inventory, gradually increasing the availability of reusable parts over time (Anastasiades et al., 2021). Even so, Ostapska et al. (2024), in line with the key informants of Study 5, note that DfD in the building sector is still an emerging field, which suggests that the full integration of DfD into building design practices will take a significant time.

While DfD's adoption is slow in the building sector, research and application are growing rapidly; however, without embracing DfD and implementing digital inventories of reusable building parts as standard practices, the reuse potential of existing and future building stocks as banks might remain highly constrained.

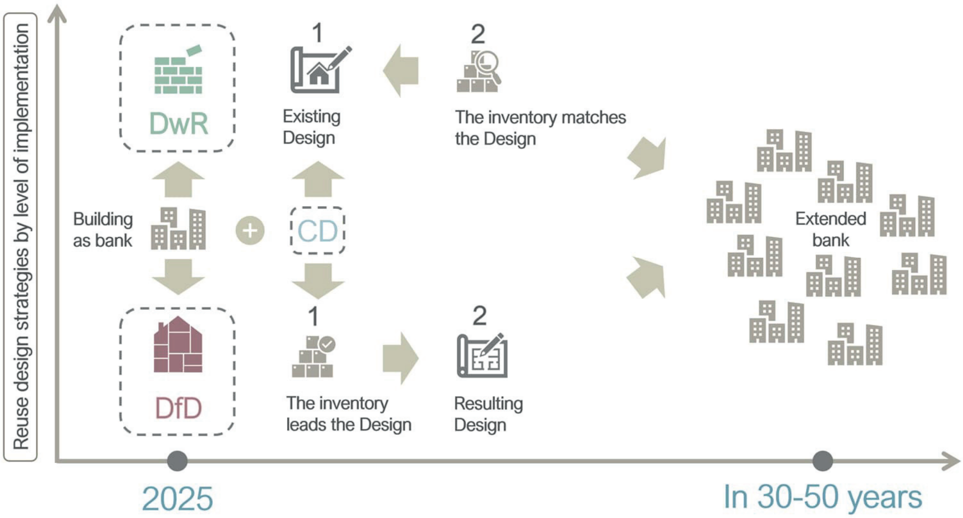

Figure 9. Implementation of DfD over time (modular house by Jonathan Wong from https://thenounproject.com)

Key informants 3, 4 and 7 from Study 5 provide an explanation for why DfD is not implemented, arguing that it requires a lot of effort to design something that will happen in the future and will, according to one informant, *"ease up the work of the next designer, which falls out of our responsibility in a way"*. Cost is frequently mentioned by key informants from Study 5 as a barrier in accordance with Ostapska et al. (2024). DfD requires long-term investment, as one informant puts it: *"[it means] invest early on to have a later payoff"*. This could explain the current focus on DwR, as highlighted in the findings, *"because everything that is designed for the future gives revenue in the future"*.

5.1.2 The role of CD in addressing design challenges

In the building design process, decisions can be either objective or subjective, depending on whether they are guided by data or the designer's intuition (Sajjadian, 2024). Adopting a CD approach can expand the range of reuse possibilities, enabling designers to explore multiple aggregation scenarios that would be difficult to conceptualise manually (Saadi & Yang, 2023). This approach transforms the designer's role from one of direct form-making to that of a system orchestrator, where the focus is on guiding computational processes to achieve appropriate outcomes. The findings from Studies 4 and 5, consistent with previous research, indicate that CD promotes interdisciplinary collaboration by involving engineers, data specialists and circularity experts in the early design stages, fostering a more integrated and holistic approach to reuse (Ostapska et al., 2024; Saadi & Yang, 2023). While concerns about computational constraints on creativity persist, CD can, in fact, enhance creative potential by automating repetitive tasks, allowing designers to concentrate on higher-level decision-making and strategic innovation. Rather than replacing traditional design intuition, computational design can act as a tool that amplifies and refines the creative exploration (Saadi & Yang, 2023; Nabiyev et al., 2022; Erioli, 2020; Buccellato et al., 2016) of reuse-centred solutions.

A CD approach offers an alternative to rigid, linear workflows, moving toward a more flexible and iterative process (Saadi & Yang, 2023). Notably, iteration was mentioned by all key informants from Study 5, as it is crucial when developing CD tools. For example, one key informant noted that *"iterative processes become more detailed"* as the project evolves, allowing for adjustments based on new information and site conditions. Adaptability is, therefore, vital to ensure that CD applications can accommodate changes in project scope, particularly when resource availability might vary. Moreover, adaptability is one of the key principles of DfD.

As discussed in the previous chapter and in Chapter 2, connectors play a pivotal role in implementing DfD as they directly influence how easily building parts can be separated and reused at the end of their life (Arisya & Suryantini, 2021). For instance, CD can improve the development of disassemblable joinery by enabling rule-based design of reversible connectors (e.g. mechanical fastenings instead of adhesives). Key informant 7 from Study 5 suggested that CD tools can aid in this development, by providing solutions that optimize connections for both structural integrity and ease of disassembly.

5.1.3 Balancing computational efficiency and design quality

A key concern in computationally assisted RCD is the trade-off between efficiency and craftsmanship. Constraint-driven design typically prioritizes performance, which might result in qualitative aspects being given less emphasis in the design process (Saadi & Yang, 2023). The findings from Study 4 suggest that while CD accelerates the selection of building parts and design iterations, it can also prioritize speed over detailing and durability. When implemented improperly, CD could reduce architecture to a purely technical optimization process, neglecting human creativity and long-term design quality. Moreover, it could impair the aesthetic and individuals' perceptions of how the new building will look when complete.

CD should support rather than dictate the design process and serve as a tool to optimize time, allowing designers to enhance human decision-making rather than replacing their expertise. As noted by key informant 6 from Study 5, if machine learning and AI become the norm in the future, CD should remain *human-ruled* rather than the other way around. This appears to be supported by the findings of Kołata & Zierke (2021).

5.2 Data Framework

The availability of detailed, sufficient and accurate data is considered crucial both for classifying existing building parts to create digital inventories and for generating new building projects designed for disassembly. This finding emerged from the literature, as well as from Studies 4 and 5, particularly in relation to the identified strategies, challenges and soft aspects discussed below.

5.2.1 Data as the foundation for RCD

One of the major challenges of implementing RCD, particularly DfD, that emerged from Studies 2, 4 and 5 is the lack of structured and reliable data on existing building parts. Current data collection and assessment methods are fragmented, making tracking building parts inefficient (Ostapska et al., 2024). There is a need for comprehensive digital inventories that allow designers to source and integrate reused building parts efficiently into new projects.

CD, combined with digital material passports and BIM-based inventories, can offer a potential solution by enabling real-time data management of reusable building parts, as emerged from the findings of Study 5 in line with (Heisel & McGranahan, 2024). Nevertheless, interoperability and accessibility issues remain, as many practitioners lack the technical skills to engage with complex digital tools, as discussed in Studies 3 and 5. Another risk identified in the findings from Study 4 is the potential for computational errors to be replicated at scale. Given that a CD approach is based on efficiency and accuracy, as confirmed by key informant 3 from Study 5, if input data on reusable parts or modules in DfD are inaccurate or incomplete, CD tools might generate flawed designs, leading to structural inefficiencies. This, while noting the potential for gathering incorrect or unnecessary data as a result of the large data volume (Bangre et al., 2024), underscores the need for data validation and verification processes before computational tools are applied.

5.2.2 Financial and cultural barriers to data-driven RCD

The findings from Study 5 also reveal that financial constraints and resistance to digital adoption are key barriers to the implementation of computational-assisted RCD strategies. According to the key informants from Study 5, many clients and developers do not see the immediate economic benefits of investing in computational tools, viewing them as unnecessary upfront costs rather than part of a long-term efficiency strategy.

This has significant implications for education and training in the building sector. Without targeted academic programs and industry training incentives, computational approaches to reuse will remain underutilized. Addressing these barriers is essential to integrating data-driven reuse practices into mainstream design and construction workflows.

5.3 Human Factors

5.3.1 Interdisciplinary collaboration as a strategy for implementing RCD

The findings of this research, as supported by the literature (Keles et al., 2025), suggest that successful adoption of RCD and CD requires a fundamental transition toward interdisciplinary collaboration. The emergence of new roles, such as data miners, augmented architects and circular economy specialists, reflects the growing need for interdisciplinary expertise. Yet, traditional construction workflows remain hierarchical and discipline-specific, limiting the integration of digital and circular design expertise (Dokter et al., 2021). This presents a challenge for the sector, as many organizations lack the willingness to invest in interdisciplinary training and collaboration. It follows that adapting the current building design process to circular and computational design requires a fundamental rethinking of roles and sector structures.

5.3.2 Overcoming cultural resistance to change

The findings from Studies 3 and 5 further emphasize the perceived conservatism in the building sector (Ostapska et al., 2024; Munaro & Tavares, 2023; Dams et al., 2021; Munaro et al., 2021; Pomponi & Moncaster, 2017) as a major obstacle to RCD adoption. There seems to be a widespread preference for conventional workflows, and many practitioners lack computational literacy, viewing CD as complex and impractical. Furthermore, other, more subjective considerations might be at play alongside aesthetics, such as individuals' preferences and prejudices regarding reused building parts.

When discussing sustainability in the building sector, Grazuleviciute-Vileniske et al. (2021) argued that committed practitioners and policies inevitably determine a specific level of sustainability. Numerous regulations and certification systems, however, contribute to a building sector that is process-oriented and primarily focused on the building's life cycle. As a consequence, intangible and subjective aspects – such as sense of place, aesthetic value and artistic quality, risk being neglected or lost (Grazuleviciute-Vileniske et al., 2021). A similar reasoning could be applied to CE principles and human aspects associated with alternative design approaches – as in DwR and DfR. Grazuleviciute-Vileniske et al. continue arguing that a good balance between social, economic, environmental and cultural aspects should be achieved to avoid techno-centrist or eco-centrist approaches. Yet, the aesthetic perception of reclaimed building parts continues to discourage their use, despite the potential for design innovation and unique architectural expressions. Key informant 2 from Study 5 briefly touched on this issue, remarking, *"I have had colleagues or others saying that it is very important that you cannot say that something is built with reused elements."*. Overcoming the aesthetic stigma of reusing reclaimed building parts, seen as *imperfect* or *unreliable*, is crucial in mainstreaming circularity, as design narratives that celebrate material history can redefine how reuse is valued in architectural practice. Successful projects have demonstrated that reclaimed materials can enhance architectural character, authenticity and uniqueness, changing perceptions from old and worn to sustainable and valuable (Nußholz et al., 2019).

Addressing these barriers, however, requires both regulatory intervention and a change in perceptions, where reuse is seen not as a compromise but as an opportunity for innovative design. Without a transformation in mindset within the sector, the full potential of computational and circular design cannot be realized. Encouraging education, policy incentives and successful case studies appears crucial to overcoming this resistance.

5.4 Conclusion

The discussion highlights that while CD has the potential to enhance RCD strategies, its successful employment depends on addressing technical and cultural challenges that currently hinder the widespread adoption of computational-assisted RCD. The research has found that:

- technical barriers (e.g. lack of standardized building parts, design by availability and deconstruction inefficiencies) limit the feasibility of RCD, although CD can optimize the aggregation of reclaimed building parts and reversible connectors;
- data reliability and accessibility are fundamental to scaling reuse practices, yet systematic errors and sector resistance hinder the adoption of data-driven RCD; and
- human factors, including interdisciplinary collaboration, education and perceptions of reused building parts, play a crucial role in

embedding RCD practices, yet cultural resistance to change remains a major obstacle.

It can be concluded that a thorough quantitative and qualitative analysis of the field is crucial for fostering knowledge exchange, disseminating experiences, and advancing the transformation of the built environment in response to global climate change (Ostapska et al., 2024).

6 Final conclusions

This research has explored the strategies and challenges in reuse-centred design (RCD), arguing that digitalization might enhance its adoption. Particularly, design for disassembly (DfD), has been suggested as a strategy to promote sustainable development in the building sector, proposing that its widespread adoption, assisted by CD, could support the development of a broader building stock conceived as a bank of reusable building parts. The research has critically examined the technical and cultural challenges associated with RCD and the adoption of CD tools in circular design, identifying pathways to enhance their feasibility and effectiveness. Through literature review, empirical studies, workshops and interviews, this research has aimed to increase the knowledge and bridge the gap between theoretical advancements and practical applications, contributing to achieving a more circular and resource-efficient building sector and, by implication, the built environment.

The main findings underscore the urgency of standardizing RCD strategies, developing digital tools for building parts tracking and enhancing interdisciplinary collaboration in the sector. Furthermore, the research highlights that CD has the potential to streamline the integration of reused building parts, optimize industrialized construction and facilitate the use of reversible connectors. Yet, financial aspects, cultural resistance and lack of training remain major barriers to wide implementation. Reuse strategies and computation are not new topics in research or in the sector, but they have gained increasing importance over the last few decades. The novelty of this research lies in integrating the two topics – RCD and CD – while broadening the focus beyond the load-bearing structures of a building, as emphasized in much recent research, to encompass all its constituent parts.

The following sections summarize the key contributions of the research, reflect on its implications for research and practice, discuss limitations and propose future research directions.

6.1 Contributions of the research

One of the core contributions of this research is the identification of barriers to the implementation of RCD strategies in building design. The findings confirm that designing with reused or reclaimed parts presents technical and cultural challenges, including the following.

- Lack of standardized classification systems for building components, making it difficult to integrate reused building parts into new projects.
- Absence of DfD features in most existing buildings that means building parts recovery is inefficient and costly.
- Design by availability requires designers to adapt projects based on an unpredictable supply of reclaimed parts rather than relying on free choice of components.
- Cultural scepticism and lack of awareness regarding the value and aesthetic potential of reused building parts.

These findings emphasize that without a systemic transformation of the construction practices, RCD strategies will remain niche rather than mainstream. To overcome the aforementioned barriers, the potential of CD has been discussed as a means of supporting designers in the following ways.

- Optimizing modularity, adaptability and standardization to make buildings more circular.
- Facilitating design iterations, allowing designers to quickly explore multiple reuse scenarios.
- Enabling parametric design, allowing reclaimed building parts to be integrated into the design process dynamically.
- Enhancing the development of reversible connectors, making disassembly and future reuse more feasible.

However, this research also cautions that CD should support, rather than dictate, the design process. While CD enhances efficiency, there is a risk of prioritizing technical optimization over creativity and craftsmanship. Therefore, a balanced approach that integrates human decision-making with computational capabilities is needed.

A significant limitation of current RCD practices is the lack of structured, reliable data on existing building parts. The research emphasizes the importance of digital inventories that provide real-time data on reusable building parts, assisting designers in making informed decisions. CD, combined with material passports and BIM-based databases, can facilitate better tracking of building parts, reducing uncertainty in reuse projects.

Nevertheless, challenges remain, particularly:

- interoperability between different digital tools;
- scarce accuracy of input data, as flawed data can lead to systematic design errors; and

- sector-wide resistance to investing in digital tools and data-driven methodologies.

Addressing these challenges requires not only technological advancements but also policy interventions and financial incentives to encourage data-driven RCD strategies.

Lastly, the research underscores the crucial role of education and interdisciplinary collaboration in enabling circular design practices. The transition toward RCD assisted by CD requires new competencies and emerging professional roles, such as the following.

- Data miners – responsible for collecting and structuring data from existing buildings.
- Augmented architects – integrating algorithmic modelling and generative design into circular workflows.
- Circular material specialists – assessing the performance and reintegration potential of reclaimed building parts.

Even so, cultural resistance to change and lack of computational literacy remain significant barriers. Without targeted education programs, sector training, and policy support, the transition to computationally-assisted RCD will remain slow.

6.2 Implications for research and practice

The findings have several implications for both academic research and industry practice.

The research highlights the necessity of standardizing terminology and classification for building parts, requiring collaboration between academia, policymakers and practitioners. Moreover, longitudinal studies tracking the adoption of DfD principles and CD methodologies in real-world projects over time appear to be necessary. There is alos a need for guidelines developed by policymakers to promote the use of digital inventories and computational tools in circular construction. This, in turn, requires targeted training of architects and engineers in RCD methodologies aided by CD tools to facilitate the transition to a circular building sector. Investing in technologies for tracking building parts and BIM-integrated databases appears crucial for organizations seeking to streamline reuse practices. Without institutional support, regulatory frameworks and sector-wide collaboration, the full potential of computationally assisted reuse strategies are unlikely to be realized.

6.3 Limitations of the study

While this research provides valuable insights, it has certain limitations.

- Design phase – although there is awareness of several aspects related to the design of a new building – for example, assessment, logistics, supply chain – this research focuses exclusively on the design phase, during which designers conceptualize and design the details of the project.
- Material scope – the research initially focused on timber-based construction, with later expansions into other materials. Future research should explore how CD can facilitate RCD across a broader range of building materials. Furthermore, at the centre of the studies were the building parts, but not materials *per se*.
- Technical constraints – the research did not examine AI and machine learning applications in CD due to their limited real-world integration at this stage.
- Adoption of computational-assisted RCD in the building sector – while the study identifies key strategies, actual implementation in the building sector remains slow, requiring long-term observation and validation.

Future research should address these limitations by incorporating case studies of successfully completed projects, pilot projects and real-world applications of CD in circular construction.

6.4 Future research directions

To build on the findings discussed in this dissertation, future research should focus on the following.

- AI-Driven design optimization – investigating how machine learning algorithms can enhance reuse strategies by automatically matching reclaimed building parts to new designs. These digital technologies offer significant potential to support regeneration within the built environment (De Wolf et al., 2024).
- Developing sector standards – establishing standardized digital classification systems for building parts to facilitate reuse at scale.
- Policy and regulatory frameworks – examining how governments and institutions can create incentives for DfD adoption, assisted by CD.

- The role of DfD and CD in aesthetic innovation – exploring how computational tools and reuse of building parts can not only optimize reuse efficiency but also enhance architectural aesthetics in circular design, while helping to combat reservations and prejudices over quality and appearance.

By addressing these areas, future studies can further advance the integration of CD and RCD principles, making reuse a mainstream practice rather than an exception.

6.5 Final thoughts

The research underscores the need to integrate RCD strategies with CD to advance sustainable practices in building design. While neither concept is entirely novel, their combined application represents a significant opportunity for innovation. This research has highlighted the potential of CD in optimizing reuse strategies – particularly DwR and DfR (or DfD) – as well as the barriers that must be addressed to make circular design a standard practice rather than a specialized approach. Even so, addressing the abovementioned challenges requires a holistic approach, integrating technical innovation, data management strategies and sector training programs to ensure that computationally assisted reuse strategies become an integral part of sustainable building design. Lastly, by embracing an interdisciplinary and holistic perspective, the building sector can overcome resistance to change and unlock the full potential of a smarter, more resilient and resource-efficient future – one where DfD and computational tools play a pivotal role in sustainable development to facilitate the transition toward a circular building sector.

In the near future, if interdisciplinary collaboration and the widespread adoption of DfD, along with a detailed understanding of computational techniques, become integrated within a unified sector-wide reality, the parallel paths of sustainable developments and technological advancements could converge, promoting the transition of the smart built environment from theoretical conception to practical realization.

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Challenges facing components reuse in industrialized housing: A literature review

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Abstract

Concerns over the earth's ability to sustain itself over the long term as a consequence of human consumption of Natural resources points towards sustainable development. Since a large proportion of human consumption is linked to buildings and construction, this means managing the construction process in more sustainable ways. Strategies that target greater material efficiency and which promote circular economy concepts are among several approaches that are gaining in popularity. The adoption of life-cycle thinking and practices in design, construction and end of life through the reuse of construction components and materials is one such action to achieve a sustainable built environment. Reuse is not a new concept and technical solutions do exist; however, practical realization is hampered by many interrelated challenges. This review paper is the result of a literature review for an exploratory study that aims to identify obstacles to the reuse of building components and materials. The context is industrialized housing, particularly timber-based construction, as this is a sector where modern manufacturing and onsite practices have become established. The main obstacles identified and corroborated in the literature, along with their potential solutions, are summarized and conclusions drawn on the future direction of research needs.

Keywords

Design for reuse; building components reuse; industrialized housing; timber; circular economy; sustainable developments **;**

1. Introduction

The global condition of climate change is a consequence of human consumption of natural resources when the earth's resilience goes beyond the boundary of ability to sustain itself over the long term. A large proportion of this consumption is linked to buildings and construction where one solution is to adapt the concept of sustainable development to the construction industry and to manage the construction process in sustainable ways (Jonasson et al, 2020). Defining sustainability for a construction project is a complex task. The term consists of many different and connected parts during the process, involving the client, project team members, other stakeholders, issues of aesthetics, functionality and material interactions. The construction industry is more responsible than other industries for global CO_2 emissions (UNEP, 2018). In 2014, the European Commission noted that circular economic systems were of immense benefit for sustainable development across Europe and encouraged member states to adopt them (COM, 2014). Subsequently, the United Nations Organisation framed the goals for sustainable development in its Agenda 2030, where goals 9, 11 and 12 mostly concern the construction industry. Construction, among other activities of human behavior, also generates a huge amount of waste (Iacovidou and Purnell, 2016). Over the past decade, concerns about the impact of climate change on the built environment have increased. Zero-carbon performance has been highlighted, together with a shift from solely the performance of the product, i.e. the building, to the construction process and a whole life-cycle perspective. These concerns have recently evolved to a focus on zero carbon, zero energy and, in the long run, to "retrieve what we lost" or "doing more good" by adopting a net-positive impact view that is defined as regenerative development (Cole, 2020). During the transformation to a zero-carbon, resilient, sustainable and regenerative society, buildings in most countries play a major part in the use of energy and the impact of carbon emissions. Globally, buildings consume about 35% of the total available energy, responsible for roughly 38% of total carbon emissions, and generate about 36-40% of all man-made waste (UNEP 2020).

The adoption of strategies for material efficiency, promoting circular economy concepts using life-cycle approaches in design, construction and end of life by re-using construction components or materials, is among the most critical of actions to achieve a sustainable built environment as stated in the latest Global Status Report for buildings and construction (UNEP, 2020). Furthermore, in order to meet the multiple criteria of sustainability, industrialized construction could be a part of the solution that also contributes to solving the housing shortage. A benefit of off-site construction is the production of decent quality, affordable housing that can be rapidly assembled on-site. Prefabrication can improve environmental performance considering that the building is designed to be reused (Aye et al., 2012). Industrialized housing construction (IHC) consists of different approaches (i.e. prefabrication, modularization, off-site fabrication, or modern methods of construction) (Kedir and Hall, 2021). The possibility to build parts of the structural frame as planar structural modules (walls, floors, etc.) contributes to a reduction in construction time. Moreover, the reuse potential of prefabricated timber-based structures is claimed to be at least 69% (Aye et al., 2012). The global consumption of natural resources by the construction industry is not sustainable. It is, therefore, essential to re-think the construction process in terms of the efficient utilization of natural resources, their reuse and the recycling of demolition waste, as a minimum. Construction professionals, including practicing architects, engineers and construction managers, as well as environmentalists, researchers and academics should be called upon to play a major role in helping to sustain our environment (Khatib, 2016). Hence, due to an increasing urban population and the need for affordable housing, our study focuses on the reuse of building components. This paper aims to identify enablers and challenges for the reuse of building components in industrialized housing with a focus on timber-based construction.

2. Method

In order to determine drivers and barriers for reuse of building components, a literature review has been conducted. The search engines used to retrieve the articles are, Web of Science and Scopus. The keyworks used to retrieve the articles included reuse, building components, building elements, construction, and industrialized timber construction. The search was done from 2000 to 2021. A total of 136 articles were retrived and 30 were selected for the review, because of their relevance for the study. Starting by briefly analyzing resource and waste management, the study describes the issue of housing shortage in Sweden and identifies a possible solution in Industrialized Housing. The focus, thereafter, is on demolition and deconstruction phases in a project, which are considered crucial to re-think the entire construction process. While exploring the common enablers and barriers in buildings construction, the attention is shifted to specific obstacles and opportunities to enable a reuse approach in industrialized housing concentrating on timber buildings. The latter are thereafter demonstrated to be suitable to fulfill the sustainable goals and the principles of circular economy in construction.

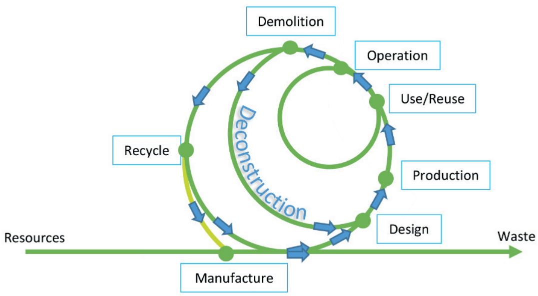

Figure 1 – Implementation of Circular Economy in construction.

3. Literature review

3.1. Resource and waste management

The circular economy (CE) and sustainability concepts are becoming a matter of great importance among policy makers, academia and industry. CE is defined "as a regenerative system in which resource input and waste, emission and energy leakage are minimized by slowing, closing and narrowing material and energy loops" (Geissdoerfer et al., 2017). To promote the concept of CE in the built environment, the Waste and Resources Action Programme (WRAP), has published considerable good practice guidance to be adopted by the industry (WRAP, 2013). This includes BIM, designing-out waste, designing for disassembly, off-site construction and sustainable procurement, as well as adopting fairness, inclusion and respect. In creating an effective CE in construction, a significant majority of building materials must be recoverable for reuse and recycling (Pan et al., 2015; Tukker, 2015). There is a shared understanding that the reuse of building components is preferable to recycling (Rakhshan et al., 2020; Arora et al., 2019; Mayer et al., 2019; Cooper and Gutowski, 2017; Hoornweg et al., 2015; Park and Chertow, 2014) since energy requirements for recovering building components for reuse are less than when recycled (Iacovidou and Purnell, 2016). Although recycling is a common practice, a more value-driven approach is reuse. As noted by Iacovidou and Purnell (2016), the production of new construction materials in Europe consumes 5-10% of total energy use. Landfill resources are limited and natural resources are scarce and when the ecological impact of the increased extraction of raw materials is taken into account, it seems fairly obvious that traditional construction methods have to give way to more sustainable processes and practices. The construction components need to be seen not as problematic waste, but as an investment opportunity to achieve the big change required to make the construction industry more "sustainable, smarter and resourceful" (Iacovidou and Purnell, 2016).

Buildings are made by assembling components (e.g. foundations, columns, beams, façades, windows, doors and appliances). According to Niu et al. (2021), cascading construction and demolition (C&D) materials is imperative. The authors define the term "cascading" as the combination of reusing, recycling and material recovery of C&D and divide the elements in a building suitable for cascading into two main categories: load-bearing elements (e.g. foundations, walls, floor slabs, columns and beams) and non-load-bearing elements (e.g. light/partition walls and facades). Reuse has the highest priority among all cascading scenarios (i.e. reduction, reuse and recycling) (Niu et al., 2021). It is, therefore, important to change the terminology and thinking from *material stock* to *components stock*, and from *waste management* to *building components management* (Arora et al., 2019).

3.2. Housing shortage in Sweden

A shortage of housing is not uncommon in developed countries; see, for example, Boverket (2020). In common with other countries, the shortage is due to a lack of investment in new and refurbished housing stock. The situation has been made worse by substantial immigration. In 2020, 212 of Sweden's 286 municipalities (i.e. 74%) reported housing shortages. Even though this number has been decreasing slightly over recent years, it indicates a persistent problem. Iacovidou and Purnell (2016) have proposed initiatives to enforce changes that can lead to more sustainable construction management and less production of construction and demolition waste (CDW). According to Iacovidou and Purnell (2016), such initiatives are: re-thinking the design of buildings by using materials that are both durable and recyclable, and therefore carrying low embodied energy; reducing the use of materials with a high carbon footprint and promoting manufacturing practices that take resource efficiency into account; and enabling reuse of construction components. To improve the potential for reuse in construction, it is first necessary to prove its technical feasibility in a holistic way. In other words, there is a need to re-think the way we plan, design, construct and deconstruct in order to make the entire process "more resource efficient and reduce its carbon footprint" (Iacovidou and Purnell, 2016).

3.3. Industrialized housing

The need for new housing calls for increased productivity and affordable, sustainable and cost-effective buildings. Industrialized housing (IH) has long been promoted as a solution to house shortages, in many countries, including Sweden, where the arrival of prefabrication was identified in the Portable Colonial Cottage for Emigrants advertised in 1833 (Ågren and Wing, 2014). A more recent proposal is Horden's helicopter-delivered home in 2012 (ibid). With the advent of newer digital technologies, IH could increase substantially given a reduction in the time needed to design and build multiple units as a result of repetitive processes and the pre-determined use of different materials and layouts. An example of what can now be achieved is Svenska Allmännyttans Kombohus, where a cost reduction of up to 25% is possible (Svenska Allmännyttan, 2020). Moreover, IH does not have to be devoid of architectural or aesthetic quality; it simply has to be among its primary objectives. Even if standardization of design work in house-building has, for the last 20 years focused on production, economics and sustainability (Aitchison, 2017; Lessing and Brege, 2018), it is important to have "the involvement of architects in [the] industrialized house-building processes to meet future demands for aesthetics and functionality that satisfy end-user and client values and requirements and to ensure the creative work of artistic and engineering design" (Jansson, 2018). Indeed, over much of the 20th century, architects such as Wright, Le Corbusier, Fuller and Gropius have contributed their interpretation of prefabrication to housing, proving that it is the result of sociological, economic and political constraints and requires more than just technical know-how to become successful (Ågren and Wing, 2014). Industrialized house builders prefabricate building modules for assembly on-site, are responsible for almost the entire building process and can control and improve the quality of building manufacture in a better way than conventional construction companies (Johnsson and Melling, 2009). Moreover, introducing more industrialized methods into the construction industry could increase efficiency and reduce defects, closing the gap between manufacturing and construction based traditionally on craftsmanship (ibid). There is therefore a need to shift from project-based to process-based production as argued by Winch (2006). IH also provides opportunities for the reuse of building components instead of recycling, which equates to a higher level in the waste hierarchy (WRAP, 2008a) and contributes to a reduction in CDW. The latter represents a significant benefit from the perspective of the CE. A building's life-cycle and the possibility to reuse building components rather than recycle materials is a crucial aspect of "circularity". According to Tavares et al. (2021), the benefits of prefabrication are waste reduction, cost and time saving, growth of productivity and better building performance. A few studies have compared prefabricated buildings with traditional buildings. The results reveal a reduction of 5-40% in environmental impacts when using prefabrication methods, and an investment cost reduction of 30% compared with traditional construction (Tavares et al., 2021). In IHC, structures can be manufactured off-site "as a volumetric element (3D) or as a panelized system (2D)". Unfortunately, there is a lack of literature concerning resource efficiency with respect to IHC (Kedir and Hall, 2021). So far, our literature review has not revealed any cases where the reuse of building components in IHC has been explored. This confirms the need for further research in the field, which could support the thesis that a new design concept, based on the reuse of building components, is crucial to satisfying the criteria of sustainability and the global goals of Agenda 2030.

3.4. Deconstruction and reuse

Iacovidou and Purnell (2016) define deconstruction as "the careful dismantling of a building or structure to maximize the recovery of its components for reuse". They identify various strategies that promote component reuse in construction.

Design for Deconstruction: a design approach that aims to "close the construction components loops" also named as Design for Adaptability and Deconstruction (DfAD). Among the advantages, we can count the extended duration of the structure which leads to economic and environmental benefits. There are, unfortunately, challenges connected to "technical, economic and logistical barriers".

Design for Reuse (DfR). When designing a new structure, reclaimed components are included in the project. If the layout is similar to the previous building then DfR can be successful. Otherwise, many design adjustments are required. It is critical to form a close collaboration between all stakeholders, for instance, architects, other designers, engineers, contractors and trades.

Design for Manufacture and Assembly (DfMA). The construction components are fully manufactured off-site and assembled on-site. Assembly and disassembly are fundamental in order to enable deconstruction and recovery of components and therefore sustainability of the products and structures.

Van den Berg et al. (2020) identify, in the practice of Design for Disassembly (DfD), some principles for building components to be suitable for reuse, namely that building connections should be minimized, accessible and reversible. In addition, their study defines economic demand, proper disassembly routines and element control performance as conditions for element recovery. The most suitable definition for the purpose of this study is the one suggested by (Cristescu et al., 2021), i.e. Design for Deconstruction and Reuse (DfDR). The main principle supported by both definitions is a new way of designing a building, allowing the reuse of its parts, repaired or properly dismantled, in new applications. This can be for the original purpose or a different purpose, while prolonging the life-cycle of the building components and materials (Cristescu et al., 2021). The difference between Design for Deconstruction or DfAD and DfD, as described by Long (2014), among others, is that the latter involves recycling building materials and components and so preserves just a small amount of embodied energy. It is, therefore, less environmentally friendly and sustainable than DfAD, where the building components are reused directly or relocated in a new or existing building. Awareness about buildings changes over time and proper planning is required to re-think current approaches to construction in order to reach environmental goals (ibid). Further support for the reuse of components as a way to save more energy, when compared to recycled materials, is to be found in da Rocha and Sattler (2009). Moreover, the reuse and recovery of elements and components are good practices according to the European Waste Framework Directive since 2008. Even so, the reuse of building components in a systematic way is far from being a common procedure in the construction industry.

3.5. Reuse in construction: enablers and barriers

Rakhshan et al. (2020) suggest that reuse drivers are "economic (25%), organizational (23%), environmental (17%) and social (15%)". Economic drivers are the lower price of reused components and the higher price of landfilling, although they might differ depending on the geographic location. Reducing CDW generated by construction companies and "promoting the green image of the companies" are the most important organizational drivers. In reducing CDW during renovation and demolition of buildings, reuse of building components appears to be a preferable solution which allows for recovery of functional components, e.g. tiles, bricks and windows (da Rocha, and Sattler, 2009), interior walls, panels and doors. Rakhshan et al. (2020) identify the scarcity of landfill sites as a major environmental driver. Among the social drivers are society's environmental concerns and a better understanding of the advantages of reuse among stakeholders. Rakhshan et al. (2020) state that practices that prefer deconstruction over demolition could lend themselves to the reuse of recovered components. Considering the entire building process, deconstruction and reuse appear to be preferable over demolition and recycling, by offering higher environmental and economic benefits. Nonetheless, training in deconstruction techniques together with policies and, possibly, legislation that promote such practices are probably required to achieve the durable benefits of deconstruction.

Rakhshan et al. (2020) identify the economic, social, and technical barriers when reusing building components. Economic barriers are further categorized into supply chain level by identifying the lack of reuse market, component level and project level, the latter highlighting the need for a financial risk assessment in the early planning phase of a project. According to Rakhshan et al. (2020), overcoming these barriers is possible if collaboration between construction and demolition firms is established and financial incentives are available. Moreover, the cost of reclaimed components should be sufficiently attractive. One possible solution is offered in the UK where the tax for landfilling has increased in order to encourage reuse practices.

According to Rakhshan et al. (2020), social barriers can be classified into perception, awareness and risks. Studies mostly focus on the negative approach of stakeholders towards reuse practices which hinder its adoption in the construction industry. Arora et al. (2019) define the way evaluations about material stock and outflows are made and introduced to the public as one of the major obstacles which hinders the suitability of the results. The authors state that, usually, those reports focus on single material-type results, whereas a representation as *component-type* could increase interest on the part of policy makers and decision makers (Arora et al., 2019). Developing "standard test procedures to test, evaluate and certify the recovered building components" (Rakhshan et al., 2020) is the proposed solution to overcome these barriers, which could expand the reuse market.

Lastly, technical barriers are categorized into deconstruction level, performance level, and health and safety level. Presently, buildings are not considered or designed for deconstruction and this represents a challenge; however, this barrier can be overcome by adopting innovative designs for new buildings. At the performance level, reusability of the element represents a barrier to the reuse of building components at their end of life as a consequence of damage, design changes, etc. At the health and safety level, precautions necessary to increase health and safety during deconstruction activities could also increase the total cost of the project (Rakhshan et al., 2020). To promote reuse and environmental efficiency, it is necessary to reduce material excess in new building components and optimize the design, which could save a considerable amount of material (Iacovidou and Purnell, 2016). The goal of the stakeholders involved in the construction process should be to ensure adaptable design, to optimize recovery of building components for reuse and to apply new design strategies. Enabling assessment of the reuse potential of components during the manufacturing phase of a project would save time that would otherwise be spent during on-site assessment (Iacovidou and Purnell, 2016).

3.6. Industrialized timber housing (ITH)

Cristescu et al. (2021) describe a long history of timber building techniques; however, timber's popularity as a construction material on a significant scale in Europe has been mostly confined to the second half of the last and present century where the primary use is for housing. Currently, in Sweden, 80% of single-family houses are built off-site, as a result of a long development history of prefabrication, which has led to a reduction of 20-25% against the cost of traditionally constructed buildings and an 80% saving in time (ibid). While the use of light-frame prefabricated structures has become more common for multi-storey housing, cross-laminated timber construction is the most widely used. Timber for multi-storey buildings has, however, increased from 13% in 2018 to 20% at the end of 2019 (ibid). In Sweden, as in Finland, Slovenia and the UK, panels with the insulation layer inserted between studs and joists is the most common practice (ibid).

As a widely available and biodegradable material that grows naturally, timber is considered crucial to achieve the environmental goals of the European Union, even though its reuse can be problematic (Huuhka et al., 2015). Indeed, as a natural material, reclaimed components demand special care and control if they are to be reused (Cristescu et al., 2021). The benefits of using timber in housing are identified in a reduction of the carbon footprint, by extending the life-cycle of building materials, and in a reduction of the environmental burden, by reusing structural components. The growth of off-site construction is expected to contribute to the diffusion of timber-based construction because of waste reduction, as well as material and time efficiency. Despite these encouraging signs, timber-based construction is not following the principles of the circular economy neither is it taking into account the whole life-cycle cost of the buildings, suggesting a further field for research (ibid).

Currently, the reuse of timber structural components is hindered by a lack of design standards (for example, demolition practices that prevent damage to components); the lack of a sufficient market for recovered materials; restrictive building regulations and constraints imposed by the fixed dimensions of available components, negatively impacting the flexibility of a design (Cristescu et al., 2021). Concerns about technical performance and safety, when reusing structural timber components, would suggest that policy and regulation should drive the CE with respect to structural timber (Niu et al., 2021). Glue laminated timber in common with traditional timber framing has a high reuse potential and both offer environmental benefits (Huuhka et al., 2015). The literature has documented those barriers commonly obstructing the development of timber reuse in construction. The obstacles are mainly to do with cost, inconsistent quality, inconsistent quantity, perception and trust. As reported by Huuhka et al. (2015), the highest reuse potential is offered by prefabricated steel components while the lowest is concrete. Nevertheless, timber's potential is relatively close to that of steel. In identifying reuse potential and barriers, local issues such as structural systems, climate and societal conditions should be taken into consideration, since they vary from country to country (ibid).

According to Iacovidou and Purnell (2016), reuse potential measures "the ability of a construction component to retain its functionality after the end of its primary life". When considering timber construction, timber trusses have a low reuse potential of <50%, while timber floorboards have a medium reuse potential of 50% and structural timber has the highest >50% if properly deconstructed. It seems to be difficult to deconstruct timber components correctly when cleaning, de-nailing and sizing. Design interventions such as holes for wiring have made timber components more reusable, allowing for efficient deconstruction (Iacovidou and Purnell, 2016). A recent study showed that timber-based structures are mostly reusable: 65% of building materials are reusable and 35% are recyclable (Akanbi et al., 2018). This value could be increased by, for example, designing for deconstruction and using demountable connections (e.g. dowels and bolts) in the process (ibid). Rakhshan et al., (2020) argue that structural and non-structural timber components can, if properly deconstructed, have a high potential for reuse. However, timber components are difficult to deconstruct, require specialist skills and equipment during reclamation of components, and are exposed to decay. Hence, efficient deconstruction is essential and, consequently, special design features to reduce damage are needed to promote the reuse of timber sections and contribute to decreasing the environmental impacts, which Rakhshan et al. (2020) estimate to be 83%.

In Sweden, there is an ongoing development of reusable products database by the Center for circular construction (Centrum för cirkulärt byggande). By creating such a systematic database of components with unique IDs, and by utilizing available digital tools and building information modeling the acceptance of reused components in the construction industry could increase.

4. Discussion

Despite the economic, social and technical barriers, reuse in construction seems inevitable in the future, because of global population growth, scarcity of resources and housing shortages. As Iacovidou and Purnell (2016) have argued, a research commitment is necessary to demonstrate the economic, environmental, technical and social benefits of reuse. Doing so will lead to a better understanding of how to optimize the recovery of value for stakeholders through deconstruction and reuse, by simply changing current practices. There is an inevitable concern about the availability of timber for industrialized timber construction in the future, which could undermine the sustainability of the entire process (Mantau et al., 2010). Therefore, the concept of cascading is being used more and more to indicate the need to prolong the use of the same resource (i.e. building material or component), placing recycling for energy purposes last (Niu et al., 2021). Chisholm (2012), in recognizing the environmental benefits of using timber as a construction material for housing (e.g. carbon dioxide reduction, availability of timber in Europe, less energy to process timber components, high strenght-to-weight ratio, good thermal performance and carbon capture), emphasizes how “timber contained in the housing stock can act as an urban forest for harvesting” if the practice of reuse becomes popular. Moreover, the strategy of DfDR should be centered around modular and component deconstruction (e.g. floors, roofs and walls), rather than single parts or materials to support a reuse approach (Chisholm, 2012). Our literature review confirms the need for a holistic approach to the entire construction process, which should examine the conception and design phase and current demolition procedures. In addition, digital solutions are required to develop an efficient virtual building components’ database for a growing market. Furthermore, a decision-making tool and global, as well as regional, regulations need to be adapted to these newer forms of construction. Last, enabling reuse practices could easily and rapidly contribute to a reduction in CDW. Nevertheless, to demonstrate the above, further studies must be conducted to examine the economic value of reuse of building components by manufacturers, particularly planar and volumetric elements (Cristescu et al., 2021), rather than recycle building materials. Figure 1 shows how increased knowledge of the construction process while involving all stakeholders in the different phases, develops and improves the entire process and can generate, as a result, a reduced amount of CDW. Further education and training in new skills for all stakeholders, together with incentives, would encourage active participation in reusability strategies. There is a need to implement the enablers and overcome the barriers to reuse. It is evident that in order to overcome many of the barriers pointed out in this research, strong collaboration is needed among the different stakeholders involved in the construction process. For example, construction firms and architecture design firms could learn from deconstruction firms on the reuse of building components. Furthermore, the implementation of platforms for knowledge sharing are needed to be able to spread the knowledge about reusing practices.

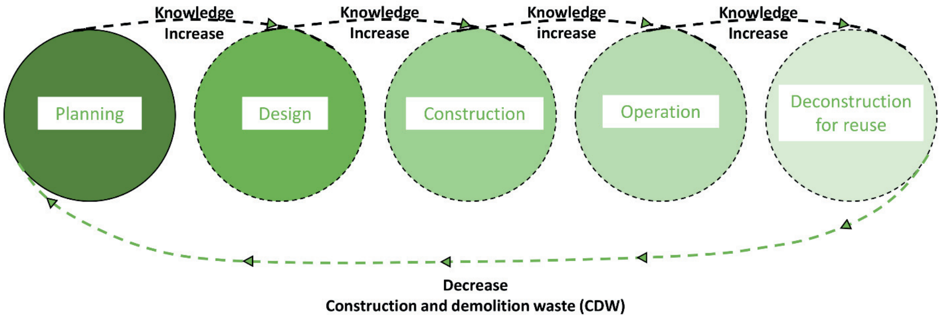

Figure 2 – Re-thinking the construction process.

5. Conclusions

Most political decisions and legislation focus on waste management when trying to solve sustainability in construction. This is agreeable since the amount of waste generated is a significant concern and the availability of landfill is increasingly scarce. However, attention should be directed to the design phase, which is the most influential stage in the delivery of decent, affordable housing, where change is necessary to ensure circularity is achieved. Once the reusability of building components andelements is introduced in the design process, a major contribution to solving the problem of waste will have been found.

Resource efficiency in housing construction should be able to fill the gap between housing demand and current construction methods. Furthermore, the demolition phase of the construction process has to be better analyzed and improved to reduce the amount of CDW and, consequently, the carbon footprint of the construction industry. Reuse of building components is a recommended practice from a circularity perspective. It seems necessary, therefore, to reintroduce building components in the supply chain, replacing the perception of a waste problem with an opportunity to make the construction industry more sustainable and resourceful. ITH has much to offer as a solution to housing shortages and has less environmental impact than traditional construction, which could be reduced even more through the reuse of building components. Unfortunately, a lack of quantitative and qualitative data about the benefits of reuse in construction hinders the spread of this practice. With this in mind, it is evident that reuse of building components needs to be adopted on a large scale and embraced by all stakeholders in a project. It is crucial to change attitudes towards reuse in construction and to establish a broader involvement and stronger collaboration between all the stakeholders responsible for the different phases of the construction process, starting with planning and design, and continuing with manufacture, construction, handover and maintenance to the point of refurbishment or deconstruction for reuse from a holistic perspective. Industrialized timber housing construction is a potential area which provides many opportunities for reusing building components. There is a need to study the reuse practices of building components in industrialized timber housing construction, thus, this study will further explore the field by analyzing multiple cases. This study will explore the barriers to, and enablers of, reuse in ITH from the perspectives of clients, building contractors, designers and demolition contractors.

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Paper II

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

Source: Created by authors

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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Paper III

Circular economy competencies in Swedish architecture and civil engineering education

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Abstract. The transition from a linear to a circular AEC sector requires redefining processes and roles, accompanied by the acquisition of new competencies and skills. Despite existing literature delineating various competencies pertinent to this transition, the lack of knowledge among the actors remains a significant barrier to enabling it. This study involves a comparative analysis of the competences needed in the AEC sector with the bachelor's educational programs in architecture, civil engineering, and real estate and construction management offered by five higher education institutions (HEIs) participating in the Swedish Universities of the Built Environment (SBU). Aiming to emphasize the need to improve the integration of circular economy concepts and strategies within academic curricula, the overarching objective is to identify both circular-focused syllabi and the potential implementation of circular competencies in existing courses within the SBU programs. First, the results show the technical competencies deemed necessary for the transition to a circular building process. Second, by analysing course syllabi from the five Swedish HEIs, this study identifies gaps in circular-focused education and the level of integration of these competencies within the curricula. Ultimately, this study contributes to bridging the gap between Swedish education on circular economy in the AEC sector and its practical application.

Keywords: Circular economy, competencies, course syllabi, higher education institutions

1. Introduction

The adoption of circular economy (CE) strategies in the AEC sector is considered essential for creating a more sustainable, resource-efficient, and resilient future. It aligns with global efforts to address environmental challenges, supports economic growth, and enhances the overall social and environmental performance of the built environment. Life cycle analysis (LCA), adaptive reuse, construction flexibility, design for disassembly (DfD), reuse of building materials and components, and circular business models are some of the strategies that, if implemented in the AEC sector, can contribute to conserving natural resources and stimulate economic growth by extending the life cycle of buildings and their materials, thus ensuring their continued circulation [1], [2], [3], [4], [5], [6], [7].

The AEC sector, which nowadays mostly relies on engaging individual actors or small businesses [5], [8], faces several barriers hindering a successful implementation of CE. Incorporating CE into HEIs' curricula and ensuring that their students have the suitable competencies to address the CE challenges is considered crucial to overcoming cultural barriers such as conservatism and lack of knowledge, tools, and proper skills [9].

HEIs are widely acknowledged to be the enablers in shaping the mindset and values of future generations [10]. At a global level, acquiring "the knowledge and skills needed to promote sustainable development" by 2030 is the aim for all learners included in target 4.7 of the SDGs [11]. This is also reinforced by the vast literature dedicated to the role of HEIs in guiding society towards the adoption of sustainable practices. Moreover, the key contribution of HEIs in promoting topics related to sustainable development, CE and building a smart and resilient society is also stressed in the European Commission legislative framework and six funding priorities [12]. Nonetheless, the implementation of CE in HEIs educational activities is still an emerging topic.

According to Kozminska et al. [6], the majority of the literature related to CE implementation in the AEC sector focuses on the reusability of resources and materials due to the contribution to environmental pollution of construction and demolition activities. Nevertheless, upon closer inspection, the list of competencies and skills that designers, architects, facility managers and civil engineers should acquire according to the literature is quite long. Janssens et al. [13] categorize the relevant competencies for the transition to CE within the specific context of Lindburg into three primary clusters: technical, valorisation and transversal competencies. Similarly, Sanchez et al. [14] employ a five-category framework to delineate competencies for sustainability classifying them based on whether they involve "learning to know, learning to do, learning to live together, learning to be, and learning to transform oneself and the society". While Sumter et al. [15] identify seven new competencies that designers need to master to be able to design circular products and services, Haase et al. [16] focus, instead, on the integration of competencies into a comprehensive education of circular practices for Facility management master's students with the intent of preparing them for a future centred on sustainability and circularity.

Despite the emphasis of the literature on the importance of introducing new subjects and competencies into the curricula to enable students to apply and critically interact with CE strategies and methods [13], [14], [15], [17], [18], a study conducted by Obrecht et al. [12] shows how CE is currently the least addressed topic in the curricula, especially in considering its relationship with competencies about social responsibility. Moreover, a recent study into students' perception of the effectiveness and utility of compulsory courses in sustainability at the Faculty of Engineering at Lund University, showed how students remain sceptical about the usefulness of these courses for their future careers [19].

Although the Swedish HEIs are trying to incorporate CE at different institution levels by hiring competent teaching staff, creating specific research groups, and implementing circular strategies in campus management, there is no information available on the status of the integration of CE principles in bachelor-level programs. Therefore, the aim of this paper is to describe to what extent CE concepts, strategies and tools are currently integrated into the programs of five Swedish HEIs. This paper also aims to evaluate how far the HEI programs align with the needs of the AEC sector in transitioning from a linear to a circular building process. It is worth noting that is out of the scope of this paper to examine in-depth the skills and the pedagogical approaches considered relevant for this transition.

This paper is structured in the following sections. Section 1 introduces the research context and the aim of the study. Section 2 describes the research methodology. In Section 3 the technical competencies map and the results from the syllabi analysis are presented, and in Section 4, the results are discussed and potential ways to integrate circular competencies into the existing courses are presented. In the Conclusions, the main findings are drawn and ideas for future studies are presented.

2. Methodology

The research conducted in this study is descriptive, aiming to present the state of the art of the integration of CE concepts in the current academic offer provided in the architecture, civil engineering, real estate, and construction management faculties of five Swedish HEIs affiliated with the Swedish Universities of the Built Environment (SBU). The five Swedish HEIs used for data gathering were Chalmers University in Gothenburg, the Royal Institute of Technology (KTH) in Stockholm, Lund Faculty of Engineering (LTH), Jönköping University (JU) and Luleå University of Technology (LTU). The research adopted both quantitative and qualitative approaches. The empirical design consisted of a literature study and an in-depth survey employing questionnaires sent to relevant actors. A comparison between data from the literature study and questionnaires was employed to identify 13 clusters of technical competencies. These clusters served as reference points for the content analysis. Finally, the data analysis consists of content analysis of relevant course syllabi.

2.1 Data collection methods

The process to gather the data consisted of two phases: the identification of technical competencies and the identification of the relevant course syllabi. The next paragraphs explain the strategies used to collect and select the data.

2.1.1 Identification of technical competencies. The competencies needed in the AEC sector were mapped using a literature study. In this context, technical competencies encompass technical information, expertise, manufacturing techniques, data, material specifications and other pertinent information used in the AEC sector for the production of circular building materials, products and structures as well as during construction, maintenance, repurposing and deconstruction processes.

The competencies retrieved from the literature were categorized first according to Janssens et al. [12] classification framework into technical, valorisation and transversal competencies. Then only technical competencies were selected and further classified into 13 clusters of thematic areas. The eight studies selected for technical competence identification were [12], [13], [14], [15], [19], [20], [21], [22].

A similar process was also applied to the list of competencies collected with questionnaires sent out to 19 relevant actors. With relevant actors, the authors refer to both individuals and organizations interested in the shift to a CE in the AEC sector. In particular, for this study, the actors were selected among those previously contacted for other related studies and with proven experience or knowledge in the field of CE. Furthermore, they were chosen according to their different professional role aiming to cover the entire value chain and thus obtain a more extensive and verified list of relevant competencies needed by the Swedish AEC sector. Among the 11 actors who answered the questionnaire, three had rather limited experience with circular projects. The remaining actors are all actively involved in CE implementation in the sector. Table 1 displays the actors, who answered the questionnaire, with their roles and CE experiences.

Table 1. List of Swedish participants in the questionnaire

ID	Type of organisation	Role	CE experience
1	Contractor	Environmental specialist	Reuse-focused building projects
2	Supplier and remanufacturer of building materials and services	CEO	Material reuse and remanufacturing
3	Property/facility manager	Maintenance coordinator	-
4	Developer	Project manager	Material reuse and building adaptation
5	Consultancy company	Architect and computational designer	-
6	Consultancy company	Interior designer	Furniture reuse
7	Architectural firm	Architect	-
8	Consultancy company	Environmental geo-technician	Management of excavated materials
9	Supplier of building materials and services	Sustainability manager	Circular material use and design of demountable building systems
10	Architectural firm	Architect and local sustainable responsible	Material inventory and reuse-focused building projects
11	Consultancy company	Sustainability manager and strategist	Circular projects

The qualitative questions sent out via e-mail were asking for responses concerning the following topics:

- A general perception of practitioners about the education for sustainable and circular practices in the AEC sector received by recent graduates in Sweden.
- The specific competencies they consider essential for professionals working with CE practices in their same roles.
- Recommendations to the Swedish HEIs to better align their curricula with the competencies required in a circular AEC sector.

2.1.2 Identification of course syllabi. During the second phase of data gathering, the websites of the five Swedish HEIs were searched for programs and courses.

A total of 31 programs were considered relevant for this research of which 20 are architecture and civil engineering five-year programs (300 credits) and 11 are bachelor's programs (180 credits) in real estate and construction management, civil engineering and technology management and economics. For each program, a list of courses was created distinguishing compulsory and elective courses. Course duplicates were eliminated and non-relevant courses, such as courses in mathematics or languages, were discarded. Only compulsory courses at the bachelor level were then selected for this study (see Table 2).

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Table 2. Number of compulsory courses per Swedish HEI

Chalmers	KTH	LTH	JU	LTU
85	113	112	43	82
				Tot: 435

Since nine courses at LTU were new and their syllabi were not yet published, 426 course syllabi were downloaded from the respective HEIs website between December 2023 and January 2024.

2.2 Data analysis

The course syllabi study consisted of two parts. In the first part, a quantitative approach was undertaken using NVivo. In the second part, the course syllabi were qualitatively categorized by two researchers who read the syllabi entirely autonomously to understand the level of connection between the course content and circular-related concepts.

As underlined by Bowen and Glenn [20], document study typically involves the systematic review and evaluation of materials that can be both physical and digital. In the context of course syllabi, document study entails a methodological examination and assessment of the written outlines and content of these documents. Each syllabus represents the structure, content and objective of a course and therefore its review provides insight into the learning objectives, pedagogical approaches and incorporation of specific topics and competencies within the curricula. The purpose of the document study was to analyse whether each course syllabus addressed any of the competencies identified. After downloading all the syllabi, they were imported into NVivo for a comprehensive *term recurrency search,* a *text search* and then both quantitative and qualitative content analysis were made. The 13 clusters and the technical competencies map served as a guide for identifying CE-related competencies within the syllabi. Courses were classified only if they demonstrated a clear connection to the competencies outlined in the mapping. If a course addressed multiple thematic areas, it was classified under more than one cluster.

2.3 Methodological limitations

For this study, a wide range of CE-related terms were searched; nevertheless, courses addressing relevant issues related to CE but using a different terminology might not have been identified. Moreover, it should be noted that what is in the syllabus is a short text; while topics might be covered in the course, they might not be explicitly mentioned in the syllabus. Furthermore, it is important to consider the challenges encountered during the classification and analysis of the syllabi. First, NVivo has difficulties with prefixes, suffixes and compound words that are typical of the Swedish language. For instance, searching for *processen* (process) might not have highlighted words with prefixes like *byggprocessen* (building process). This limitation means that some relevant terms might have been missed during the search process. Subsequently, several of the course syllabi of KTH provide only brief descriptions of the course content, lacking a description of the intended learning outcomes or aim of the courses. As a result, 15 courses that did not even provide information about the course content were discarded.

Additionally, the methodology employed in this study was not designed to capture transversal and valorisation competencies or to investigate which skills students might develop through course participation. As such, the investigation of these competencies and skills falls outside the scope of this study.

3. Results

CE practices are recognized as crucial for achieving the SDGs of the United Nations'2030 Agenda, leading to a growing body of literature on CE implementation in HEIs [21]. This section presents the results from both the literature study and the questionnaire before examining the integration of CE competencies into educational programs across the five Swedish HEIs.

3.1 Identifying technical competencies from the literature

The need for integrating new competencies and subjects into curricula is undeniable and crucial for effectively applying and critically engaging with CE strategies. More specifically, initial theoretical background and technical competencies are both considered essential to prepare students for the circular AEC sector [9]. Table 3 presents the technical competencies identified in the literature [13], [14], [15], [16], [22], [23], [24], [25] categorised according to the 13 clusters created for sorting the competencies per thematic area. The clusters are: environment and impacts; governance and legislation; financial consideration; CE concepts, strategies and challenges; development approaches; procurement; processes; design approaches; methods and tools; technology; products, materials and components; energy use; and waste.

Note that some of the competencies have been combined and shortened to fit the table. Among the new competencies identified in the literature, there are circular business models, circular impact assessment, circular materials and manufacturing, circular system thinking, circular user engagement, CE collaboration, CE communication, design for recovery and design for multiple use cycles [13], [15]. Additionally, competencies such as cradle-to-cradle [22], [25], eco-design [23], life cycle analysis [13], [14], [23], waste management [24] and zero waste [25] are considered relevant for understanding the CE concepts.

3.2 Identifying technical competencies with a qualitative questionnaire

One of the central questions posed in the questionnaire was whether the respondent believed new graduates possessed the necessary competencies for sustainable and circular practices in the AEC sector. It is notably significant that none of the 11 respondents answered affirmatively to this question. Specifically, six respondents replied negatively, indicating that new graduates lack expertise in this area, while five respondents stated that they do not have enough information to answer this question. Among the 5 respondents who expressed uncertainty in providing an answer, Respondent 9 highlighted the need for a balanced approach between theoretical knowledge and collaboration with experienced colleagues to gain practical wisdom and flexibility in decision-making. This respondent appears to be sceptical about providing students only with academic theory and stated:

> *I think it is easy to end up in the ditch if you only follow academic theory and firmly pursue this line; you need to have intuition, understanding and flexible thinking in practice.*

In contrast, Respondent 11 expressed optimism about the mindset of graduates stating:

> *I feel that recent graduates have a more open mind about the issue and don't have the input* "it doesn't work" *in all forums.*

Table 3. List of CE-related technical competencies from the literature study

Clusters	Competencies
Environment and impacts	Groundwater; Stormwater; Management of environmental flows; Emerging and future water quality issues; Environmental impact assessment; History of sustainability discourse; Impact on carbon accounting at portfolio level;

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	Specific 'green' competencies; Sustainability assessment and benefits of environmental assessment; Sustainability rating system and criteria.
Governance and legislation	Certification
Financial consideration	Capital cost; Company value; Economic advantages and disadvantages; Financing and capital structure; Investments and risk management; Cost accounting of sustainability optimized dismantling in a quantitative manner
CE concepts, strategies and challenges	CE geographical and technical insight; CE social impact; Challenges for CE systems in the real estate context; Circular business models; CE strategies and principles; Circular impact assessment; Circular planning; Circular use and operation; Circularity assessment; Closed loop systems of the future; Cradle to Cradle; Upcycling
Development approaches	Re-development of existing buildings; Transformation of existing structures; Restoration of the built environment
Procurement	Procurement of construction and FM services.
Processes	Quality assurance of construction and FM services; Expertise with quality systems; Logistic knowledge; Project management during re-development; Materials purchasing.
Design approaches	Building as layered model; Eco-design; Circular building; CE design options; Design for multiple use cycles; Design for recovery; Water sensitive urban design; Wetland design; Sustainability planning.
Methods and Tools	Data analysis; Modelling and simulation techniques; Life cycle analysis; Life cycle cost: Social life cycle assessment; 3D printing of building components; Methodological approaches for environmental assessment.
Technology	Knowledge of electricity (installation and operation).
Products, materials and components	Efficient use of materials; Development of functional physicochemical of (biobased) building blocks for different applications and sectors; Material impact quantification; Sustainable and regenerative materials; The Madaster vision; Theory of sustainable production; Transformative production frameworks; Urban Mining; Material selection.
Energy use	Thermal energy systems; Integration of renewable energy; Energy minimization; Energy efficient construction; Energy management; Energy quantification and monitoring; Energy costs and trade; Non-renewable technologies; Building skills; Buildings carbon assessment.
Waste	Cost accounting of waste avoidance; Recycling and recyclables management methods; Waste processes, Waste management systems, Waste technologies, Waste minimization; Aquifer storage and recovery

The subsequent question aimed at creating a list of specific competencies considered essential for professionals working in the same role as the respondents to contribute to CE practices. Table 4 displays all CE-related technical competencies listed by the respondents. In total, the respondents provided a list of 70 competencies. The most frequently mentioned competency was *reusability* cited by five different respondents. Following closely were *Material proprieties and qualities* each proposed by four respondents. Other frequently mentioned competencies included cost analysis, recyclability and construction technology mentioned three times each. Additionally, competencies such as circular concepts and understanding, logistic, time schedule, life cycle assessment (LCA), reused products and materials, and material lifespan were mentioned twice. To note is that the cluster related to Energy use competencies remained unaddressed.

Respondents were also asked for recommendations to better align HEI curricula with competencies required in the circular AEC sector. Six respondents believe that is necessary to foster collaboration between HEIs and sector organizations as much as connections with the AEC sector for practical experience. For example, respondent 4 believes, that students need to:

Get closer to the sector to get the knowledge that is growing today both with private and public actors and networks.

Other key recommendations include integrating applied technology and providing comprehensive education on CE opportunities. Moreover, respondents emphasized the importance of mindset shifts towards reused materials, early exposure to industry developments, and a balance between theoretical learning and practical experience, as already expressed by respondent 9. Overall, the respondents underline the importance of hands-on learning and interdisciplinary approaches to prepare students for a circular AEC sector.

Table 4. List of CE-related technical competencies from the questionnaire

Clusters	Competencies
Environment and impacts	Basic environment competence; CO_2 impact; Sustainability impact; Transport environmental impact; Soil contamination migration conditions; Weighing of different environmental aspects.
Governance and legislation	Authority requirements; Building legislation and regulations; CE marking; EU standards; Legal requirements understanding; Policies and directives: CSRD, EU's Green Deal, EU taxonomy, etc.
Financial consideration	Basic of economics; Cost analysis; Finance and VAT.
CE concepts, strategies and challenges	Barriers to CE implementation; Basic of CE; CE concepts and strategies; Long-lived, flexible, efficient and demountable constructions; Recyclability; Reusability; Reused products and materials.
Development approaches	Adaptive reuse; Building extension; building renovation; Conservation.
Procurement	Contracting forms in the linear economy.
Processes	From linear to environmentally friendly building process; Logistic; Time schedule.
Design approaches	Design for adaptability; Circular design for products and services; Data-driven approach to architecture; Computational design; Parametric design.
Methods and Tools	BIM; Dynamo; Database analysis (SQL); Grasshopper; LCA; Life cycle management; Reused material retrieving; Python programming; Reused material retrieving.
Technology	Construction techniques and technology; Construction techniques history; Circular construction; Long-term exposure scenarios. Post-treatment of soil contamination in situ during ongoing exploitation
Products, materials and components	Material and products circularity; Material flows in the linear economy; Materials and products climate impact; Material history/characteristics according to period of production; Material lifespan; Material properties; Material reusability; Material technology; Material quality; Natural Resource and resource utilization.
Energy use	-
Waste	Waste hierarchy; Waste flows proprieties; Construction waste recycling.

3.3 Course syllabi study

The first part of the course syllabi quantitative analysis involved the *term recurrency* approach made in NVivo. A total of 14,380 terms, each with a length of five letters or more, were considered. While *hållbar* (Swedish for sustainable) and *sustainable* ranked 249th and 355th, respectively, among the most frequently occurring words, the term *circular* made its first appearance at 3,218th place. More exactly the term and its variations, whether in English or Swedish, appear 20 times, but only six times it is used to refer to CE or its strategies and processes. Nevertheless, the *term recurrency* approach has been considered inappropriate to retrieve all the competencies as listed from the literature especially because part of the syllabi is in English and part in Swedish. Therefore, the text search approach has been used in NVivo to facilitate the categorization.

The qualitative content analysis of the syllabi reveals that none of the five Swedish HEIs offer a dedicated course focusing on CE. However, certain courses stand out for explicitly covering CE concepts, strategies, and challenges. Among these courses, there are *TEK940 - Sustainability transitions* and *ENM165 - Environmental and resource analysis for a sustainable built environment* at Chalmers and *AF1301 - Building materials, basic course* at KTH. Moreover, two courses at LTH introduce circular processes (*VBEA10 – VBEA35*) and one course at KTH on natural resources theory (*AL1301*) gives space for the introduction of CE concepts related to natural resources. Among the courses offered at Chalmers University the *MMS270 – Energy technology* course also introduces circularity as an approach that students should be able to evaluate. At LTU *A0013B - Waste Science and Technology* is about the waste stream in society and sustainable waste management, while at JU the course *THPN10 - Sustainable Product Realization* focuses on circular systems, circular business models and approaches to industrial product manufacturing.

Rather than focusing on a single HEI and instead looking at the combined offer from the five Swedish HEIs, both the quantitative and qualitative analysis showed that a total of 13 courses have already integrated CE concepts, strategies or tools in their education. 49 courses have some topics related to CE principles implementation and thus can be considered relevant for further development of these aspects. The majority of the courses (264) show a basic connection with sustainability aspects and potential relations with CE implementation in the AEC sector. Finally, 100 courses do not have any correlation with CE education. Clusters with the highest number of courses are *technology* with 95 courses, *products, materials and components* with 87 courses and *design approaches* with 73 courses. Whereas the clusters of *development approaches* and *waste* have 11 courses each, and the cluster on *procurement* has six courses. The cluster with the least number of courses is *CE concepts, strategies and challenges* cluster with only three courses.

Looking at the number of integrated and related courses within each cluster, *products, materials and components* is the one with the highest score (18), followed by *design approaches* and *environment and impacts* with respectively 16 and 14 courses. Figure 1 summarises the distribution of the courses according to the CE-related clusters.

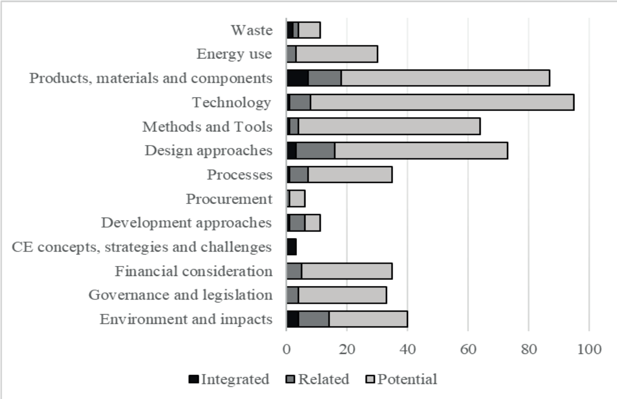

Figure 1. Course distribution per cluster

Considering that some courses addressed multiple clusters the number of courses shown in Figure 1 does not represent the total amount. On the other hand, Figure 2, displays the actual number of courses based on the level of integration of CE according to this scale: integrated, related, potential and with no connection with CE.

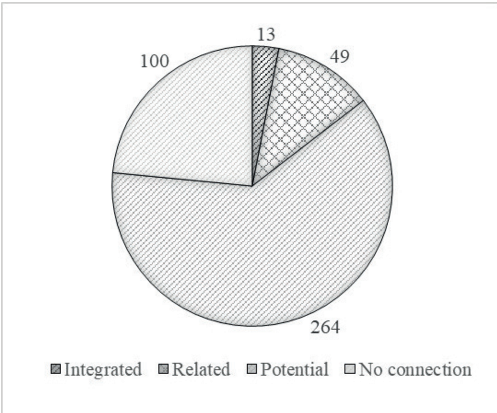

Figure 2. Level of CE integration in the courses

It should be noted that the data depicted in Figures 1 and 2 may not be entirely comprehensive due to methodological limitations.

4. Discussion

Achieving the transition of the AEC sector to circularity is not an easy task given the multitude of CE concepts and strategies related to each phase of the building process and the difficulty in identifying the parameters of the body of knowledge to transfer these concepts from theory to practice [26].

The literature search has provided a plethora of competencies, yet only technical competencies have been taken into account and assigned to a thematic area defined by the authors. The identification of necessary competencies to implement in the courses has been subsequently compared with those provided by the respondents. Interestingly, from the respondents' answers, in contrast to the literature, issues related to energy efficiency are not mentioned. Conversely, competencies regarding reusability and a better understanding of the materials and components are prioritised. Moreover, topics such as deconstruction or tools such as GIS, are not presented either in the literature or by the respondents.

The analysis of the syllabi course content has confirmed the lack of competencies regarding CE taught at HEIs, which was also highlighted by the respondents. An interesting finding is that, based on responses from the questionnaire, new graduates should acquire further competencies in both material proprieties and qualities, as well as construction technology. However, the results of this study, indicate that courses dedicated to these topics already constitute the largest portion of student education regarding CE. Among the 13 courses whose content already integrated CE-related aspects, the most frequent topics are environmental impact and lifecycle perspective, whereas crucial concepts and strategies such as climate impact, reuse, adaptation, LCA, deconstruction, recycling and waste are rarely considered. A further implementation of specific CE strategies and tools in those courses seems to be necessary. Similarly, there is a great opportunity to include those aspects in the 49 courses which are based on achieving sustainability knowledge, with CE-related competencies. Additionally, 264 courses have the potential to contribute to CE learning outcomes. It should be emphasized that sustainability aspects are constantly mentioned in HEI programs, and this explains the high position of the term sustainability in the rank list. However, sustainability has not been analysed, rather considered a necessary condition for the AEC sector, and most of the 264 courses refer to different aspects of sustainability.

The building process consists of several phases and includes various roles which need to be analysed with a holistic approach to concretely contribute to its transformation towards CE. Merely including circular topics in course content is insufficient to achieve this transformation, whereas the students need to adopt system thinking skills and be familiar with societal and economic aspects [27]. Therefore, it seems crucial to integrate CE concepts, strategies and tools at the program level, rather than limiting those aspects to specialist compulsory courses. The need for holistic knowledge is reinforced by the perspective of Respondent 1, who emphasizes that the sector's transition to CE cannot rely solely on environmental and circular specialists. Instead:

> *Purchasing managers, Calculations specialists, Designers, Constructors, Communicators, CEOs and managers, etc. need to develop their competencies and integrate these into their work* (Respondent 1)

Both literature and the respondents recommend engaging students with field trips [25], participatory workshops [25], [28] and living laboratories [5], [29], [30], [31]. Furthermore, both also highlighted the importance of collaborating with practitioners to increase student engagement by taking an active role and decrease the perception that the AEC sector has of new graduates as:

> *naive and [who] see everything in black or white, [and] have difficulty with nuances and contrasting different aspects* (Respondent 8).

This is in line with Kopnina [32] who suggests equipping students with the intellectual tools to discern the disparities between theoretical ideals and practical realities.

5. Conclusions

5.1 Conclusions
Shifting from a linear to a circular AEC sector involves a transformation of processes and roles which, consequently, leads to the need to integrate new competencies and skills into current educational programs.

This paper has tried to dig into the level of integration of CE competencies in the bachelor-level programs of five Swedish HEIs. To understand if the new graduates receive the requested circular technical competencies, the course syllabi were analysed and categorized into 13 clusters of thematic areas. The competencies searched came from a literature review and a questionnaire. Due to the qualitative nature of the questionnaire, this study might have overlooked technical competencies relevant to other professional roles of the value chain.

The results have shown that the number of courses in which CE is presented and discussed is still limited since it represents only 3% of the total courses offered by the five Swedish HEIs. However, there are opportunities for further implementation of CE concepts, strategies, and tools; since many courses have CE-related aspects and most have the potential to contribute to CE aspects.

In conclusion, it is important to highlight that while technical competencies are essential, they alone might not adequately equip graduates to tackle the complex problems within the circular transition.

5.2 Future studies
To better prepare students for leadership roles in the circular AEC sector future studies should focus not only on technical competencies but look on the pedagogical approaches used to develop useful skills for this transition. Moreover, it would be valuable to conduct interviews with program leaders to gain deeper insight into the level of integration of CE concepts and content within the architecture, civil engineering, real estate and construction management faculties. Program leaders can indeed offer valuable perspectives on the effectiveness and challenges of integrating CE concepts into courses.

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Paper IV

Exploring the combined impact of Generative Design and Reuse-centered Design.

Purpose: Digitalization and circularity are core elements to achieve a sustainable development and call for innovation in the building sector. Although reusing building parts is recognized as a viable strategy, it requires adapted design approaches. Generative design (GD) could assist designers in elaborating suitable solutions using the existing building stock as well as in designing for future reuse and seems therefore to support a Reuse-Centered Design (RCD). This paper aims to explore implications and potential tensions of implementing GD for RCD, as perceived by designers in the building sector.

Design/methodology/approach: An exploratory approach was chosen to build the foundation for future in-depth research. During a series of workshops conducted in four Nordic countries, the implications of using GD for RCD were discussed. The findings were analyzed using a thematic approach, and a paradox perspective was then applied to discuss organizational tensions emerging when applying GD for RCD.

Findings: The study identified several tensions between design as a process and design as a product, arguing that these tensions are further intensified by the combination of GD and current pressure for reuse. By exploring practitioners' perceptions of this ongoing transition, the paper provides theoretical contributions as well as several implications for practitioners. Additionally, the paper stresses the importance of nurturing collaboration between researchers and practitioners who focus on the design process and those who prioritize the design outcome when using GD for RCD.

Originality: The combined impacts of two ongoing transitions regarding design in the building sector have been explored using a paradox perspective.

Keywords: circularity; building; reuse; design; generative design; paradox; tensions; transition

Introduction

In recent years, two topics extensively debated within the building sector are circular economy and digitalization. Circular Economy (CE) is considered a way of contributing to sustainable development and has become a topic of serious debate among practitioners in the sector, policymakers, and academia. Indeed, developers, designers and other actors are encouraged to adopt CE strategies for a sustainable development (European Commission, 2020; UNEP, 2020; James and Mitchell, 2021; Council directive 2024/1275, 2024), which means that the operation, maintenance, and end-of-life phases of a building should be considered during the design phase (Bekkering *et al*., 2021).

A circular approach is adopted when operating one or several principles of the waste hierarchy, often referred to as "Rs", e.g., Reduce, Reuse, Recycle (Cramer, 2017; Campbell-Johnston *et al.*, 2020; Johansen and Rönnbäck, 2021). The common objective is to replace the linear model of 'take-make-[use]-dispose' with the circular model where resources are used repeatedly (Joensuu *et al*., 2020). Among the different principles mentioned above, the possibility of reusing building parts at the end-of-life phase of a building is at the center of this study, being a feasible and crucial aspect of circularity, when the adaptive reuse of the whole building is not possible.

Buildings, however, are usually designed for a lifetime of 50 years or more (Brand, 1995; Clements-Croome, 2020; Andersen and Negendahl, 2023), which, together with their often project-specific and unique features, aggravate the reuse of existing building parts. Therefore, it seems feasible to revise existing design principles (Bekkering *et al*. 2021), for example by creatively reusing building parts and introducing design for disassembly in new building projects to enable future reuse, as well as adopting digital design tools in novel ways in these two endeavors. Hence, shifting from a linear to a circular design process requires new expertise and new roles for designers (*ibid*), as requirements on future reuse are strengthened and the creative process transforms from "anything can be designed in any shape and size" to "what can be designed with the building parts available"? This shift might substantially change the design process in terms of tempo and creative work, but also the product and outcomes in terms of technology development, and eventually generate a new architectural language (Schumacher, 2019).

Digitalization, specifically Generative Design (GD), could be the catalyst to achieve the desired shift, by aiding the actors involved in the design phase to find different and even unexpected ways to reuse existing building parts as well as develop concepts that facilitate future reuse. Although multiple digital tools have assisted designers in the past decades after the advent of CAD and BIM, the digital revolution (Panait, 2012, Soulikias and Cucuzzella, 2021, Nabiyev *et al*., 2022, Zatsarinnaya *et al*., 2023) is an ongoing process adopting emerging technologies, and is perceived by some people as a threat to traditional architecture (Nabiyev *et al*., 2022). Identifying practicable designs that fulfil the set of requirements including aspects of reuse could be accomplished by GD, especially in the early phases by quickly obtaining multiple alternative solutions that take specified conditions into account (Loyola, 2018).

Thus, it seems as if reuse-centred design (RCD) can be enhanced by using GD in the design process; however, as described above, both RCD and GD impose changes for people working in the building sector in general and designers in particular. As highlighted by for example, Lewis (2000), Smith and Lewis, (2011), Weick (1979), changes often entail tensions between old and new ways of working as well as between opposing interpretations of new routines and principles. This paper therefore aims to explore implications and potential tensions of implementing GD for RCD, as perceived by actors involved in the design phase of buildings.

Data were collected by means of a series of workshops with practitioners and researchers, followed by identification of thematic areas and tensions relating to design as a process and design as a product. The premise here is that the findings can act as a springboard to future research that explores the identified tensions through, for example, case studies.

Theoretical framework

Digital transformation is considered crucial to the transition to the CE, as stated in "Europe's Digital Decade" (2021), with digital technologies enabling CE in many ways (Çetin *et al*., 2021). Furthermore, design innovation could create a connected digital ecosystem where interactive systems rather than static objects are designed and driven by technology on three levels: *process* (better informed buildings), *product* or outcome (better performing buildings), and *operational* (better managed buildings) (Lombardi *et al*., 2017). This paper focuses on the first two levels from an RCD perspective.

Design viewed as process and product

Building design processes are interdisciplinary and require collaboration among many different practitioners, who are also involved in decision-making (Panella and Ailin, 2023; Loyola, 2018; Sariyildiz *et al*., 2000). Functional, formal, and technical requirements need to be fulfilled in a design process that results in a design outcome (Sariyildiz *et al.*, 2000). The architectural representation of a design as a product is characterized by duality: on the one hand, the virtual object and the digital environment (i.e., drawings and the 3D model); on the other hand, the physical object and the materiality (the real building) (Loyola, 2018; Picon, 2004; Sariyildiz *et al.,* 2000). Knowing how to merge materials into components to construct a whole is at the core of each design (Bekkering *et al*., 2021), more so when applying RCD, where the level of complexity increases due to the availability of materials and components to realise the design and to "build designs as future sources for components" (*ibid*). Architectural processes can be improved by digital technologies (Khakzand and Mozaffar, 2007), and it is suggested by Sheil *et al*. (2020) that the creative aspect might benefit from a collaboration between designer and computer, transforming the early design process. Remarkably, a digitally driven process (Kolarevic, 2001; Schnabel, 2015; Schumacher, 2019) might originate a new architectural language defined as *parametricism* by Schumacher (2019) and, therefore, new outcomes, which are likewise expected in RCD where form follows availability (Josefsson and Thuvander, 2020).

Reuse strategies

When discussing RCD, a primary distinction should be made between Design for Adaptability (DfA), and Design for Disassembly (DfD) (Lisco and Aulin, 2023). DfA occurs when the whole building changes its function, with minor intervention, and is out of the scope of this study. DfD comprises Design with Reuse (DwR) and Design for Reuse (DfR) (Lisco, 2022). DwR addresses the problem immediately by means of integrating building parts from the existing building stock into new building projects. In DfR, the new building is designed to facilitate future reuse by comprising reusable building parts and reversible connectors. The role of reuse, as a promising and viable solution to significantly reduce the environmental footprint while overcoming obstacles (Iacovidou and Purnell, 2016; Bertin *et al*., 2020; Rakhshan *et al*., 2020; Anastasiades *et al*., 2021), seems to be acknowledged. Unfortunately, existing buildings are constructed with many unique features, limiting the potential for complete reusability (Minunno *et al*., 2018; Rakhshan *et al*., 2020; Bekkering *et al.*, 2021). Hence, a necessary condition to facilitate reuse at the end of life of a building is a major change in the way buildings are conceived and designed. As mentioned above, digitalization could enhance RCD, and particularly a GD approach could guide and assist the transition to a circular building design, by providing unexpected alternatives. Nevertheless, although several recent studies investigate different aspects linked to reuse strategies in building design, (e.g. Guy *et al*.; 2008; Gorgolewski, 2019; Josefsson and Thuvander; 2020; Rakhshan *et al*., 2020; Çetin *et al*., 2021; Chiletto *et al*., 2024; Wöhler *et al*., 2024), few studies investigate the role of digital tools in reuse efforts to enable a circular built environment. Most of them focus on the reuse of structures and/or on BIM applications (Hradil *et al*., 2014; Bertin *et al*., 2020; Çetin *et al*., 2021; Psilovikos, 2023), while there seem to be no studies exploring the implications of applying GD tools addressing the reuse of the building parts, i.e. RCD.

Generative design

Defining GD univocally is challenging, and its definition depends on the field in which it is applied. Nevertheless, some recent studies provide a similar interpretation of GD, being an iterative process that generates designs by means of rules and algorithms (Agkathidis, 2015; Abrishami *et al*., 2020; Buonamici *et al*., 2020; Caetano *et al*., 2020). Generative computational tools are prominent in the development of digital design in architecture (Schumacher, 2019). Hence, as argued by Picon in Caetano *et al*. (2020), it is not a matter of whether computational design is good or bad for architecture, but rather how these technologies reshape the design process, collaboration, and the architectural profession. The increased use of GD in recent years raises concerns regarding the automation of the design process, implying that the computer might take over tasks previously performed by a designer. According to Saadi and Yang (2023), the human designer and algorithmic computation can coexist to provide improved outcomes compared to those created by either means.

GD has been applied to solve several architectural and engineering issues in the last two decades (Casini, 2022); for example, free-form building shapes and daylight optimization, as well as energy and thermal efficiency. Nevertheless, there seems to be a lack of research on applying GD principles to enhance reuse specifically. It thus seems important to increase the understanding of potential problems and tensions of such a transition as perceived by practitioners.

Organizational tensions and paradoxes

There are many different types of organizational tensions, categorized meritoriously by Smith and Lewis (2011). Many seem paradoxical in the sense that the interrelated elements appear logical when studied separately, but impossible to combine (Lewis, 2000). Indeed, several researchers highlight the benefits of applying a paradox perspective to organizational tensions by, for example, promoting holistic views (Clegg *et al*., 2002), and arguing for focus on both elements rather than on either one of them (Beech *et al*., 2004; Smith *et al*., 2010; Lewis and Smith, 2014). Focus on one element often leads to vicious cycles (Lewis, 2000; Smith and Lewis, 2011), whereas a both/and-approach can nurture virtuous cycles where the two elements provide strength to each other.

One specific tension is between short-term efficiency and long-term innovation (e.g., Benner and Tushman, 2003; Andriopoulos and Lewis, 2010). Both tasks seem important for any organization, but hard to combine considering resources and managerial focus, hence the tension has paradoxical features. Short-term efficiency is traditionally referred to as exploitation of existing knowledge, whereas long-term innovation demands exploration of new ideas creating new knowledge (March 1991; O'Reilly III and Tushman, 2013). The ability to combine exploitation and exploration is often called *organizational ambidexterity* (Duncan, 1976), and it is highlighted by Eriksson (2013), which is regarded as particularly challenging in project-based organizations due to decentralization and strong project cultures among other factors. Moreover, Eriksson *et al*. (2019) argue that proactive development enables long-term innovation much better than reactive problem-solving since the latter most often creates highly context-specific solutions.

Paradoxically, during the design process, a designer works to avoid paradoxes. The goal is to manage conflicting issues and creatively redefine a paradoxical situation in order to solve it (Dorst, 2006). This is true in traditional design pursuing a linear process. This study therefore investigates this paradox when applying GD to enhance RCD.

Method

An exploratory study was conducted aimed at collecting overarching insights to build the foundation for future in-depth research (Robson and McCartan, 2016; Elman *et al*., 2020). Rather than seeking to explain a phenomenon, the main goal was to understand more about how practitioners perceive the two aforementioned ongoing transitions. Due to the exploratory nature of the study, workshops were chosen as a method to collect data and considered particularly useful when investigating emerging domains, as argued by Ørngreen and Levinsen (2017).

Data collection and sample

Since the aim was to gain an understanding of the current views among practitioners involved in the design of buildings, an invitation to participate in the study was sent to a wide range of architectural and project firms. The main requirement for the participants was to be knowledgeable or at least familiar with the GD tools and/or RCD. All in all, 55 signed up but in the end 31 attended (23 practicing architects, 5 other practitioners in the field and 3 researchers in the field). The empirical data were gathered in four different workshops held in Sweden, Finland, Denmark, and Norway between August and November 2023. The participants were encouraged to share their views, and jointly elaborate on emerging ideas and concepts, with the two-fold aim to provide useful insights and to co-produce valid research data (Shaw, 2006; Ørngreen and Levinsen, 2017; Thoring *et al*., 2020).

Each workshop comprised four blocks with different objectives and methods to foster reflections and discussions, as well as to document the results. To encourage openness, sessions were not recorded, and participants were assured all data would be used anonymously (Alvesson, 2011). Flipcharts and sticky notes were transcribed and stored to preserve important information (Baxter and Jack, 2008).

Block 1 – Introduction to the Generative Design concept

The aim was to have an initial discussion in plenum on the topic of GD to achieve a common view on terminology and some basic principles. Feedback and conclusions were written on a flipchart by the moderator and elaborated by the participants.

Block 2 – How can Generative Design facilitate RCD?

The aim was to explain briefly the different design strategies linked to RCD, and then let the participants elaborate in smaller groups on how GD could facilitate such efforts. The results were presented and discussed in plenum, with the moderator adding further ideas that arose.

Block 3 – The impact on the design process and roles when introducing GD in RCD

Participants were asked to brainstorm individually using sticky notes on opportunities and threats concerning the architect's role and the design process when introducing GD to enhance reuse. The notes were collected, and the moderator produced a tentative structure/consolidation based on themes, which was adjusted and further refined in a discussion in plenum.

Block 4 – Concluding reflections

At the end of each workshop, a quick around-the-table discussion was conducted, where the moderator took notes on flipcharts whenever something deemed important or interesting was mentioned.

Data Analysis

Although some analysis was undertaken during each workshop, the main part of the analysis was afterwards using a thematic approach to identify and group frequently expressed views (Eisenhardt, 1989), and statements that were deemed particularly relevant to the underlying research aim (Dyer and Wilkins, 1991). The data were then analyzed through several additional rounds with the specific aim of identifying contradicting views, representing tensions between separate, logical but opposing views on related matters (Lewis, 2000).

Findings

In this section, the empirical findings are first presented in terms of identified themes and then in terms of tensions that all relate to both GD and RCD.

Themes identified

The results from the workshops are clustered in themes, comprising both opportunities and threats as expressed by the participants in the workshops. The eight themes are presented in Table 1.
(Table1here)

Organizational tensions derived

Based on the information in Table 1, 11 organizational tensions were derived. The elements A and B of each tension (T1-T11) are described below, where T1-T6 relate to Process vs Process (see Table 2), while T7-T11 are Process vs Product (see Table 3).

During all four workshops, issues related to the creative process were discussed at length and are present in five out of six tensions within the Process vs Process category.

T1: *Creativity and reuse level* and T2: *Less or more creativity* relate to co-existing perceptions of GD for RCD as diminishing creativity as well as a source of creativity in reuse. Letting the software suggest design solutions could reduce the creative aspect in terms of the act of creating something. However, other participants argued that obtaining more options, choosing from a vast set of building parts could enhance the reusability level of the building sector. This is aptly demonstrated by the following quotes: *"job becomes boring, with the loss of creativity"* versus "*easier creative phase from concept to project*". One practitioner stated that designers might have "*more time to think [about] the whole design if reuse of building parts can be assisted with GD*", and another participant highlighted greater collaboration between different competencies as an opportunity.

T3: *More creativity and new role*, emerges from the increased engagement of more and diverse team members (B in T2), and the contrasting view that it might be a threat to the traditional role and responsibilities during the design phase, as stated by most of the participants, even though agreeing that "*new skills for the architect*" are necessary.

T4: *New role: threat or opportunity* concerns the double-sided nature of the new role of the designer dealing with GD and RCD. It seems inevitable that designers are facing an era of progressive change interpreted either as a threat to the traditional role, or to achieve the transition to a new role. In each workshop, education was mentioned as a key enabler in this shift, to "*re-train architects augmented by AI*". In one workshop, possible change was foreseen in the "*type of person who is drawn to the profession*".

T5 and T6 differ slightly in element B, while having element A in common, as also shown by the title: *Tempo and less creativity* and *Tempo and more creativity*. When accelerating the production of multiple design outputs, the time for evaluating the solutions and giving space to reflections and creativity could either: decrease, because expectations of a shorter schedule are expected/required; or increase, because those expectations are not compelling. T5 could be summarized by the concerns expressed by some participants that a faster design process could create "*pressure to deliver even quicker*" and the designer could be "*burdened with greater output demands 'because we can [do it]'*". By contrast, others stated that, with the high tempo offered by GD tools, designers could get "*to work less*", or "*free up time to make creative decisions".*
(Table2here)

T7 is still about tempo but linked to the quality of the design as a product: *Tempo and less quality*. Having a faster design process as the main goal could lead to overlooking the need for long-term quality in buildings. At the same time, focusing solely on the long-term quality of the end product could extend the design process over time. As claimed in one workshop, "*competition keeps squeezing away the time saved given by GD as happened with CAD and BIM*", even though saving time during the design process could give the opportunity to focus on "*things that matter*".

T8: "*More functionality and less quality"* highlights the risk of a lack of quality assurance of the buildings, with the risk of "*losing track of the whole*", when an increased number of design outputs from a functional perspective is provided.

T9: *More functionality and less aesthetic value*, differs from the eighth tension merely for element B which considers the aesthetics of the design output. The many options and alternatives arising when using GD for RCD might take focus away from aesthetics, and produce a "*generic design*", or "*homogeneous design solutions*".

T10: *Larger building stock and standardization*, highlights an increased level of standardization and an enhanced building stock over time when designing for reuse and applying GD, which could also have a possible negative impact on the design output, defined as a "*Cookie-cutter architecture*". In one workshop, it was noted that "*standardized components limit the possibilities of variations*" and could result in "*boring architecture*" as noted in another. In contrast, a high level of standardization, as required i.e. in modular construction while promoting GD as early design strategy (Zheng *et al*., 2024), could "*enable architects to design buildings that are easier to change and adapt to future needs*", and provide "*new aesthetics*", and "*over time give new opportunities, new standardized systems*", as argued by one participant.

T11: *Less or more mistakes*, considers on the one hand the possible use of GD as a tool to avoid mistakes in RCD, due to its features as "*recognizing threats, possibilities, values*", and "*observe/analyze and verify/recheck the quality of desired outcome*", as discussed in one workshop. On the other hand, if the source is fed with "*distorted data*" and for reason of the high level of standardization required, there is a "*great risk of very large design errors*" which "*can propagate to a huge scale".*
(Table3here)

Discussion

The identified themes and tensions resemble phenomena often arising in traditional design practice, although deviate to some degree. Quality and creativity emerge as two

main themes featured in six out of 11 tensions. The tensions are related to the different themes and are often nested as shown in Figure 1.
(Figure1here)

Concerns about diminished long-term quality in a building, as a result of insufficient time for reflection caused by the high tempo (T7-B) and high number of design solutions (T8-B) provided by GD tools (Soulikias and Cucuzzella, 2021), might seem comparable to similar concerns in traditional design practice.

Creativity seems to be a sensitive topic highlighted in three of the four workshops strictly related to GD for RCD. Despite some literature considering the aid of digital tools beneficial for creativity (Bekkering *et al*., 2021; Buccellato *et al*., 2016; Erioli, 2020; Nabiyev, 2022), many of the participants voiced their concerns about the impact that digitalization (Soulikias and Cucuzzella, 2021), particularly GD for RCD, might have on creative processes (T2-A). Conversely, some participants believe that such approaches might involve more design specialists during the conceptual phase of design, making room for reflection and creativity (T3-A, T2-B and T6-B) and, thereby, augmenting the level of reuse in design as confirmed by, for example, Bekkering *et al*. (2021), Çetin *et al*. (2021) and van Stijn and Gruis (2020).

Another concern is the possibly significant change of the traditional role of designers expressed in T3-B and T4-A, also supported by some literature (Gorgolewski, 2019; Soulikias and Cucuzzella, 2021). Even so, this development of roles might entail the involvement of more people in creative work (T3-A, T2-B and T4-B), as confirmed by Bekkering *et al*. (2021), Lombardi *et al*. (2017) and A. Nabiyev *et al*., (2022). This tension between 'building upon the past' and 'destroying the past' to bring about innovative ways of working, represents a classic organizational tension highlighted by, for example, March (1991) and Smith and Lewis (2011). This paper suggests that the combined pressures for RCD and GD intensify this tension, where both mean valuable opportunities from a societal perspective, but at the same time drive change at a pace that might impose real and potential risks for society and different actors.

T5 and T6 present two sides of the same issue and using GD for RCD can thus increase the tempo and pace, and subsequently decrease the time available for creativity and quality assurance, should a shortened schedule be expected/required (T5). However, it could instead increase the time available for reflection and creativity (T6), as highlighted by Buccellato *et al*., (2016).

A further consequence of significant use of GD for RCD might be, according to some practitioners, a lower level of aesthetics (T9), due to the way reusable elements are combined, which in turn might generate a new aesthetic value (Gorgolewski, 2019; Kołata and Zierke, 2021), Comparable issues are confirmed by Gorgolewski (2019) and Josefsson and Thuvander (2020).

Directly related to aesthetics is standardization (T10), which might occur since DfD requires higher standards and demountable building parts. Practitioners are concerned that DfR, while providing new opportunities and buildings easily adaptable to the changing needs of future occupants, might also limit the possibilities of variation and a uniform architecture, with a *"McDonaldsification"* effect, as noted by one participant.

Last, T11 brings up another important research topic that goes beyond the scope of this study. When acknowledging the need to store building data, a question arose about the proper handling of data linked to new buildings designed for reuse which is broadly supported by the literature (Bertin *et al*., 2020; Buccellato. et al., 2016; Çetin *et al*., 2021; Lombardi *et al*., 2017),. Although digital tools might prevent mistakes and errors, distorted data might affect many other projects utilizing the same data and thus produce repetitive errors on a large scale within the sector.

Zooming out and applying holistic views of the findings (Clegg *et al.*, 2002) sheds light on the overarching tension between the focus on design as a process and design as a product. Although one the goals of the design process is the building as an outcome, T7-T11 show that it is necessary to continuously reflect on both aspects of design rather than one or the other (Beech *et al*. 2004, Smith *et al*. 2010, Lewis and Smith 2014), to avoid vicious cycles (Lewis 2000, Smith and Lewis, 2011). For instance, a one-sided focus on using GD for RCD to shorten the design process and ensure that all types of functional requirements are considered might reduce long-term quality as well as the aesthetics of the building stock. Similarly, too strong a focus on standardizing building parts to facilitate the use of GD for RCD can, over time, create the risk of repetitive errors. This would happen when it becomes clear at a later stage that one or several aspects were not considered in the design of standardized building parts. At the same time, it seems logical not to "reinvent the wheel" in every project, thus calling for standardization on a certain level. Hence, this tension has paradoxical features, and holistic approaches are therefore needed to avoid suboptimizing the outcome over time.

Moreover, DwR is, in many aspects, an exploitative approach (March, 1991; O'Reilly III and Tushman, 2013) to enable the short-term creation of new buildings, using building parts from the existing building stock with minor or no change in terms of technology. DfR is accordingly a more explorative approach (*ibid*) to address CE in the building sector over the long term, requiring a higher level of development of technology as well as processes. In many aspects, DwR as of today can be viewed as a reactive (but necessary) measure restricted by context specifics, whereas DfR enhances proactive explorative innovation over time (Eriksson *et al*., 2019).

It might be challenging to apply GD for DwR, due to a lack of digital inventory and because of several constraints (e.g., unique features, non-standard connectors etc.). On the contrary, given that DfR implies a higher level of standardization and modularization, a GD approach might indeed enhance the level of reuse by assisting designers and stakeholders involved in finding the most appropriate solution. Consequently, the explorative aspect of the process should be prioritized where DfR becomes the norm in new projects. Over time that would lead to a substantial base of buildings prepared for disassembly and future reuse. In this scenario, DwR will eventually become the same as DfR, when the exploitation aspect will be saturated and DfR will be the default design approach to achieve sustainable development. Until then, the building sector needs to work simultaneously with DfR and with reuse of existing building components despite the inherent barriers. Hence, all actors in the building sector need to elaborate and discuss jointly how to achieve *organizational ambidexterity* (Duncan, 1976) over time, to use GD for short-term DwR and long-term DfR simultaneously.

Conclusions

Sustainable development, enabled by digitalization and reuse, requires innovation. Effective innovation involves managing tensions "from competing demands" (Gaim, 2018). Paradoxes are inherent in the design professions (Becher, 1980; Raisbeck, 2011), as designers address "potentially conflicting considerations" (Dorst, 2006). While prior studies highlight tensions in relation to the architect's identity (Ahuja, *et al*., 2017), and between creativity and commerce (Bos *et al*., 2018), research into tensions in GD for

RCD is limited. This paper uses a paradox perspective to explore and discuss organizational tensions emerging when applying GD to RCD, offering theoretical contributions as well as highlighting several implications for practitioners involved in the design phase.

Theoretical contributions

Prior research on organizational tensions in general, and a paradox perspective in particular, provides important insights into the ongoing transition from a linear approach to the design and construction of buildings to a circular approach. In transitions, there are always tensions between stakeholders and different aspects of the design process (e.g., creativity, quality and tempo), and a paradox perspective enables identification and understanding of how such tensions can play out over time. Accordingly, further interplay between scholars of organization theory and researchers in construction management can develop the understanding of tensions arising when using GD for RCD. Such an understanding can provide help to avoid vicious cycles where too much focus on one aspect reduces or intensifies as other aspects are ignored. In line with this thinking, this paper further concludes that it is indeed important that researchers focusing on the development of the design process are collaborating continuously with researchers focusing on the outcome of the design process, i.e. the buildings. Hence, researchers in e.g., construction management, structural engineering, building physics, and architecture need to collaborate more in order to achieve virtuous cycles where different perspectives are dealt with simultaneously. In addition, it would be beneficial to increase the involvement of researchers in, for example, data management.

Implications for practitioners

Similarly, practitioners would benefit from enhanced collaboration between different actors in the building sector (and most likely also in the construction industry as a whole, although it is not covered in the empirical data gathered and analysed for this paper). The transition to CE is complex and considering the time-frame for which buildings are designed, sub-optimized solutions will have a long-lasting and potentially extensive impact. Moreover, considering the digital transformation that the building sector is facing, this study suggests that designers need to be open-minded and be ready to learn new skills and take on new tasks. This transformation might change their traditional role and introduce a new aesthetics' paradigm where standardization is not considered negative but is further explored to enhance a circular building sector.

Limitations and further research

Although workshops can be an effective way to collect data from many people, it is recognized that there are also limitations in terms of depth and time available for drilling down into detail. The explorative approach utilizing a convenience sample was not optimal; however, the findings provide valuable insights into how practitioners are currently thinking and reacting. At the same time, it provides confirmation of the need for further qualitative research with a larger sample comprising diverse actors in the building sector, including all major design disciplines. The findings and conclusions in this paper provide guidance for such research, enabling dedicated studies of more specific tensions and paradoxes. Moreover, this paper sheds light on issues related to big-data storage and data ownership, required for circular approaches in the building sector, as well as authorship when using an algorithm to generate design outcomes, as previously highlighted by (Kołata and Zierke, 2021). The difficulty in taking 'soft aspects' into account and the loss of the human factor during the design process have been raised in all four workshops, but not enough to constitute an exhaustive discussion. Finally, the lack of circular design strategies and GD principles, as topics in current education, was thoroughly discussed by the participants but was considered to be beyond the scope of this paper.

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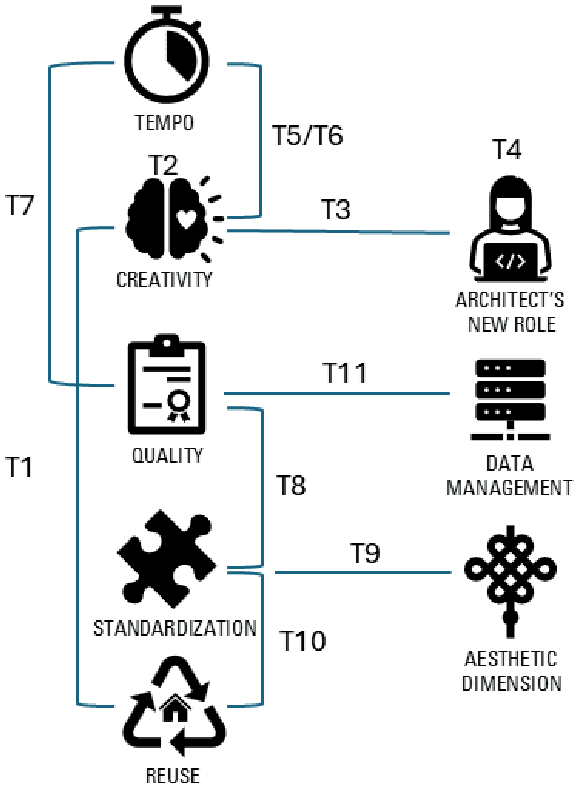
CREATIVITY	Loss of creative aspects; GenAI as driver for a creative use; less time to get many solutions; more time to make creative decisions.
TEMPO	Faster design process; time saving; new ideas faster; tempo expectation: pressure to deliver quicker; gets us to work less; speed of design fast Knowledge; a lot of generative solutions in shorter time
REUSE	Quick and cheaper sustainable design; better use of existing resources; more sustainable construction; investigate new ways of assembling; new joinery with 3D printer; design for less material use
ARCHITECT’S NEW ROLE	Data driven architect; unemployment; obsolete current tasks; AI agent to clean the data for a database; architect’s role less meaningful; education changes; architect as total designer as in the 20th century; holistic driven architect
DATA MANAGEMENT	Extensive data stored in database; data collection by means of 3D scanning; data optimization; data enrichment; reusability score; data ownership
QUALITY	More collaboration of different designers; evaluation of design; exploration and evaluation for decision-making; holistic analysis when designing with reuse; efficiency in design process and better synergy
AESTHETIC DIMENSION	Limited variation; form follows availability; standardization and generic design adaptability; new standardized systems; novel Design: new forms emerge
STANDARDIZATION	Standardization and generic design; new standardized systems; new ways to build; potential to explore new typologies in architecture; non-standard connectors; unique features

	No.	Tension’s title (T)	Element A	Element B
Process vs Process	1	Creativity and reuse level	Using GD for RCD can diminish the creative aspect and fun.	Using GD to RCD can increase the level of reuse by finding more options from a vast set of existing or standardized building parts.
	2	Less or more creativity	Using GD for RCD can diminish the creative aspect and fun.	Using GD to RCD can indirectly spur creativity amongst more team members and engage more people in creative work.
	3	More creativity and new role	Using GD for RCD can indirectly spur creativity amongst more team members and engage more people in creative work.	Using GD to RCD might be interpreted as a threat to the traditional role during design.
	4	New role: threat or opportunity	Using GD for RCD may be interpreted as a threat to the traditional role and responsibilities during design.	Using GD to RCD may be interpreted as a means to drive necessary change and development of roles.
	5	Tempo and less creativity	Using GD for RCD can increase the tempo and pace.	The increased tempo when using GD to RCD can decrease the time available for reflection and creativity, if shortened schedule is expected/required.
	6	Tempo and more creativity	Using GD for RCD can increase the tempo and pace.	The increased tempo when using GD to RCD can increase the time available for reflection and creativity, if shortened schedule is not expected/required.

	No.	Tension's title (T)	Element A	Element B
Process vs Product	7	Tempo and less quality	Using GD for RCD increases the tempo and pace.	The increased tempo when using GD for RCD takes away focus from long-term quality of the end product.
	8	More functionality and less quality	Using GD for RCD increases the number of alternative solutions from a functional perspective.	The many options and alternatives arising when using GD for RCD takes away focus from long-term quality of the end product.
	9	More functionality and less aesthetic value	Using GD for RCD increases the number of alternative solutions from a functional perspective.	The many options and alternatives arising when using GD for RCD takes away focus from aesthetics.
	10	Larger building stock and standardization	Using GD for DfR develops the building stock over time in terms of standardization.	Using GD for DfR impacts the existing building stock negatively over time (e.g., *McDonaldsification*).
	11	Less errors but more severe consequences	GD diminishes the number of errors when DfR.	Using GD for DfR causes repetitive errors if the data input is distorted.



TEMPO
T5/T6
T2
T4
T7
T3
CREATIVITY
ARCHITECT'S
NEW ROLE
T11
QUALITY
DATA
MANAGEMENT
T1
T8
T9
STANDARDIZATION
T10
AESTHETIC
DIMENSION
REUSE

Paper V

Design by availability: a computational approach to facilitate Design for Disassembly.

Abstract

Various studies and guidelines advocate for circular strategies in the building sector and promote design for disassembly (DfD). Nevertheless, there seems to be a disconnection between theoretical advancements and practical application. Instead of prioritizing the implementation of DfD in new building projects, the sector focuses on reusing building parts from existing donor buildings or promoting Design for Adaptability (DfA), which mainly addresses interior elements. Instead, the sector should be engaging in planning for the disassembly of entire structures. There is a need to bridge this gap by identifying the strategies currently considered crucial for implementing DfD. Accordingly, this paper explores the role of a computational design (CD) approach to implement DfD in building design. The aim is to examine the potential of integrating existing computational technologies into design practices to pave the way for a truly circular built environment in the coming decades. Interviews were conducted with experts in the field of CD and knowledgeable in reuse-centred design (RCD). Findings have provided valuable insights into current applications of CD tools in building design, confirming its potential to drive increased application of DfD, thereby contributing to the transition to a circular building sector. This integration could close the gap between theory and practical outcomes.

Keywords: design for disassembly, computational design, circular economy

Introduction

The required transformation of the building sector to embrace the principles of the Circular Economy (CE) and address climate change is a topic widely discussed by practitioners and academics. Various approaches have been proposed, with the literature offering a broad range of principles and strategies. Among the strategies, Reuse-Centred Design (RCD) stands out as a solution that suggests a pivotal role due to its minimal energy consumption requirements when compared with recycling (Arora et al., 2020; Mayer et al., 2019; Rakhshan et al., 2020). The reuse potential of the existing building stock, though, is typically limited to a deconstruction plan

(Sanchez and Haas, 2018) intended to reclaim reusable materials and building parts to the greatest possible extent. This is a consequence of conventional methods used in building design and construction, which generate waste (Durmisevic, 2006; Forghani et al., 2023). Planning for future reuse at the design phase extends the life cycle of building materials and parts, thereby avoiding the traditional cradle-to-grave model (Crowther, 1999). Guldager and Sommer (2018) identified three key areas for the future built environment in *design for disassembly*, *material passport* and *circular economy*. The research reported here examines DfD.

DfD principles adopted in designing new buildings are applicable to reuse activities since they bring both economic and environmental benefits. In fact, conventional design methods not only contribute to waste and pollution but also result in the significant loss of the embodied energy invested in the production of materials and building components (Crowther, 1999). DfD, as a strategy, could enable the future reuse of nearly 100% of building parts, striving toward the ambitious goal of zero carbon emissions and a building stock that regenerates over time (Bertino et al., 2021; Guy and Ciarimboli, 2003).

Frequently, DfD is compared to the *Lego*® system, in which each element can be repurposed across different configurations and functions. However, if its elements were glued together, it likely would not have become a successful framework but rather a disposable system, thereby contributing to waste generation. Unfortunately, conventional construction practices, and even most buildings currently under construction, resemble this glued-together scenario. They are designed in ways that hinder the disassembly of different components, limiting reuse potential to partial deconstruction at best. Research and guidelines support circular strategies and encourage DfD (Casini, 2022a; Cheshire, 2021; Guldager and Sommer, 2018; Lausselet et al., 2023; van Vliet et al., 2019).

Although standardized procedures for building design exist (SIS, 2020), the building sector has demonstrated limited engagement in formulating widely accepted strategies and tools to efficiently support DfD (Akinade et al., 2017; Dams et al., 2021). Indeed, a very limited percentage of existing buildings are completely demountable (Bertino et al., 2021; Chiletto et al., 2024; Kanters, 2018). Clearly, a gap remains between theoretical progress and practical application. Instead of prioritising the implementation of DfD in new building projects, current strategies often focus either on reusing building materials and parts from existing donor buildings or on promoting DfA and merely reuse the same building for different purposes (Lisco and Aulin, 2024). Another under-researched aspect is the use of digital tools to support a design approach that relies on a finite set of available building parts rather than an unlimited range of customized products.

Building Information Modelling (BIM) and Virtual Design and Construction (VDC) are considered as key tools in circular design (Guldager and Sommer, 2018). BIM provides detailed, up-to-date models with precise information on each component, supporting design, constructability and documentation. VDC fosters early collaboration among stakeholders (e.g. clients, designers, engineers and suppliers), enabling informed decision-making and optimising building performance through integrated data use for future operation and maintenance. Besides the six dimensions of a VDC model (i.e. three geometric dimensions, time, cost and quantities and integration of data for facility management), it is argued that the seventh dimension involves integrating disassembly and reuse data into the VDC model (*ibid*). This allows clients to plan for future resale of structural elements and enables the design team to consider reuse potential early, optimising not only life cycle cost, design and performance but also future recycling value (*ibid*). CD is considered for the purpose of this study a suitable approach to deal with challenges represented by designing according to the limited availability of materials and parts. A CD approach could optimise the design by better matching availability with the design intent.

Based on the principles and strategies identified by the literature, this study aims to gain a deeper understanding of the role of CD as an enabler of DfD by providing key insights into the state of integration of DfD principles and the potential of implementation offered by a CD approach. Three research questions have guided the study.

RQ1: What are the potential and challenges of CD tools?

The emerging importance gained by CD in the last few years is not without related issues. The possibility offered by the tools to accelerate the process by automating repetitive tasks allows for improved optimisation opportunities. The threats, however, need to be addressed.

RQ2: To what extent are these CD tools currently addressing DfD?

This question focuses on identifying which aspects of DfD are currently addressed, aiming to assess both the mechanisms (how) and the depth (extent) through which CD tools integrate DfD principles, highlighting current strengths and potential gaps in functionalities.

RQ3: How can CD tools facilitate the widespread adoption of DfD?

By moving from analysis to application, this study explores how CD tools can support the early integration of DfD into the design process, aiming to uncover practical strategies and workflows.

Background

DfD origins

One might assume that reuse and DfD strategies in the building sector are modern concepts. On the contrary, the practices of recycling and reuse have been common since the Roman era (Duckworth and Wilson, 2020; Jacks, 2008). Moreover, half-timber construction has historically been the predominant timber building system in Denmark. Characterized by the use of timber pegs, it enables straightforward disassembly. Its modular and prefabricated components contribute to a flexible and adaptable structural system (Guldager and Sommer, 2018).

Accordingly, trying to date the emergence of DfD in the history of architecture is difficult. Often, it is the Crystal Palace, a symbol of nineteenth-century architecture, which initiated the transformation from traditional construction methods to influence the Modern Movement in Europe (Addis, 2006). Indeed, modern architecture provides many examples of construction methods that were based on design for assembly, often expressing the structure's assembly through its materials and connectors (Guy and Ciarimboli, 2003; Sadraee, 2020).

Even so, most buildings are designed for easy assembly but often not for disassembly (Durmisevic and Yeang, 2009). Perceiving buildings as manufactured artifacts could facilitate the integration of DfD strategies within the building sector as well (Guy and Ciarimboli, 2003). By providing a review and analysis of buildings designed for disassembly Ostapska et al. (2024) adequately describe the current research state of DfD in the building industry and identify principles guiding and challenges hindering its implementation.

DfD principles and strategies

DfD is defined as *"an approach to the design of a product or constructed asset that facilitates disassembly at the end of its useful life, in such a way that enables components and parts to be reused, recycled, recovered for energy or, in some other way, diverted from the waste stream"* (ISO, 2020).

As a design strategy, DfD supports future reuse by treating buildings as temporary assemblies. It emphasizes designing structures for easy separation and reconstruction using the same materials (Fatourou-Sipsi and Symeonidou, 2021). By exploring the concept of systematic assembly and disassembly, the design of a building seeks to create its components efficiently, focusing on materials, layers and joints that can be separated (Arisya and Suryantini, 2021).

Here, DfD is defined as a way of designing a building that involves early-stage planning to ensure that both the building structure and its non-structural parts can be easily assembled and dismantled to accommodate changes in use. The primary goal is to enable the reuse of all building parts, thereby conserving resources and minimizing waste.

A total of 34 principles for DfD were retrieved from several research studies (Ostapska et al., 2024). Yet, a clear overview of these principles appears to be lacking, with noticeable overlaps and opportunities for consolidation among several of them. Furthermore, the boundary between principles and strategies becomes frequently blurred. Each principle should be analysed based on five levels (systems, elements, components, subcomponents and materials) (ISO 2020). Strategies should also include aspects like stakeholder engagement and the active involvement of the design team, client, and contractor (Walsh and Shotton, 2021).

A tentative summary of the principles, divided into five categories, is provided in Table 1.

Table 1. Overview of principles and strategies for DfD.

Principles	Strategies
Flexibility and adaptability	
Versatility Convertibility Independence Accessibility	Layered-based design
Easy assembly and disassembly	
Simplicity Minimal amount of materials, components and connector types Element accessibility for demounting Parallel assembly/disassembly capability	Exposed and reversible mechanical connections Lightweight materials Transportability
Modularity, standardization and prefabrication	
Expandability Material systematisation Element edge standardisation Service-life-based element separation Mechanical connectors	Prefabrication and modularisation Separable services
Reusability and sustainability	
Recyclability Reusability Refurbishability Re-manufacturability Inherent finishes Clean material separation between components	A holistic approach within LCA

Design transparency and planning	
Ownership of products and components Durability	Documentation of disassembly information Proper identification of project objectives Deconstruction process design

DfD challenges

Arup (202x) identified two main challenges: i) higher material use initially, but long-term benefits and ii) greater early impact, yet sustainable over time. Moreover, disassembly processes can be challenging due to stabilising elements optimised for the original construction; for example, walls that are difficult to remove, invisible screw heads that can complicate access, moisture-sensitive fire protection layers and exposed beams that require careful weather protection, while physical labelling is essential for tracking components. Meeting high aesthetic standards during reuse adds another layer of complexity, all of which demands extensive planning and coordination (Sandin et al., 2023). Lastly, a UK study by Walsh and Shotton (2021) found that architects and engineers currently lack clear, practical and easily accessible guidance or tools to effectively support DfD and reuse, which also poses a significant challenge.

CD features and strategies

An attempt to define different concepts related to CD is offered by Caetano et al. (2020) where parametric, generative and algorithmic design are described and defined for a better understanding.

Parametric design (PD) is “a design process based on algorithmic parameters and rules to constrain them”. *Generative design* (GD) is “a design paradigm that employs algorithmic descriptions that are more autonomous than parametric design”. *Algorithmic design* (AD) is “a design paradigm that uses algorithms to generate models and, therefore, we also consider it generative”. Since it appears difficult to distinguish between generative and algorithmic design, the authors consider the latter as a subset of generative design, as shown in Figure 1.

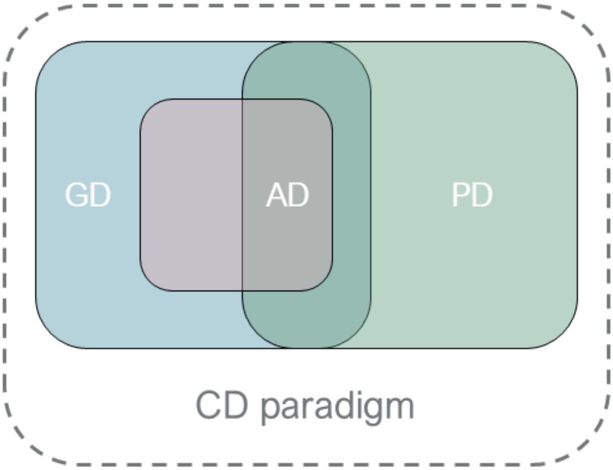


Figure 1. Representations of the concepts related to CD (adapted from Caetano et al. 2020).

CD challenges

While BIM effectively supports construction management, current information models lack support for selective disassembly planning due to two key limitations: i) inadequate level-of-detail for parametric disassembly models to define physical interfaces between building parts; and ii) the lack of efficient methods to automatically extract disassembly parameters from high-quality information models (Sanchez et al., 2021). Computational tools (e.g. *Madaster*, *One Click LCA* and *RhinoCircular*) currently aid the designers in matching supply and demand in a circular design process or in assessing the environmental impact from a circular point of view (Heisel and McGranahan, 2024). The adoption of CD tools in DfD projects appears limited, as does the dissemination of the knowledge required to develop proficiency in their use.

Research on CD and DfD

Reusing building elements and materials was common practice in vernacular architecture and even in Roman times (Bertino et al., 2021; Lisco and Aulin, 2024; Moussavi et al., 2022). Similarly, although CD did not appear in the literature until the late 1990s, its origins can be traced back to the 1960s influenced by the modernist movement and technological advancements. Although there are some attempts to use some form of CD tools within the reuse of unprocessed rubble (Wyller et al., 2024) waste material (Lokhandwala, 2018; Pedersen et al., 2024) or to calculate embodied carbon in structural design (Fusari et al., 2024). The innovation consists of integrating the two topics while broadening the focus beyond the load-bearing structures of a building to encompass all its constituent components and elements.

Method

This qualitative research study aims to develop a theoretical understanding of the role of CD in facilitating the adoption of DfD by building an empirically grounded theory through interviews (Glaser and Strauss, 2017). The design of the study included a literature study and interviews. The interview transcripts were structured using software, with interpretation undertaken by the author.

Data collection method

The data collection was conducted in two stages. The first stage involved an initial literature review aimed at understanding the principles, strategies and challenges associated with CD and DfD. A special effort was placed on identifying research papers that explored the integration of CD methods with DfD principles, along with studies on projects that implemented DfD strategies. Definitions were identified, along with key principles, strategies and challenges related to both DfD and CD. The findings from the literature study formed the foundation for developing the interview guide used in the second stage. The sample for interviews was based on the key informant method, focusing on identifying and recruiting key individuals with relevant expertise and insights (Kumar et al., 1993). This approach was chosen for its effectiveness and efficiency in facilitating in-depth data collection. By targeting knowledgeable key informants, the study ensured access to rich, high-quality information, making it particularly suitable for qualitative research. Additionally, this method helped capture diverse perspectives while maintaining a focused and purposive selection process. First, designers who participated in the author's previous studies were contacted together with experts identified through business media. A snowball sampling technique was chosen to extend the sample size due to the difficulty of accessing individuals with the target characteristics (Naderifar et al., 2017). The size of the sample suggests that CD methods and skills are not widespread within the building design field, especially in circular design. In this phase, practitioners proficient in CD and highly knowledgeable within reuse design were interviewed.

A structured interview guide, with pre-determined questions, fixed wording and a predefined order (Robson and McCartan, 2016) was deemed appropriate to avoid bias while gaining the required insights. The interview guide consists of five sections: i) background information; ii) understanding computational tools features;

iii) challenges and limitations of computational tools; iv) embedding DfD in new projects; and v) closing questions.

After conducting a pilot interview to assess the quality of the interview guide, it was revised and enhanced by adding more questions and reorganizing the existing ones to better fit the purpose and increase knowledge of the topic. One question about the final users of the tools was removed because it appeared obvious that they were designers or computational designers.

The interviews were conducted online via *Microsoft Teams* and recorded to ensure no important data were lost. All respondents were informed about the procedure and assured of the anonymisation of their answers. When asked if they wished to be acknowledged for their participation in the study, all responded positively. This situation supports the view that since computational design tools are relatively new, designers with over three years of experience could reasonably be considered experts with (Saadi and Yang, 2023). The expertise of the key informants in the field of CD ranges from three to over 20 years. Details of the key informants are given in Table 2.

Table 2. Information on the key informants

Key informant	Background	Company	Years of expertise in CD	Country
1	Architect	Self-employed	>10	Sweden
2	Architect, PhD	Research Institute	>20	Sweden
3	Architect	Architectural firm	>5	Sweden
4	Structural engineer, PhD	Consulting firm	>15	The Netherlands
5	Architect	Architectural firm	>10	Finland
6	Architect	Architectural firm	>10	Sweden
7	Structural engineer	Consulting firm	>3	The Netherlands
8	Diverse, PhD	Consulting firm	>20	Denmark

Data analysis

The transcription files collected via *Microsoft Teams* were analysed in multiple phases through a structured, multi-step process. Organising and systematising content while preserving its meaning involves classifying, sorting and identifying patterns (Säfsten and Gustavsson, 2020). Furthermore, an inductive thematic analysis, or data-driven analysis, does not rely on any predefined frameworks (*ibid*). The themes emerge from the data by coding, which is an iterative process that plays a central role in grounded theory and in the computer-assisted analysis of interview transcripts (Gibbs, 2018).

While thematic analysis is a commonly employed method for identifying, analysing and interpreting patterns of meaning in qualitative research, it can be time-consuming. Therefore, exploring alternative approaches to streamline this process can be beneficial (Zhang et al., 2023). Recent technological advances have seen a growing use of AI in research, with the potential to significantly transform the thematic analysis process (Christou, 2024). AI enhances efficiency by reducing the time spent on data preparation and supporting researchers during coding and analysis. It can automatically identify patterns in qualitative data, suggest potential codes, and assist in accelerating the initial stages of thematic analysis (Christou, 2024). Researchers are increasingly exploring AI in qualitative analysis, from coding to insights extraction, highlighting its potential to automate tasks, handle large datasets consistently and reduce cognitive bias (Jalali and Akhavan, 2024). The use of ChatGPT for thematic analysis has been discussed in recent studies (Jalali and Akhavan, 2024; Turobov et al., 2024; Yan et al., 2024; Zhang et al., 2023). Moreover, AI technology has been integrated into qualitative data analysis software to improve the efficiency and accuracy of tasks like coding and pattern recognition in qualitative research. For this study, data analysis software *Delve* was used to match the coding with the interviews' transcriptions.

The steps undertaken for data analysis are listed as follows.

1. *Initial review and correction* – the transcripts were carefully read multiple times and any spelling errors were corrected.
2. *Data organization* – the responses were compiled into a spreadsheet to provide a comprehensive overview of the collected data.
3. *Categorization* – all responses were printed, cut and sorted into categories based on their corresponding questions.
4. *Coding process* – initial codes were assigned and written on the front of sticky notes, while the back contained details about the key informant and the associated question. This approach helped minimize bias during the analysis.
5. *Thematic classification* – the responses were grouped into three main thematic areas.
6. *Thematic analysis* – each thematic area was analysed individually, with connections and relationships between categories identified for further discussion.
7. *AI-assisted coding* – given the study's focus on data generation (CD and GenAI), *Delve* – digital qualitative analysis software – was employed. Manually identified codes were first created and then imported into the software, where an AI assistant automatically applied them to the interview transcripts.

8. *Coding review* – each excerpt was subsequently manually reviewed to refine the coding, correct AI-generated misclassifications, add classifications and identify additional codes and subcodes.
9. *Topic identification* – the AI tool initially generated a total of seven main topics; however, upon review, these were found to be occasionally inaccurate and overall insufficient. As a result, they were disregarded in favour of a conventional, manual approach to identify the main topics and derive the study's findings.

Unlike content analysis, thematic analysis does not focus on the frequency of words, expressions or themes (Säfsten and Gustavsson, 2020). Hence, no deliberate attempt was made to quantify these elements. Throughout the analysis, ongoing efforts were made to refine, develop and label themes. This approach combined thorough manual analysis with efficient AI-assisted processing, thus enhancing the reliability and depth of the qualitative findings while also testing the tool's ability to identify unexpected or overlooked coding patterns.

Findings

The data analysis uncovered three key thematic areas: *features, requirements and challenges*. Each of these areas serves as a foundation for understanding the complexities of the subject. Within them are interconnected and overlapping sub-themes. The interconnections highlight the multifaceted nature of the main topic, demonstrating how the principles and strategies embedded within the features shape the challenges, while requirements serve as enablers for future implementation. This intricate web of relationships confirms the need for a holistic and interdisciplinary approach.

DfD features

Sustainability, environmental impact and resource management in DfD

In expressing concerns on the environmental impact of the building sector, participants placed great importance on DfD and responsible resource management. They highlighted the potential of these approaches to reduce waste, improve resource efficiency and promote material reuse in construction. There is a shared recognition of the need to consider the entire lifecycle of materials, ensuring that design choices align with long-term sustainability goals. Layer-based design

Notwithstanding the building layers model by Brand (1995), the CD approach to DfD also requires a layer-based design. Key informant 6 highlighted the importance of breaking down complex building work into smaller, manageable components/layers to facilitate effective integration and problem-solving:

> *"we could imagine disassembly for façade, disassembly for structure, interiors, ceilings and so on."*

It was further discussed that dividing the overall project into several discrete parts allows for isolated successes and manageable failures rather than a binary outcome of success or failure for the whole project. By utilising separate tools to address specific challenges, the overall efficiency of the project can be improved, reducing risks associated with large-scale architectural changes.

Focus on details and the design of connectors

Some key informants highlighted the potential value of looking *"back to an earlier construction culture, an earlier building culture with more craftsmanship"*, where meticulous attention to detailing and joinery, particularly, was more than just a structural necessity – it was a deliberate aesthetic feature, reflecting craftsmanship and design intent. Additionally, as noted by key informant 2, it is important to have the *"understanding and knowledge of old traditional materials that we have not been able to use in a long time because it did not fit into an industrialised model"*.

Eclectic assembly

According to the participants, DfD might reshape aesthetic values. New aesthetics are emerging, characterized by temporal looks and the use of raw materials.

> *"I would welcome eclectic assembly of all the new construction techniques, etcetera, to influence the design for a richer environment."* (Key informant 2)

There is an acknowledgment of the need to revisit earlier construction cultures, mostly examples from modern architecture that had a willingness to show the connectors that can lead to more thoughtful and aesthetic design.

Built-in inventory

When a building is designed for disassembly, it innately contains all the necessary information about its materials and components, automatically generating a digital library that can be used in future design projects, as highlighted by the following responses:

> *"...you can already create a smart library* […] *and you could already connect your existing building, or you should connect your existing building towards the library"* (Key informant 6).

> *"So, in a future where you would know where all materials are, whether they are already outside in the yard or still encapsulated in the building, if the building is*

earmarked for demolition in a certain time from now, you could actually design with stock that is available by the time your project is going into execution" (Key informant 4).

Solving the puzzle

According to some participants, DfD features resemble those related to the *Lego®* system when discussing the building parts, to the *IKEA* model when considering the connectors and to a puzzle to solve when dealing with the complexity of aligning a finite set of elements with the intended design and DfD principles. The comparison to *Lego®* serves as a metaphor for creating customizable structures from a library of components that are part of a building designed for disassembly. As key informant 1 noted:

> *"it is like you are creating your own* Lego® *[model] out of, you know, a library of different parts".*

Similarly, *IKEA's* construction technique embodies the principles of modularity and ease of assembly. Key informant 6 described DfD as a method where *"you could then disassemble and reuse",* making it simpler to replace parts without demolishing the entire object. This *IKEA-like* model suggests a design approach that facilitates easy assembly and disassembly, aligning with the principles of DfD.

The term puzzle frequently arose in these discussions, symbolising the challenge of combining different elements to achieve a cohesive whole. As key informant 4 mentioned, this often involves *"figuring out what there is, digitising the data, and then solving that puzzle between having a design and having a certain supply for DfD principles"* or as put by key informant 3:

> "*we have a mapping of the types of joinery* […] *and then* […] *we take* [them] *to the next project with computational tools and then we are able to build the puzzle again on another, let us say, iteration".*

CD features

Efficiency

All key informants identified time-saving as the main feature of CD tools. By automating repetitive tasks, CD allocates time for designers to concentrate on more complex design problems, such as those related to DfD. When designing for disassembly, computational tools can facilitate the early investigation of suitable connectors and their implications for project outcomes and, therefore:

> *"avoid redesigns later on and ultimately save on time and money for the clients"* (Key informant 4).

Key informant 1 remarked that rule-based aggregation algorithms provide flexibility and control over design processes. *Wasp*, a *Grasshopper* plug-in, was named as a powerful tool that offers a vast array of possibilities for connecting parts from a digital library while consistently applying the same set of rules to the same type of object.

> *"So, you control the rules, but the tool helps you actually explore the possibilities that could come out of this".*

Key informant 2 highlighted the importance of integrating various special competencies early in the design process to implement the investigative approach to finding optimal solutions. Regardless, reaching this collaboration goal

> *"…is very hard when you get everything on board from day one".*

The opportunity to generate many more alternatives in the early stage of a project "*that will probably never come to one's mind" … "opens a way bigger design catalogue than the normal design process would usually do"*. Moreover, CD ensures accuracy and efficiency, allowing for deeper refinement and innovation in the design process.

Informed and user-centred design

It emerged that the aforementioned rule-based aggregation requires a solid understanding of data management and manipulation for the successful implementation of DfD principles. A user-centred design approach is another critical factor in the adoption of CD tools. Key informants 4 and 8 underscored the need for usability testing and user involvement to ensure that these tools effectively meet the needs of users, thus conforming their suitability.

Matching function

The analysis of the data reveals a significant focus on the complexities and opportunities associated with integrating existing building parts into new designs. Digitizing the existing building stock, to create material passports, is deemed fundamental to facilitate better matching between design intent and availability.

One key informant also noted the limitations of a traditional approach in managing the complexity of larger projects, especially when sourcing materials from multiple donor buildings. It was made clear that, when adding layers of logistical and design constraints, the tools are necessary to navigate the complexity:

> *"if you start to talk about multiple donor buildings for one project, then you are out of luck without these tools. And we have been looking only at structural element types like posts, beams and slabs. They still have joints, different kinds of joints that we*

> *have not addressed […] then the question becomes much more complex."* (Key informant 5)

As noted by key informant 7, in a conventional approach, first, the design is decided, then designers look for ways to implement DfD. Conversely, with CD tools:

> *"you can do it the other way around, so you can start at Design for Disassembly and see which possible solutions there are to make your structure in that way."*

Iterative approach

The iterative nature of CD processes emerged in all the interviews. Enabling iterative development by starting with initial features allows for learning and improvement over time. For instance, one key informant noted that "*it is better to iterate through multiple trial* [and] *error versions than to come up with the perfect final thing"*. This iterative approach is not only about refining designs but also about adapting to changing circumstances, as pointed out by another key informant who mentioned that *"the design process itself will become much more iterative due to the evolving availability of structural elements"*. The concept of breaking down larger problems into manageable parts was frequently mentioned as a method to facilitate this iterative process, as discussed in the section on layer-based design.

CD requirements to enable DfD

Interoperability

Apart from one, all participants highlighted the need for enhanced interoperability between different design tools, and four of them discussed the importance of having open-source tools and easily accessible material libraries. Interoperability is a crucial theme in the context of CD, impacting collaboration, efficiency and the successful implementation of innovative practices. Addressing interoperability challenges could lead to more effective workflows and facilitate the transition to sustainable and technologically advanced design solutions.

Challenges of standardisation and data integration in CD

A major challenge in CD is the lack of standardization of digital workflows, which hinders interoperability and effective communication across different software and disciplines. Additionally, managing and integrating data into existing workflows is crucial for ensuring seamless collaboration and informed decision-making. Participants underscored the importance of establishing consistent standards and reliable data management practices to improve efficiency, enhance trust in design processes and enable a more cohesive workflow between stakeholders.

Usability, accessibility and trust in CD tools

A recurring concern among participants is the usability and accessibility of CD tools. User-friendliness and accessibility play a key role in encouraging a broader adoption of CD tools among architects and engineers. Their complexity, however, often creates barriers to understanding and application, limiting their effectiveness in practice as demonstrated by the recurrent expression of *black-box* to describe the tools.

Beyond usability and accessibility, trust and transparency play a crucial role in the adoption of CD tools, according to five out of eight key informants who highlighted the importance of clearly communicating the strengths and limitations of these tools to overcome scepticism and resistance within the design team. Ensuring that computational models are accessible, reliable and easy to interpret can foster confidence, leading to wider acceptance and more effective integration into design workflows.

Prototyping and pilot projects

Using pilot projects or prototypes to test and demonstrate the feasibility of new tools and approaches is mentioned by seven out of eight participants. The ripple effect of these explorations in small projects is seen as a way to foster confidence and encourage the broader adoption of innovative practices.

Practical application and scalability of CD

CD is closely tied to real-world applications, where tools and methodologies enhance the overall design process and project outcomes. While these approaches seem promising, a key challenge lies in scaling them effectively for larger projects. The need for practical, adaptable solutions that integrate seamlessly into existing workflows is highlighted as essential for maximizing the impact of CD in the building sector.

Given the iterative nature of this design process and in order to facilitate continual improvement, prototyping and a trial-and-error approach in small-scale projects were identified as crucial by seven out of eight participants, highlighting their role in refining methodologies and optimizing outcomes over time.

The importance of interdisciplinary collaboration

Collaboration between disciplines, such as architecture, engineering and computational design, was recognised as essential for addressing complex design challenges and achieving successful project outcomes. Participants emphasised the importance of interdisciplinary teamwork in facilitating knowledge sharing, strengthening problem-solving and improving the overall design process.

Education and training in CD and DfD

A strong consensus emerged on the need for augmented education and training in CD tools and DfD within architectural and engineering curricula. The need arises from a widespread knowledge gap and lack of understanding of these topics, a concern echoed by all participants. Indeed, seven out of eight key informants emphasised the point that current programs might not adequately prepare students for the skills demanded by the industry and the desired transition to circular design. Key informant 4 discussed the differences in educational approaches to CD across countries, highlighting a gap in knowledge and expertise that can affect collaboration in multidisciplinary teams:

> *"...some schools are heavily investing in computational design courses, whereas others are not. I see also gaps between countries.* […] *Denmark's universities are teaching computational design. ...But in France I do not see this at all.* […] *I think there are gaps between countries also in terms of education in these things that create limitations, especially if you are aiming for a European market where everybody can bid for the same work."*

According to key informant 7, a country where CD is taught in the curricula is the Netherlands. All informants agreed that by imparting the necessary knowledge and skills, educational institutions can better prepare the new generation of designers for real-world applications, ensuring they can effectively implement CD and DfD strategies in practice as fast as possible:

> *"We have been training craftsmen and contractors, architects and engineers to build what we have today, and now we need to train them to build something else. And we need to do it fast."* (Key informant 8)

Challenges when adopting CD for DfD

The findings indicate that while technical challenges are acknowledged, participants do not perceive them as major obstacles but rather as manageable requirements to be addressed. Instead, the data analysis revealed other constraints that more significantly hinder the widespread adoption of DfD and CD in the building sector.

Financial constraints

Budget constraints represent a key barrier to innovation. The financial implications of integrating new technologies and practices can limit their widespread implementation, particularly for firms operating under tight budgets. There is a strong emphasis on the need for cost-effective solutions that balance economic feasibility with technological advancements. Stakeholders might be unwilling to invest in CD tools if they cannot see immediate financial benefits.

Similarly, the need to make upfront investments for future benefits without direct financial returns poses a significant barrier to the widespread adoption of DfD. This challenge discourages stakeholders from embracing DfD principles, as the long-term advantages often do not translate into immediate economic gains. As underscored by key informant 3:

> *"the practice* [of DfD] *is still not there because it is in the future, right?* […] *To ease the work of the next designer* […] *falls outside our responsibility."*

The client's limited understanding of the value of such innovative design practices and budget constraints can lead to a reluctance to invest in these methodologies.

Resistance to change and the need for cultural and organizational transformation

Traditional practices often act as barriers to innovation, making it difficult for new approaches to gain traction, as stated by key informant 1.

> *"The biggest barrier, in my opinion, is this resistance against new tools and new workflows and methods. Because it could be intimidating for people who do not really know* […] *how computational design works."*

Participants emphasized the need for a cultural and organizational transformation that fosters an environment of openness, collaboration and support for technological advancements. Encouraging a mindset that embraces change is essential for integrating innovative solutions and improving industry-wide adoption of emerging design methodologies.

Regulatory challenges and barriers to innovation

Building codes and regulations significantly influence the implementation of DfD in construction. Participants noted that existing regulations often focus heavily on carbon footprint, which can detract from promoting DfD. Regulations can both hinder and facilitate the reuse of building parts; for instance, some regulations might force designers to incorporate a certain percentage of reused materials (key informant 1), while others might create challenges, such as time limits on stored materials that could turn into waste, as happens in Finland, according to key informant 5. Furthermore, key informant 8 claimed that the current building codes are shaped by the interests of the building sector.

> *"So, we need to change the interest in the construction sector, and we are also trying to do that. We are also lobbying for a change of the building codes towards a more sustainable construction practice, and I think that what is needed is that we look at everything and say, well, this is just stupid because we are not taking the planetary boundaries into consideration. Of course, we need fire safety, we need acoustics, we need a lot of stuff, but we also need the planetary boundaries in the building code."*

It seems, therefore, that current regulations might not adequately support innovative practices like DfD.

Future innovation and research in CD and DfD

There is strong optimism about the future of CD and DfD, with participants emphasising the need for continuous research, development and implementation. As the field evolves, there is growing interest in exploring new technologies and methodologies to optimise the design process and improve sustainability outcomes. Ongoing innovation through a trial-and-error approach and interdisciplinary collaboration were seen as essential for ensuring their effective integration into architectural and construction practices. Six out of eight participants argued that the main trend and a step forward is represented by the integration of AI and machine learning in the field of CD, balanced with considerations of necessary skills, education and the recognition of their limitations.

Discussion

While buildings are typically valued for their size, location, design and function, they also hold residual value in their materials and components. This value, often seen only as demolition cost, can be maximised if elements are recoverable for reuse at end-of-life (Casini, 2022b). Currently, the reuse of materials and components, particularly structural elements from existing donor buildings, stands out as the predominant practice. Practical applications of DfD remain largely confined to temporary buildings, exhibition structures or selective applications of disassembly principles, partly implemented when feasible in new projects. This indicates that while the concept of reuse is gaining traction, fully integrated DfD practices are still in their early stages of adoption within mainstream construction. This observation aligns with insights gathered from online sources and informal discussions with designers, revealing that clear and detailed DfD plans are not incorporated into the design of new buildings. However, a common assumption persists that timber structures are by default disassemblable, as confirmed by (Cramer and Sandin, 2021).

Key barriers to reusing structural components include design compatibility (e.g. integrating the new building's design with the structural capacity of the reclaimed element), hazardous coatings and potential issues with collateral warranties – a factor less explored in existing studies. Further research is needed to address these challenges (Rakhshan et al., 2021).

The findings reveal that most of the tools used for reuse and design are focused on how to integrate building parts available from a donor building into a new project and are based on a principle of matching the existing stock with the new design. Thus, there is the infrastructure for DfD, but implementation challenges remain.

According to Bertino et al. (2021), when approaching reuse activities, there are two different kinds of deconstruction: structural and non-structural. Reusing the elements belonging to the second category is considered a solid market and should obviously be done as the first activity. Followed by the structural deconstruction process realized from top to bottom to avoid the collapse of the building.

The findings also indicate that the field of DfD is still emerging, and clear, detailed and accessible design guidance or tools to support architects and engineers in effectively designing for disassembly and reuse are lacking (Walsh and Shotton, 2021). Even though deconstruction design principles have been acknowledged for the last twenty years, the current deconstruction methods indicate that this approach has not fully realized its potential and fewer than one percent of existing buildings are completely demountable (Akinade et al., 2017b). This is confirmed by the responses of the key informants.

An important feature of DfD is its emphasis on modular assemblies, which are typically designed for ease of connection and separation. These modules are often produced using prefabrication techniques, allowing for greater precision, efficiency and quality control during manufacturing. This approach not only facilitates faster construction and potential cost savings but also supports the principles of circular design by enabling components to be easily disassembled, reused or repurposed at the end of a building's life, thus reducing waste (Tavares et al., 2021; Wei et al., 2022).

Nearly a decade ago, a comparison between the future building sector, specifically prefabricated housing, and the automotive industry was approached with caution (Aitchison, 2017). As stated by Crowther, many automotive and computer companies had implemented structured product return for dismantling programs (Crowther, 1999). Notably, while the building sector is embracing design strategies to implement reuse, the automotive industry appears to be at a turning point. The latest generation of electric vehicles, characterized by complex digital systems and high levels of software integration, have batteries often not suitable for disassembly and reuse (Harper et al., 2019; Hellmuth et al., 2021). Moreover, increased digitalization, as implemented in connected vehicles (Abdelkader et al., 2021), introduces greater susceptibility to technical malfunctions, including software glitches and sensor failures, which can impair vehicle performance and safety.

Aitchison (2017) also highlighted how CD, among other developments like digital fabrication, new management methods and material innovation, will reshape the building sector. Subsequently, Caetano et al. (2020), while providing clarity among terms referring to the CD paradigm, argue that the focus should not be on questioning if the paradigm is good or not for architecture, but rather how to benefit from it.

In this light, the use of CD when designing for disassembly should be approached carefully. Rather than uncritically adopting new tools amid the trend toward digitalisation, it could be more effective to *"combine domain knowledge with technology",* as emphasised by key informant 2. Indeed, not all processes benefit from a computational approach, "*some things could still be done in a traditional way quicker"* (Key informant 4). Based on Belluomo (2025), GD methods generally fall into two categories: design-by-search, which emphasises creative exploration of the solution space, and design-by-optimization, which focuses on performance-driven solutions implementing structural optimisation algorithms.

Accordingly, it could be argued that design-by-search occurs when developing new designs with an infinite set of elements and a focus on DfD, whereas design-by-optimisation is applied when trying to match the finite set of elements with a predefined design. As DfD becomes more integrated into new projects, this distinction between the two approaches might gradually fade.

Unsurprisingly, all participants agreed on the crucial role played by data management, also considering that the tools are *power hungry* and even the storage requirements for databases of materials and building parts contribute to sustainability challenges that need to be addressed.

A recurring theme across interviews is the evolving relationship between DfD and architectural aesthetics. Several participants noted that the principles of DfD influence building aesthetics, often resulting in a more raw, temporal and adaptive design language. One key informant expressed concern over the quality and longevity of modern buildings, sharing a sense of shame and frustration with the current state of the sector:

> "*I am glad I am not an architect,* […] *because I could be rather ashamed to have been part of this wave of construction that has been there for almost 50 years. And then I know a lot of architects who are, and I know a lot of young architects who will not work in the business because of this"*.

As highlighted in the literature, revisiting pre-modernist architecture and emphasising details design and material expression can support the implementation of DfD while also enhancing aesthetic value (Guy and Ciarimboli, 2003; Merrild, 2024; Sadraee, 2020). By reintroducing traditional technologies and materials, architects can craft buildings that are both disassemblable and architecturally compelling, blending sustainability with aesthetic innovation. At the heart of this discussion is the importance of detailing and joinery, which serves as a bridge between aesthetics and functionality. It should be noted that disassembly features characterise modular construction, which is often perceived as limiting creativity and leading to monotonous design outcomes (Arisya and Suryantini, 2021).

Conversely, multiple participants stressed that meticulous attention to detail is essential, not only for ensuring structural integrity but also for elevating the design's visual and material expression.

Computational tools could play a key role in this transformation, offering new design possibilities that enhance both functionality and aesthetics. These tools assist in identifying joinery solutions, optimizing material connections and ultimately shaping the visual and structural quality of disassemblable architecture.

When discussing the challenges linked to the reuse of structural elements, key informant 4 noted that, according to the Dutch guideline for steel reuse, while structural steel elements can be reused, connection details such as bolts must be made from *virgin* materials, which could be a sustainable solution to increment the reusability of structural elements. Notably, the Netherlands stands out for its advanced education in both DfD principles and CD tools. It also hosts the highest concentration of buildings designed for disassembly (Ostapska et al., 2024), positioning the country as a role model in fostering a circular built environment.

Conclusions

Theoretical implications

This study enhances the theoretical understanding of how CD can support DfD within a broader CE framework. Findings confirm the importance of adopting a layered, system-based approach to building design, where individual elements are governed by principles of reuse, adaptability and lifecycle thinking. As design processes increasingly incorporate CD tools, there is a pressing need to define strong criteria and rules for determining how reclaimed building parts are selected, assembled and assessed for reuse. Standardized input criteria are essential for consistent, quality-driven circular design.

Moreover, the research underscores the potential of embedding DfD principles not only in theory but also directly into early-stage design processes. The shift from merely repurposing existing structures and material banks to actively designing with disassembly in mind represents a critical evolution. Theoretical frameworks must now account for the role of AI and machine learning in shaping future design. This transition toward informed-based 3D models, carrying data for both assembly and disassembly, points toward a new epistemology in architectural design, where buildings serve as material banks with built-in inventory for future use.

Practical implications

From a practical perspective, the integration of CD into DfD workflows offers tangible benefits such as time-saving, automation, material traceability and early design exploration by iteration. However, to fully realise these benefits, several challenges must be addressed. The study highlights the need for improved interoperability, standardisation of workflows and greater usability of CD tools to ensure wider adoption. Education and training remain critical for preparing the next generation of practitioners to navigate these advanced digital systems confidently and effectively.

Equally important is the need to act in the present, by not only reusing existing building stock through adaptive reuse or matching processes but also by designing future projects with disassembly and reuse principles from the outset. Such practices will allow the creation of 3D models that serve not only for construction and operations but also as accessible inventories for future reuse. Yet, this transition will not occur in isolation. Industry, government and academia must collaborate to create the regulatory frameworks, incentives and knowledge-sharing platforms necessary for success. Moreover, as advancements in CD, AI and machine learning accelerate, practitioners must adapt to evolving workflows and data management paradigms, balancing innovation with usability and trust. Ultimately, these tools will serve not only to optimise current processes, but to radically reshape how buildings are conceived, constructed and reused across generations.

Limitations

While the study offers valuable insights into the integration of DfD and CD, its geographical scope is limited, which might affect the generalisability of the findings. Moreover, the thematic analysis was based on both AI-assisted and manual coding and qualitative interpretation, which relies to some extent on researcher judgment. As AI-generated insights become more prominent, it is essential to balance algorithmic analysis with human expertise to ensure rigour, nuance and contextual relevance in future research.

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