THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

Design for Structural Adaptation in Timber Buildings

On Industry Potential for Implementation Towards Resource-Efficient Timber Structures

VERA ÖBERG

Department of Architecture and Civil Engineering
Division of Structural Engineering
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2024

Design for Structural Adaptation in Timber Buildings
On Industry Potential for Implementation Towards Resource-Efficient Timber Structures

Vera Öberg
© Vera Öberg, 2024.

Thesis for the Degree of Licentiate Engineering

Technical Report No. 2024:7
Lic /Architecture and Civil Engineering / Chalmers University of Technology.

Department of Architecture and Civil Engineering
Division of Structural Engineering
Lightweight Structures
Chalmers University of Technology SE-412 96
Gothenburg, Sweden
Telephone + 46(0)73-140 53 20

Cover:
The figure illustrates a structurally adaptable multistorey building, where the elements affected by functional changes or repairs are highlighted in green.

Printed by Chalmers Digitaltryck
Gothenburg, Sweden 2024

"All things are so very uncertain, and that's exactly what makes me feel reassured."

Too-ticky
Moominland Midwinter (1957) by Tove Jansson

Abstract

Building service life extension has been identified as a key strategy for the construction sector's transition to a circular economy. Yet, there is an increased awareness that business-as-usual buildings lack the adaptability needed to accommodate changed user needs or damages. As an approach to rectify this, the concept *Design for Adaptation* has gained traction within the field of building circularity research. The concept aims to slow down resource loops by creating buildings that accommodate physical changes, thereby facilitating service life extensions. While there are self-evident motivations to apply such strategies to non-renewable and carbon-intensive building materials, there are particular benefits of applying them to timber as well. Extending the use phase of timber products promotes resource efficiency and waste reduction, with the added benefit of prolonged carbon storage. The common concept of Design for Adaptation is, however, mainly concerned with non-structural building adaptations. If the load-bearing structure is damaged, or extensive conversions are needed, the building may face demolition still.

This thesis introduces the concept *Design for Structural Adaptation* (DfSA) and applies it to load-bearing timber structures. The subsequent research work described in this thesis is based on the assumption that an implementation of DfSA for timber would be beneficial from an environmental perspective, but perhaps not feasible from an industry perspective. Thus, there is a need to determine the industry potential to implement DfSA for timber. The future development of the concept should further be based on key enablers of an industry implementation, which have yet to be identified.

The thesis lays the foundation for the future development of the concept DfSA for timber buildings. The benefits and barriers to an implementation are investigated by conducting semi-structured interviews with industry stakeholders in Sweden and Australia. Subsequently, the actions needed to overcome the identified barriers are determined, resulting in a roadmap towards implementation. Lastly, the practical and economic implications of implementing the concept are investigated in a Swedish context. The process of adapting a structurally adaptable timber building is mapped, and important considerations to facilitate the process are identified. To investigate the long-term economic perspective, a cost-benefit analysis calculation model is developed. This model is then used to determine whether investing in a timber building's adaptability is economically feasible, and how this economic feasibility can be increased.

The results show that there is currently a lack of direct economic benefits to motivate industry decision-makers to an implementation of DfSA for timber. However, the future development of the concept may create stakeholder incentives. To achieve this, the development should focus on cost-effective technical solutions, both from a structural engineering perspective and for building and material traceability. The solutions should further be well-documented and communicated, to increase the likelihood of implementing this strategy for resource-efficient timber structures.

Keywords
Circular economy, Timber structures, Design for Adaptation, Structural Adaptability, Implementation research, Economic feasibility

Acknowledgment

The research presented in this thesis was conducted between May 2022 and October 2024 at Chalmers University of Technology, in the Department of Architecture and Civil Engineering and the Division of Structural Engineering. The research was conducted as part of the project "Design for Adaption for resource efficient timber structures", funded by the Swedish Research Council for Sustainable Development FORMAS through grant number 2021-02499.

I want to express my deep gratitude to my supervisors. To Robert Jockwer, thank you for your dedication and valuable input which has been imperative to the quality of this work. To Yutaka Goto, thank you for holding me to a high standard and for making sure that I am proud of myself when I reach it. To Mohammad al-Emrani, thank you for always offering valuable insights and words of encouragement. Thank you also to the newest edition to the team, Zhengyao Li. I have high hopes for our future collaboration. Additionally, I would like to thank my examiner, Holger Wallbaum, for his continued support.

As part of the work described in this thesis, I conducted research activities in Australia. I deeply appreciate this opportunity and the gracious hosting by the University of Queensland. In particular, I would like to thank Lisa Ottenhaus, Paola Leardini, and Lisa Kuiri for a warm welcome and a memorable stay.

I would also like to express my gratitude to the Swedish and Australian stakeholders who participated in this study. Your active participation in interviews and workshops has been vital to this research.

I would be amiss not to mention my Chalmers colleagues as well. I am fortunate enough to belong to two divisions, and I am grateful to them both for a warm and supportive work environment. I have a lot of fun at work, and it is not only because I like thesis writing. So, thank you to my wonderful colleagues in both the Structural Engineering Division and the Building Technology Division. I would particularly like to thank my deskmate Dorotea for great company and for my newfound love of '60s Italian pop songs.

To my family, thank you for always encouraging me to choose my own path. I sincerely could not have done it without you. And finally, to my never-ending source of love, support, and of-course-you-can-do-its: Simon. Thank you.

Vera Öberg, Gothenburg, 2024

List of publications

Appended Publications

[Paper I] **V. Öberg**, R. Jockwer, Y. Goto, Design for Structural Adaptation in Timber Buildings: Industry Perspectives and Implementation Roadmap for Sweden and Australia, (2024). *Manuscript submitted to Journal of Building Engineering and under revision as of 2024-11-01.*

[Paper II] **V. Öberg**, R. Jockwer, Y. Goto, M. al-Emrani, Designing Timber Buildings for Structural Adaptation: Economic Feasibility of an Implementation in the Swedish Construction Industry, (2024). *Manuscript submitted to Building Research and Information in 2024.*

Additional contributions from the author

[a] R. Jockwer, **V. Öberg**, L.-M. Ottenhaus, P. Leardini, Y. Goto, Towards Adaptability and Circularity of Timber Buildings, in: World Conference on Timber Engineering (WCTE 2023), World Conference on Timber Engineering (WCTE 2023), Oslo, Norway, 2023: pp. 1497–1505. https://doi.org/10.52202/069179-0203.

Abbreviations

BaU	Business-as-usual
CBA	Cost-benefit analysis
CLT	Cross-laminated timber
D&C	Design & Construct
DfA	Design for Adaptation
DfSA	Design for Structural Adaptation
GHG	Greenhouse gas
LCA	Life-cycle assessment
LCC	Life-cycle cost
NPV	Net present value
OFAT	One-factor-at-a-time

Contents

Chapter 1

1 Introduction

1.1 Background

Transitioning the construction industry to a circular economy (CE) is often cited as crucial in order to achieve goals for sustainable development [1,2]. The motivation behind this view typically lies in the sector's major impact on annual global greenhouse gas (GHG) emissions, resource consumption, and waste production. While the increased use of timber as an alternative to other structural materials is often motivated by the same factors, circular thinking is also of value for timber structures. Maintaining timber resources at a high-value level for a longer time prolongs carbon storage and reduces atmospheric GHG concentrations [3,4].

A structural timber product is at its highest value level at its first use, for instance in a building. If the service life of the building is prolonged, so is the use phase of the timber product. Prolonging the service lives of buildings is a core strategy for building sustainability, leading to the Design for Adaptation (DfA) concept. The concept aims to facilitate service life extension of buildings, and by extension their contained materials, by designing them to accommodate future changes [5–7]. DfA has typically been concerned with non-structural changes, for instance functional changes that make use of movable partition walls. As such, demands for more drastic changes or structural repairs are typically not accommodated by the general DfA concept. As contemporary load-bearing timber structures are typically complex and expensive to alter [8], drastically changed user demands or structural damages may instead lead to demolition. To avoid these causes of demolition and prolong the service life of timber buildings, there is a need to design load-bearing timber for structural adaptability. In this thesis, the concept Design for Structural Adaptation (DfSA) is defined and applied to the context of structural timber. The concept has clear potential for resource efficiency and environmental sustainability, but the feasibility of implementing it in the construction industry is unknown. Before the technical development of the concept commences, it is desirable to investigate whether an industry implementation is feasible at all. The development of the concept should further be based on how the feasibility of an implementation can be increased.

This thesis investigates the industry potential to implement DfSA for timber buildings by exploring stakeholder perspectives and applying the concept to a practical and economic context. The potential benefits and barriers to an implementation are determined, and key actions to overcome the barriers are established. The practical and economic implications of an implementation are investigated, leading to a foundation for the future development of the concept.

1.2 Aim and research questions

This thesis aims to contribute to the ongoing development towards increased resource efficiency in timber structures, promoting sustainability in the construction industry. In particular, this thesis explores the possibilities of implementing adaptable design of timber structures to facilitate service life extensions of timber buildings.

While developed CE strategies for buildings are typically shown to be advantageous from an environmental perspective, many of them have not been adopted as commonplace in the industry. Rather than due to technical challenges, the main identified barriers to such implementations concern a lack of stakeholder incentives and systems in place to support an industry implementation [9–12]. DfSA, in turn, is not yet developed in terms of technical solutions. Yet, efforts to solve the technical challenges of DfSA for timber run the risk of being in vain if the development does not consider the prerequisites for an industry implementation.

Thus, this thesis investigates what the possible benefits for stakeholders are, any potential barriers, and what can be done to overcome the latter. The thesis consists of three studies. Study A serves as an introductory feasibility study, where stakeholder perspectives are collected and analyzed. Study B contributes with a closer look at the specific practical implications of implementing DfSA in the Swedish construction industry, whereas Study C investigates the corresponding economic implications. Studies B and C further contribute to the research aim as key considerations for the development of the concept are determined.

The following two initial research questions were identified:

- *RQ1: What are the stakeholder benefits and barriers to an implementation of DfSA for timber?*
- *RQ2: How can the feasibility of a successful implementation of DfSA for timber buildings be increased?*

Research questions 1 and 2 were addressed in Study A. The results of the study revealed that more information was needed to fully answer RQ2. To fill this gap, a third research question was added:

- *RQ3: What are the practical and economic implications of applying DfSA to a specific timber building project?*

Research question 3 was subsequently split into two sub-questions:

- *RQ3a: What are the **practical** implications of applying DfSA to a specific timber building project?*
- *RQ3b: What are the **economic** implications of applying DfSA to a specific timber building project?*

RQ3a was addressed in Study B, while RQ3b was addressed in Study C. Table 1 shows the relationship between the studies included in this thesis and the research questions.

Table 1: Relationship between included studies and research questions.

	RQ1	**RQ2**	**RQ3a**	**RQ3b**
Study A *Industry perspectives*	X	X		
Study B *Practical implications*		X	X	
Study C *Economic implications*		X		X

It should be noted that while this thesis continually uses the phrase “DfSA for timber”, it solely focuses on timber buildings. The phrase should henceforth be understood as the strategy of designing a timber building’s load-bearing structure for adaptation.

1.3 Limitations

Study A focused on the timber industries of Sweden and Australia. These countries were chosen as representatives for regions with active timber markets, but with different prerequisites to support those markets. Sweden has a positive supply-demand balance, exporting a majority of its yearly production of sawn timber [13]. Thus, it can be seen as representative of other countries where structural timber is frequently used and the demand is fully met by domestic production. Examples of such countries include northern European countries, Canada, and Russia. Countries that partly rely on imports to supply their domestic demand for structural timber, e.g., the United Kingdom and France, are instead represented by Australia in Study A.

Study B and C of this thesis only focused on Sweden. This narrowed scope was motivated by the fact that construction processes and costs may vary between countries. When applying DfSA to a specific case, while theoretical, the case study building ought to be placed in a real context. Still, the costs used in Study C were converted from the Swedish currency SEK to Euro. This choice was made to enhance the study's international comprehensibility.

1.4 Thesis outline

The chapters of this thesis are outlined below.

Chapter 1: Introduction
This chapter introduces the research work with a short background, followed by a presentation of its aims, research questions, and limitations.

Chapter 2: Conceptual framework
The conceptual framework lays the theoretical foundation for the studies included in this thesis. It expands on important topics and concepts such as circular economy, the intersection of timber and circularity, building obsolescence, DfA and DfSA, and the terminology of building adaptation.

Chapter 3: Methods
This chapter presents the methods chosen for Studies A, B, and C respectively.

Chapter 4: Findings and discussion
In this chapter, the findings from Study A, B, and C are presented and discussed separately. This chapter also contains a reflection on the chosen research methods.

Chapter 5: Conclusions and future research
In this last chapter, conclusions are drawn for each of the research questions one by one. This is followed by a section on overall conclusions. Lastly, recommendations for future research work are presented.

1.5 Summary of appended papers

1.5.1 Paper I

Paper I defines the concept of DfSA for timber and presents an introductory feasibility study of its implementation. Semi-structured interviews were held with timber industry stakeholders in Sweden and Australia, and a thematic analysis of the results was conducted. This resulted in a collection of stakeholder perspectives on DfSA for timber and a list of actions needed to facilitate its implementation. The study concluded that while DfSA for timber is in line with local and global sustainability goals, barriers such as cost and technical solutions need to be addressed and resolved to facilitate an implementation.

1.5.2 Paper II

Paper II explores the concept of DfSA for timber further by exploring its economic feasibility. A cost-benefit analysis (CBA) calculation model was developed and used in a comparison between DfSA and the business-as-usual (BaU). The study concluded the most crucial factor to promote the economic feasibility of DfSA is its realization cost – i.e., the added investment needed to make a timber building structurally adaptable

Chapter 2

2 Conceptual framework

2.1 Circular economy

2.1.1 Core concept

Looking at the major environmental impact of the construction industry, it is clear that there are issues with the BaU way of building. Immense amounts of natural resources are extracted to construct buildings that are often used for less than the typical intended service life of 50 years [14–17]. At the end-of-life of an average building, essentially all materials of which it was built become waste. Critique of this linear economic model, typical for most current product value chains, has been growing in line with the global awareness of the environmental toll of consumption. In the contrasting CE model, the "take, make, waste" model of the linear economy is replaced with a "reduce, reuse, recycle" philosophy [18]. These initial three CE principles, often referred to as *the three Rs*, have in time been expanded to include 10 principles in descending priority: *the ten Rs*. These principles and their priority, according to Cramer [19], are illustrated in Figure 1.

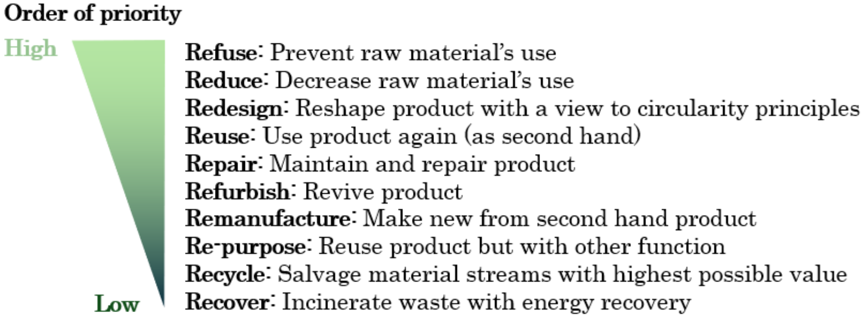


Figure 1: The ten Rs of circular economy. Figure adapted from Cramer [19].

Four general strategies have been proposed to facilitate a value chain's transition to CE: *Narrow*, *Slow*, *Cycle,* and *Regenerate* [20,21]. These strategies are illustrated from a building's perspective in Figure 2. In all of these strategies, the design phase is crucial [20]. In fact, circular economy is primarily made possible by design choices [22]. If the product in question is a building, lean design narrows the resource flows necessary for construction. Designing robust, high-quality buildings with future use scenarios in mind can slow the loop by prolonging the use phase. By using non-toxic, regenerative materials in the building, more natural resource loops can be achieved. Finally, designing for component and material reuse closes the loops of individual building parts beyond the building's service life.

This latter idea of designing a building so that its materials and components can be reused after its end of life has gained significant traction in recent years. It is the philosophy behind the concept *Design for Deconstruction* (sometimes *Design for Disassembly*). Among Cramer's [19] ten Rs, this concept can be placed in the reuse – or perhaps remanufacture – category. The concept of this thesis, on the other hand, adopts a larger scope: facilitating the reuse of entire buildings by designing them to be adaptable.

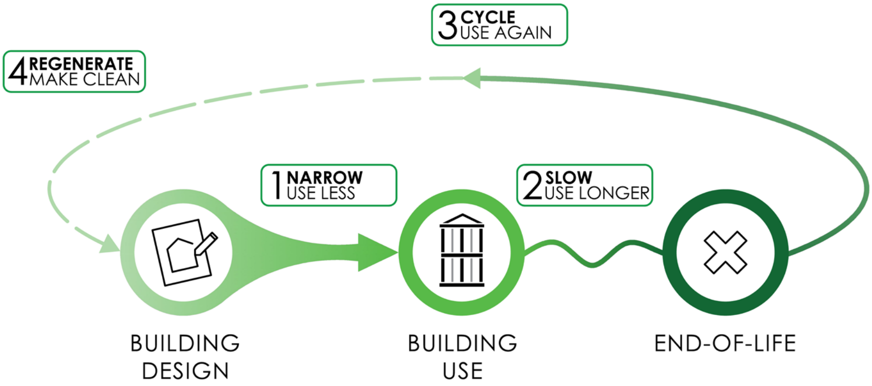


Figure 2: Illustration of four key strategies for CE in a building's life span. Figure adapted and developed from The Circle Foundation [20].

2.1.2 Circularity and timber

The reuse of timber elements can be seen as the first step in the material's cascading chain. Wood cascading is a resource efficiency strategy to maximize timber utilization through its lifespan, from virgin material to incineration [23,24]. The first product, e.g., a beam, may be reused as a shorter beam, then made into a particle-based product, to a fiber-based product, to a chemical product, and finally, incinerated [25]. The need to cascade the material before reuse can be considered unique to timber when compared to other structural materials. Steel waste, for instance, may be recovered and turned into new products. Yet, a timber particle board cannot be converted back into a sawn timber beam. Hence, timber beams are either sourced from new trees or cut from previously used beams.

At the end of the cascading chain, the wood is considered waste and is thus incinerated. Wood waste incineration is commonly referred to as "green" energy production, as the carbon released by incinerating wood was originally captured by the growing trees [25,26]. There are clear environmental benefits of wood incineration if it is used to avoid landfill and replace fossil fuels. However, the wood waste being incinerated is typically treated with coatings and adhesives, creating additional GHG emissions upon incineration [25]. Moreover, postponing the eventual incineration of a timber product prolongs its carbon storage. Thus, there is an environmental gain in keeping timber resources at a high material value level for as long as possible, and only incinerate them as a last resort when the only other viable option is landfill [4,26]. This thinking is further illustrated by the order of priority within circular economy principles, previously discussed in Section 2.1.1. While energy recovery through incineration can be part of a circularity strategy, it is subordinate to product or material reuse. In Europe, however, there is a tendency to opt for incineration rather than reuse, likely due to the financial gains of the former [25–27]. Additionally, northern and central Europe have a large availability of wood resources, decreasing the incentives for reuse. In Australia, timber waste is often landfilled rather than incinerated [28]. Wood waste landfills are sometimes considered carbon sinks, yet they may also be significant sources of carbon dioxide and methane as the wood decomposes [29]. Hence, to prolong the carbon storage of a piece of wood, efforts should be made to postpone its eventual status as "waste" through prolonged use phases.

While timber is frequently claimed to have a high reuse potential [11,30,31], it tends to be outranked by steel within categories such as demountable connections [11,32]. Without demountable connections, the reuse of individual timber elements typically relies on a certain reduction in lengths or cross-sections [33]. For structural columns, length reductions may render them unusable for structures with certain floor-to-ceiling heights. For beams, a reduction in length or cross-section may necessitate a decrease in spacing between supporting columns. This can, in turn, increase the needed amount of timber and steel for new columns to the point where timber reuse becomes an unfavorable option from a holistic sustainability perspective [33]. Hence, while material and product reuse are vital principles within the circular economy model, there may be more resource-efficient options to consider in some cases.

At the top of the circular economy priority list, we find the principles of *refuse*, *reduce,* and *redesign* [19]. For buildings, these principles aim to reduce the need for new construction by continuing to use what already exists. The principle of *repair* is also relevant to this aim. As mentioned previously in this thesis, designed adaptability is motivated by the need for buildings that promote these principles. But for timber buildings, the need to design for the ability to be structurally rehabilitated, renovated, or converted used to be less critical. Traditional timber buildings, e.g., log houses, can be considered inherently adaptable due to small constructions and simple designs, along with a high degree of prefabrication and modularity [8]. This allows for local changes or repairs of the structure, but also major actions like building relocations or global adaptations. An example of such an adaptation can be found in the 16th-century Swiss log house shown in Figure 3, where an intermediate story was added during its service life [34].

Figure 3: Adapted 16th-century log house in Evolène, Switzerland. Image from [34].

Contemporary timber structures are, on the other hand, not inherently suited for adaptations. In contrast to low-rise log houses, modern timber construction utilizes engineered wood products to build large, complex structures. These structures demand high-performance connections that typically do not qualify for disassembly or adaptability [8,11]. The size and function of contemporary timber structures further complicates adaptation. For instance, installations integrated into the load-bearing structure make structural adaptations difficult, if not impossible [35,36]. Another example is the optimization of structures to fit the specific function they were built for, which limits the possibility of functional changes [12,37]. In short, to allow for changes and repairs of contemporary timber structures, adaptability needs to be considered in the design phase.

2.2 Design for Structural Adaptation

2.2.1 Building obsolescence and its consequences

If a building is considered useful for a long time, it has a slow use cycle which minimizes the need for replacing it with a new building. Still, there does come a time in a building's life when its usefulness is considered to be too low for its continued usage to be considered beneficial to the user. In this thesis, this condition will be called building obsolescence, as it is a common term within the field of prolonging building service lives [38–40]. It should be noted that this thesis' definition of obsolescence is "a complete lack of desirability", as opposed to the broader meaning of "outdated" or "old-fashioned". An obsolete building is one that the owner has no intention of further using while in its current state. This can be caused by, for instance, aesthetic, financial, or structural obsolescence [40] in which different aspects of the building's value are lacking. In the end, the financial criteria have been found to be the leading determinant in the decision of whether to demolish a building [41]. Still, any type of obsolescence may cause demolition as they affect and cause each other. For instance, aesthetic obsolescence (i.e., an outdated appearance) may cause financial obsolescence. The same applies to structural obsolescence: If the structure cannot fulfill the owner's demands on it, the building may also become financially obsolete. If so, it may either be fully replaced, simply demolished, abandoned, or adapted.

Based on this, Jockwer et al. [42] proposed that a building can be considered obsolete if it fails to fulfill the following criteria: a) There is a demand (D) for the building's function in its location ($D \neq 0$), and b) the building's ability (A) is greater than the demand on it ($D < A$). A newly constructed building typically fulfills the criteria. Yet, after some time, a change will occur to either the building's demand or ability. The rational option of actions in response to these changes and the consequences of each action is illustrated in Figure 4. Note that this is a simplified model that does not take all possible consequences into account. The model is further based on assumptions regarding the weight of each consequence. A full building replacement is, for instance, assumed to cause more waste production, GHG emissions, resource consumption, and financial cost than a building adaptation.

Naturally, this varies on a case-by-case basis. For instance, an extensive and complex building adaptation could prove more costly than a building replacement.

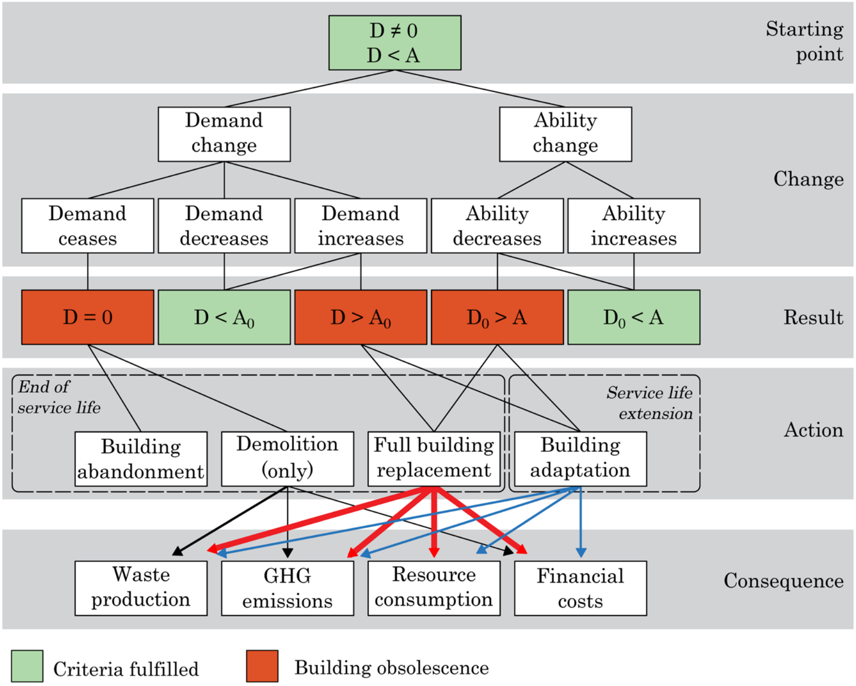


Figure 4: Simplified illustration of the effect of ability or demand changes to a building, based on the criteria that a demand exists, and the building's ability is greater than the demand. Figure adapted from Jockwer et al. [42].

A building abandonment or a demolition without replacement is likely caused by a complete cessation of demand for a building at its specific location. For instance, a building tied to a remote mining operation may be abandoned or demolished if the mine is depleted. For more populated areas, on the other hand, a ceased demand for a building's specific function is more likely to lead to a building replacement to fulfill another type of demand. If an office building in a city is no longer financially viable, it may be replaced by a building with a different function – e.g., residential.

The other option for such a building would be to adapt it to fulfill a new functional demand. The feasibility of such an adaptation depends largely on the building's layout and structure. In general, though, functional conversions of commercial and non-historic buildings occur to a very limited extent due to financial and technical uncertainties [10,41,43].

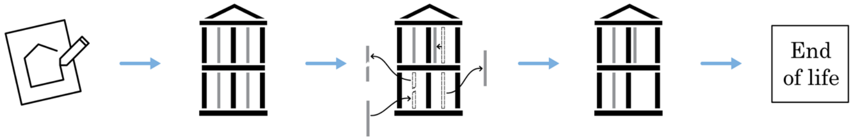
Besides demand changes, a need for building replacement or adaptation can arise if the building itself changes. In other words, the building's ability to meet the demands on it can decrease over time. This change could be gradual, due to deterioration, or sudden, due to unexpected events such as a fire. The repair work of a damaged or deteriorated building can also be labeled as adaptation. Naturally, the extent and nature of the needed repair work significantly affects whether such an adaptation will be conducted or if the building will be demolished instead.

As the decision between building abandonment, replacement, demolition, and adaptation heavily relies on the technical feasibility and expected financial outcome, the environmental implications are secondary. While it's clear that building adaptations have significant environmental advantages [44–46], adaptation prioritization is not feasible if its cost and complexity are too high. The idea of designed adaptation is to facilitate low-cost and easy adaptations, to tip the scales in favor of service life extension. Since avoiding building obsolescence altogether is unrealistic, efforts can instead be made in the design phase to increase the chances of a sustainable choice once obsolescence occurs.

2.2.2 DfA and DfSA

Design for Adaptation (DfA) is an emerging strategy to promote a building's ability to accommodate changes needed to circumvent building obsolescence [5–7]. The concept generally focuses on facilitating functional changes that do not interfere with the building's load-bearing structure. The structure still plays a vital role in this concept. By increasing ceiling heights and spans, and designing for increased live loads, the structure can allow for functional changes by simply changing the building's non-load-bearing elements [7,47]. Yet, if drastic functional changes or structural repairs are needed, the general concept of DfA falls short. *Design for Structural Adaptation* (DfSA) aims to address such needs. The focus is, instead, to design the load-bearing structure to be adaptable in itself. The demarcation between DfA and DfSA is illustrated in Figure 5. In the DfA building, only the non-structural parts are moved, removed, or replaced. In the DfSA building, these changes are instead applied to the structure, because of damages or drastic functional changes. It should be noted that while DfA is labeled as *functional* adaptability design, DfSA could also encompass functional changes.

Design for (functional) Adaptation (DfA)



Design for Structural Adaptation (DfSA)

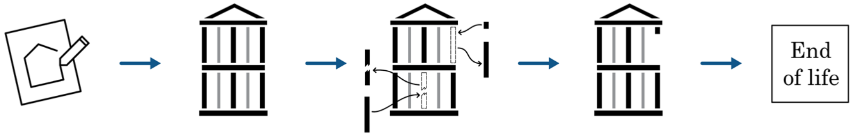


Figure 5: The concepts DfA and DfSA illustrated. Figure adapted from Jockwer et al. [42].

Until recently, representations of designed adaptability in standards and regulations have been rare. In 2020, though, the International Organization for Standardization (ISO) published standard ISO 20887: "Sustainability in buildings and civil engineering works – Design for disassembly and adaptability – Principles, requirements and guidance" [48]. This standard lists principles to be considered when adopting DfA in a construction project. Again, a demarcation should be made between DfA and DfSA since ISO 20887 is only concerned with functional changes. Hence, the concept of repairability is not considered in the standard.

DfSA does, however, consider both functional changes and repairability. An illustration of the elements affected by such interventions can be found in Figure 6.

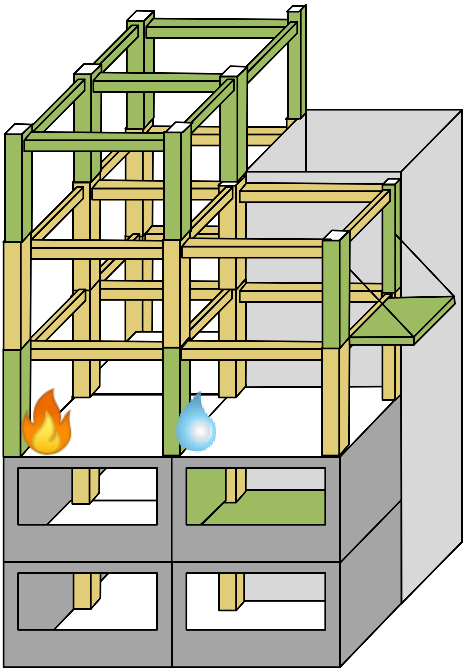


Figure 6: Illustration of a structurally adaptable building, where the elements affected by functional changes or repairs are highlighted in green.

In Paper I of this thesis, the concept of DfSA was defined and investigated in the context of load-bearing timber. Seven key design characteristics of DfSA for timber buildings, illustrated in Figure 7 were determined. These characteristics are a guide in the development of DfSA, showing which design features a timber building should have in order to be called structurally adaptable. It should be *traceable*, so that crucial information needed to perform adaptations is not lost. The structure should be *resilient* to changed loads and load paths caused by adaptations. This characteristic is associated with a certain increased material demand, which can be seen as conflicting with another resource efficiency strategy – namely, lean design. As such, an adaptability strategy should not strive for universal adaptability [12,49,50]. Consequently, the next design characteristic is *targeted*. That is to say, the building should be designed with the most probable future adaptation needs in mind. The building should also be *layered*, in reference to Brand's [51] shearing layers of change. This entails some separation between the building's structure and its other system layers such as the façade or service layer. For instance, structural adaptation is more feasible if the ducts and cables from the service layer are not embedded in the structure [35]. The building's layout and design should also be *simple*, as predictability and standardization are widely recognized enablers of adaptability [36,52–54]. The building should be *durable*, as high-quality, non-toxic materials and a robust structure will increase the likelihood of a decision to adapt rather than demolish it [55]. Lastly, the structure should be *reversible* – i.e., its structural connections should allow for the removal and replacement of structural elements.

Some of these characteristics are – to an extent – already included in buildings today, such as simple and durable design. Others need more research and development to be realized – reversible and targeted adaptability design in particular.

It should further be noted that while these design characteristics are defined with structural timber in mind, they are partly based on non-material-specific literature. Some characteristics may be directly applicable to other structural materials such as steel or concrete. Others may be used as general themes, while keeping in mind that the specific considerations for such characteristics would be material dependent. For instance, the solutions to ensure reversibility in a timber structure would likely look vastly different to those for reversible steel or concrete structures.

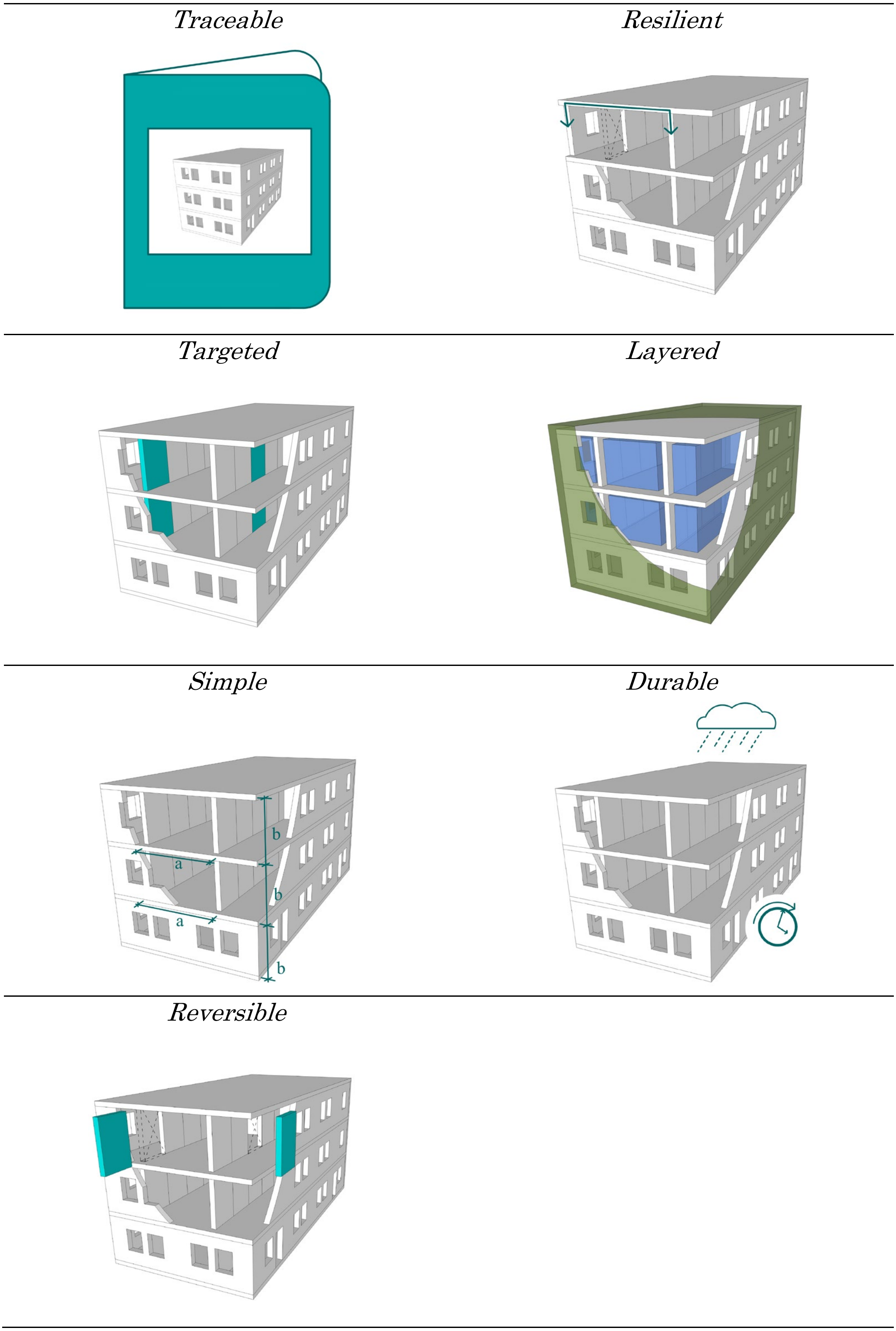


Figure 7: Key design characteristics of DfSA for a timber, illustrated for a panel structure.

2.2.3 Terminology of building adaptation

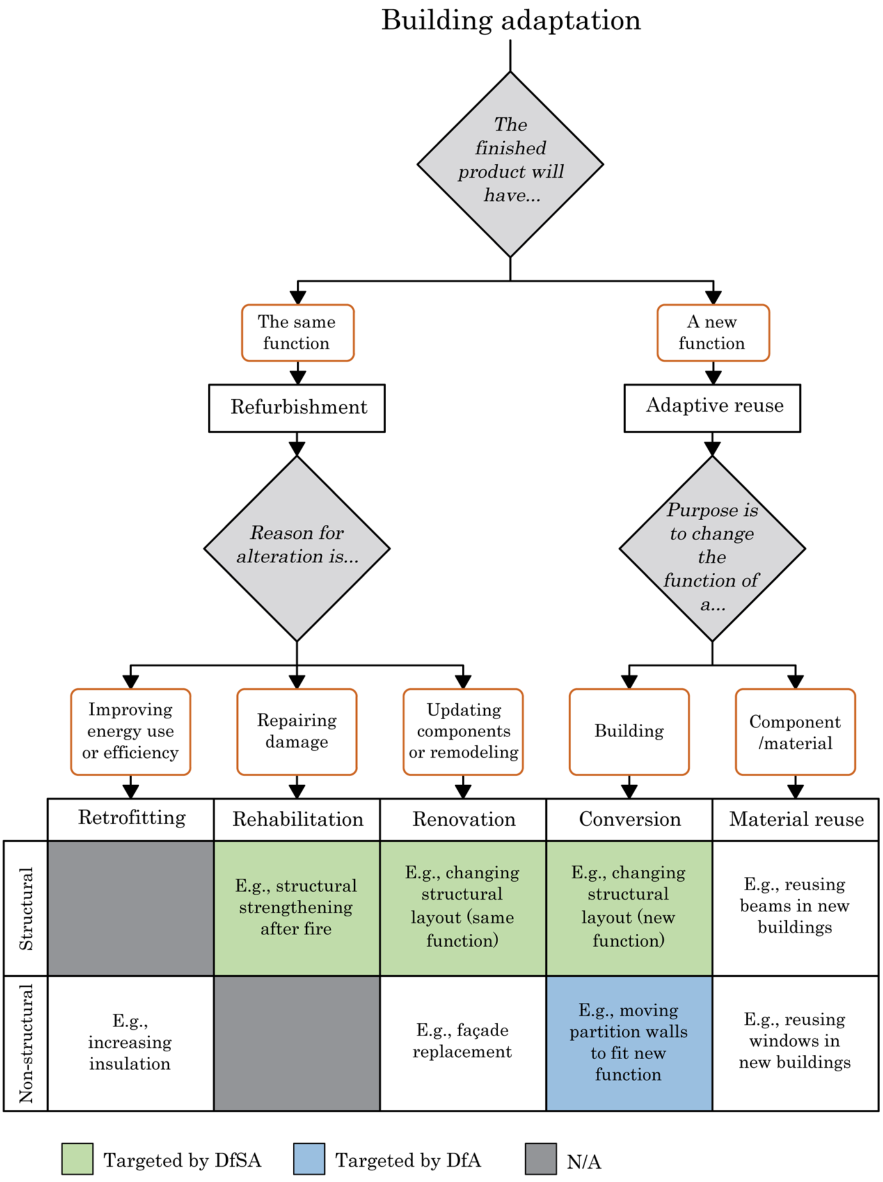
Academic discussions on building adaptability have been growing in numbers since the 1990s [37]. The definitions of building adaptability have varied somewhat, but they usually refer to a building's ability to change in some way to facilitate an extension of its *useful life* [40,44,45,56]. This expression can be interchanged with *service life* for engineering aspects.

The term adaptability is sometimes conflated with flexibility, although a distinction should be made between the two. Askar et al. [52] find varying interpretations of the two phrases in academic literature, although they allude to a theme of different magnitudes. Flexibility seems to generally concern smaller-scale, more frequent and quicker changes than adaptability [52,57]. Kuiri and Leardini [58] further suggest that a flexible building should be understood as one that allows for changes that do not alter the building's physical fabric. An adaptable building, on the other hand, is generally interpreted as one that allows for physical changes to the building [52,58,59]. By extension, the phrase *building adaptation* can be used as an umbrella term for any intervention to a building's physical fabric.

According to Shahi et al. [59], such interventions can be sorted into two categories split into five subcategories of actions. If the finished product will keep its original function, the intervention could be called *refurbishment*. The actions within this category are *retrofitting* (improving energy use or efficiency), *rehabilitation* (repairing damage) and *renovation* (updating components or remodelling). If the finished product will serve a new function, it is instead called *adaptive reuse*. The purpose of adaptive reuse could either be to change the use of a building, as in *conversion*, or a component or material, as in *material reuse*.

The five action categories described above are shown schematically in Figure 8. The figure also contains a demarcation of structural and non-structural actions, again based on Shahi et al. [59].

It should be noted that scholars differ in the use and definition of these concepts. For instance, while the term *retrofitting* generally refers to improvements in energy performance, the word is sometimes used to describe interventions for seismic performance [60–62]. In these cases, the interventions can certainly be labeled as structural. However, this kind of work can also be seen as component updates to improve the building's seismic resilience. Thus, seismic retrofits are labeled as structural renovations in this thesis.



	Retrofitting	Rehabilitation	Renovation	Conversion	Material reuse
Structural	▨	🟩 E.g., structural strengthening after fire	🟩 E.g., changing structural layout (same function)	🟩 E.g., changing structural layout (new function)	E.g., reusing beams in new buildings
Non-structural	E.g., increasing insulation	▨	E.g., façade replacement	🟦 E.g., moving partition walls to fit new function	E.g., reusing windows in new buildings

🟩 Targeted by DfSA 🟦 Targeted by DfA ▨ N/A

Figure 8: Overview of the terminology of building adaptation, based on Shahi et al. [59] and further developed to demonstrate the concepts' relation to DfSA and DfA.

Using Shahi et al.'s definition framework as a foundation, it is possible to identify the specific intervention types that are relevant to a DfSA strategy. According to the definition of *retrofitting* described above, this category should not be included. Neither should *material reuse*, as DfSA is concerned with the reuse of entire buildings. Yet, it is worth noting that designed adaptability can be an enabler of material reuse after the building's end of life [63,64].

The intervention types that should be targeted by a DfSA strategy include *rehabilitation, structural renovation,* and *structural conversion*. As alluded to earlier in this thesis, DfSA both limits and expands the concept of DfA. It limits the concept by specifying the focus on *structural* adaptability, and it expands it by including non-functional changes in its aim.

Chapter 3

3 Methods

3.1 Overview

The research questions were addressed in three studies, Studies A, B, and C, which resulted in Paper I, Paper II, and Section 4.2 of this thesis. The chosen methods in relation to these studies and papers are outlined in Figure 9.

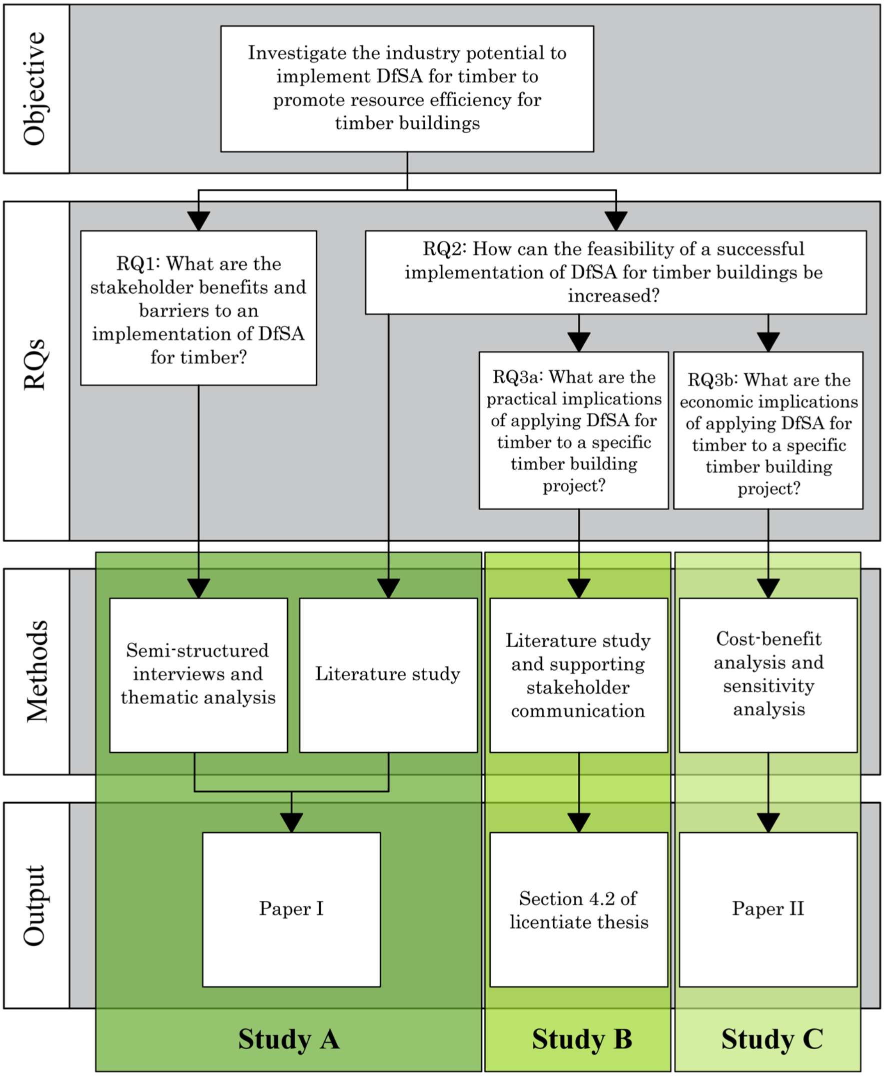


Figure 9: Outline of research framework.

3.2 Study A – Introductory feasibility study

Study A addressed RQ1 and RQ2 with semi-structured interviews and a thematic analysis, as well as a literature study. These methods are described in the following sections.

3.2.1 Semi-structured interviews and thematic analysis (RQ1)

To determine the stakeholder benefits and barriers to an implementation of DfSA for timber, stakeholder communication was set up for two groups. The groups are hereafter referred to as the Swedish group and the Australian group. These two countries were chosen to promote the scalability of the results, as described in Section 1.3.

In total, the groups consisted of 22 stakeholders from different parts of the industry: architects, housing providers, contractors, developers, engineers, consultants, timber manufacturing associates, researchers, and representatives from timber industry associations. Semi-structured interviews with open-ended questions were conducted with the stakeholders, to allow for free reflections on this new topic. In the Australian group, the interviews were held separately with each interviewee. For the Swedish group, on the other hand, a collective interview was conducted in a focus group. This combined approach was chosen for methodological triangulation. The separate interviews allowed for more detailed input from each interviewee, while the response from focus group participants was enriched by reciprocal idea exchanges and collaborative discussions.

In the focus group and the separate interviews, the stakeholders were asked to reflect on the following questions from the perspective of their professional field:

1. What would be the benefits of implementing design for adaptation for timber structures?
2. What would be the risks or disadvantages of such an implementation?
3. What would be the obstacles to such an implementation?

The separate interviews were recorded and transcribed, while the input from the focus group meeting was written down during the meeting and in consensus with the participants. A thematic analysis was subsequently conducted on the notes and transcriptions, to find the common themes among the results. The results of this analysis are presented in Paper I.

3.2.2 Literature study (RQ2)

In Study A, the results of the abovementioned thematic analysis were complemented by a literature study addressing how to overcome the perceived barriers. These results are presented in Paper I. However, a lack of sufficient information in published literature led to a further investigation of RQ2 in Studies B and C.

3.3 Study B – Practical implications

To address RQ2 and RQ3a, the process of adapting a DfSA timber building was mapped in the context of the Swedish building industry. The results are presented within this thesis.

3.3.1 Literature study and supporting stakeholder communication (RQ2 & RQ3a)

In order to map the process of adapting a DfSA timber building, an equivalent map was first created for the BaU adaptation process. It is, however, important to note that the structural adaptations of timber buildings that may be possible in the BaU are not necessarily the same adaptation types that are targeted by DfSA. The main aim of DfSA is to enable structural adaptations that would not have been possible for BaU buildings. However, Study B was based on the assumption that the phases and actors in the adaptation process would not change depending on the extent of the performed adaptations. Thus, the process of adapting a DfSA structure was based on the process of a, presumably less extensive, BaU adaptation.

The different phases and actors of the adaptation process were determined based on a literature study. This information was confirmed by an expert on the Swedish building process. Subsequently, the design characteristics of DfSA for timber (see Section 2.2.2) were applied to each phase to assess the practical implications of DfSA.

The mapped adaptation process was based on a design-and-construct (D&C) procurement model. This model was chosen as it is common to procure D&C contractors for adaptation projects in Sweden.

3.4 Study C – Economic implications

In this section, the CBA model developed in the exploration of RQ3b is described. Subsequently, the sensitivity analysis of the CBA is outlined. This analysis served as a continuation of the investigation of RQ2. The results of the CBA and sensitivity analysis are presented in Paper II.

3.4.1 Cost-benefit analysis (RQ3b)

To assess the economic implications of designing a given timber building for structural adaptation, a comparative scenario was set up. Two options were applied to a theoretical multi-residential building in Sweden. First, a BaU option which is demolished and replaced as structural obsolescence occurs. Second, a DfSA option which is adapted rather than replaced when faced with structural obsolescence, courtesy of an added DfSA realization cost at the project's initiation. The two alternatives are illustrated in Figure 10, where structural obsolescence occurs every *x* years. As shown in the figure, the chosen study period is 100 years. After this, it was assumed that the DfSA building would be demolished for a reason other than structural obsolescence, such as aesthetic or locational obsolescence. To enable a fair comparison to Alternative 0, a residual value was added to represent the potential remaining years of usage of the last building.

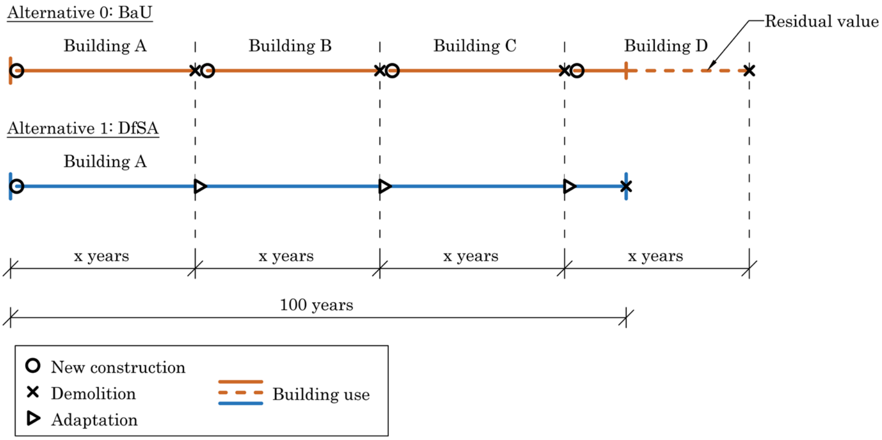


Figure 10: Graphical representation of the timelines of the alternatives investigated in the CBA.

A CBA calculation model was subsequently developed to compare the two alternatives. The main obstacle in this step was that there is a lack of statistics on structural obsolescence in timber buildings. Thus, the CBA model could not be based on an average scenario where structural obsolescence occurs a certain number of times within the studied period. Instead, the average occurrence rate of structural obsolescence was included as the variable *x*. By investigating the net present value (NPV) of the two alternatives for a range of *x*, a break-even point could be found. That point demonstrates how often structural obsolescence would have to occur for the DfSA alternative to be more economically feasible than the BaU.

The CBA model was based on the assumption that structural obsolescence always leads to demolition in a BaU building. This is a simplification. As discussed in the previous sections, structural adaptations are sometimes carried out on BaU buildings. However, they are often complex and expensive. If the needed adaptations are extensive enough that the cost is comparable to that of new construction, a full replacement tends to be chosen [65]. The purpose of DfSA is to avoid demolition by facilitating such adaptations. Thus, the CBA model was exclusively modeled around such extensive adaptation needs.

The size and construction cost of the theoretical buildings were based on the choice of cross-laminated timber (CLT) as a structural material. The calculation model could be applied to buildings of other structural systems by adjusting these factors accordingly.

3.4.2 Sensitivity analysis of CBA (RQ2)

For the last part of addressing RQ2, the aim was to determine the factors that would have the greatest effect on DfSA's economic feasibility.

To find the most influential factors determining a DfSA project's economic feasibility, a sensitivity analysis was performed for the CBA model described in Section 3.4.1. With the model, one can calculate the NPV of a BaU timber building and a structurally adaptable one. Monetary costs and benefits are defined for each included variable. Thus, a one-factor-at-a-time (OFAT) analysis could be conducted. The factors investigated in this analysis were:

- Building size
- Cost of new construction (including design costs)
- DfSA realization cost, i.e., the additional design, production and construction cost to facilitate structural adaptation
- Cost of demolition
- Cost of adapting a DfSA building
- Discount rate
- Monetary benefits of building use, e.g., rent
- Value depreciation rate, i.e., the rate at which the property loses value over time

For each factor, a baseline value was chosen based on statistics and examples found in literature. Subsequently, a lower and an upper value was set for each factor. These values are shown in Table 2.

Naturally, the costs related to DfSA are difficult to predict as DfSA for timber has not yet been implemented. To take this uncertainty into account, the spans between lower and upper values for these costs were increased considerably.

Table 2: Overview of chosen lower-, baseline and upper values for each factor in the CBA.

Variable	Lower value	Baseline value	Upper value
Building size (A)	A_ℓ = 5,000m^2	A_b = 10,000m^2	A_u = 15,000m^2
Cost of new construction (C_1)	$C_{1.\ell}$ = $A_b \cdot$ €2,767/m^2	$C_{1.b}$ = $A_b \cdot$ €3,418/m^2	$C_{1.u}$ = $A_b \cdot$ €4,069/m^2
DfSA realization cost (C_2)	$C_{2.\ell}$ = $0.02 \cdot C_{1.b}$	$C_{2.b}$ = $0.14 \cdot C_{1.b}$	$C_{2.u}$ = $0.40 \cdot C_{1.b}$
Cost of demolition (C_3)	$C_{3.\ell}$ = $0.10 \cdot C_{1.b}$	$C_{3.b}$ = $0.33 \cdot C_{1.b}$	$C_{3.u}$ = $0.50 \cdot C_{1.b}$
Cost of adapting a DfSA building (C_4)	$C_{4.\ell}$ = $0.50 \cdot$ €27,000	$C_{4.b}$ = €27,000	$C_{4.u}$ = $100 \cdot$ €27,000
Discount rate (r)	r_ℓ = 2.0%	r_b = 3.5%	r_u = 5.0%
Benefit of building use per year (B_1)	$B_{1.\ell}$ = $0.50 \cdot A_b \cdot$ €180/m^2	$B_{1.b}$ = $A_b \cdot$ €180/m^2	$B_{1.u}$ = $2 \cdot A_b \cdot$ €180/m^2
Value depreciation rate (d)	-	d_b = 0.0%	d_u = 2.0%

The OFAT analysis was subsequently conducted by keeping all factors except one at the baseline value while varying the remaining factor from its lower to its upper value. This was done for all factors respectively, to determine each factor's effect on the economic feasibility of DfSA for timber.

Chapter 4

4 Findings and discussion

In the following sections of this chapter, the results from Studies A, B, and C are discussed. This is followed by a reflection regarding the chosen research methods.

4.1 Study A – Introductory feasibility study

The interviews conducted in Study A showed little difference between the Swedish and Australian stakeholder groups. The thematic analysis resulted in three themes regarding stakeholder benefits (*sustainability and circularity*, *market competitiveness*, and *technical solutions*) and five regarding barriers (*general barriers*, *cost*, *policy*, *technical solutions,* and *traceability*). The themes are described and discussed in Sections 4.1.1 and 4.1.2.

The subsequent literature study to investigate how the identified barriers could be overcome resulted in a roadmap towards implementation. This roadmap is presented and discussed in Section 4.1.3.

4.1.1 Benefits of implementing DfSA for timber

Sustainability and circularity

Unsurprisingly, stakeholders saw many environmental benefits of prolonging the lifespan of timber buildings. In Sweden, stakeholders saw a connection to local sustainability goals and the EU taxonomy. The latter specifies the transition to circular economy as one of its six environmental objectives [66]. Australian stakeholders, while not directly affected by the EU taxonomy, saw a connection to their local sustainability objectives. Two main points were brought up. First, there are increasing demands for environmental conservation and sustainable forest management in Australia. Second, stakeholders predicted a future need for increasing the capacity of buildings rather than expanding the area of cities. The second point can be connected to the first one, as expansions of cities can negatively affect the surrounding environment and its natural habitats and ecosystems. It is also imperative to consider unsealed surface area in such countries as Australia, where many parts of the country are prone to floods. The change from natural landscape to man-made surfaces can significantly increase the flood risk of urban areas due to the loss of soil water storage [67].

Conversely, stakeholders also saw a possible risk regarding the sustainability of DfSA, in that it might demand too much material to prepare for a change that may never occur. Naturally, the conflict between lean design and adaptability needs to be considered. This conflict is the main motivation behind the characteristic of *targeted* adaptability – i.e., only preparing the building for a few likely scenarios rather than trying to implement universal adaptability.

Market competitiveness

If contemporary timber could, yet again, become an adaptable structural material, it could increase its competitiveness toward other alternatives. In the Australian group, stakeholders also mentioned that the country relies partly on imports to supply their domestic demand. Thus, resource efficiency would likely not hurt the sales of the domestic suppliers. The Swedish group, on the other hand, identified a possible risk of decreased sales as the domestic demand is more than fulfilled by Swedish timber production.

Technical solutions

Timber was said to have good prerequisites for the development of demountable connections, at least compared to cast-in-place concrete. If demountable solutions for adaptable timber could be found, stakeholders saw benefits related to standardization and prefabrication.

4.1.2 Barriers to an implementation of DfSA for timber

General barriers

The input placed within this theme regarded the general complexity of changing the standard practice of constructing timber buildings, and the fact that future adaptability needs are hard to predict. While the latter can be seen as a barrier to targeted adaptability, it can also be viewed as an argument for adaptability as a whole.

Cost

Barriers within this theme were among the most commonly identified within both groups. There is an assumption, held both by the stakeholders of this study and the author of this thesis, that an added investment is needed to realize DfSA within a project. This realization cost may encompass several things – e.g., added engineering hours in the building's design phase, more costly connection solutions, or an increased amount of material to make the building resilient to changed load paths. Swedish stakeholders also had concerns that DfSA may prolong on-site construction times. The Swedish timber industry is characterized by high prefabrication degrees and, by extension, quick on-site manufacturing. Prolonged on-site construction is another possible source of additional cost for DfSA. As DfSA could be considered non-essential to a building project, stakeholders believed that decision-makers would opt out of the DfSA realization cost unless it was reasonably low and well-motivated.

Policy

Though Sweden's and Australia's construction industries adhere to different regulations, the input within this theme was very similar between the two stakeholder groups. This input can be put into three sub-themes. First, building codes and regulations are not written with adaptability in mind, and changing them to incorporate adaptability would be a long and difficult process. Second, investing in adaptability is not clearly incentivized. This is, of course, related to the previous theme of cost. Without governmental incentives to implement DfSA, its realization cost may be too high for decision-makers. Third, building codes change over time. This could be a barrier to implementing DfSA since adapting a building may mean that the entire building needs to be updated to conform to the current building codes. This might discourage decision-makers from choosing to adapt the building. It is debatable, though, whether this possibility is a barrier or a potential benefit of DfSA. The main objective of DfSA is to allow for adaptations where a building might otherwise be demolished. Such a scenario could be that the building needs to be updated to meet new demands as it is being rebuilt for other reasons. A non-adaptable building may be demolished in such a situation due to the complexity of the required changes – whereas DfSA could facilitate them.

Technical solutions

There was a significant amount of input from stakeholders within this theme. They identified uncertainties regarding connection designs and how to support the structure while element replacements are carried out. Functional changes were also identified as complex as they can mean changed requirements for things like ceiling heights and the location and strategies for building services. Lastly, the prolonged service lives of timber structures partly relies on the longevity of remaining building parts and systems. Stakeholders noted that if the foundation is not built to last longer than the adapted timber structure, then its adaptability is in vain. Likewise, incentives for adaptation will decrease if the non-structural parts of the building cannot be maintained for this amount of time.

Traceability

The last found theme concerned the lack of an appropriate system for traceability. This was identified as important since structural adaptations would rely heavily on correct information about the building and its load-bearing elements.

4.1.3 Overcoming barriers to an implementation

Based on the identified barriers in RQ1 and the literature review, a roadmap to facilitate an implementation of DfSA for timber in Sweden and Australia was proposed. The roadmap consists of seven steps – or "actions" – that should be carried out before an implementation of DfSA for timber can be considered feasible. The seven actions of the roadmap are described below.

1. Develop, test, and document standardized reversible connection systems for adaptable timber structures.
2. Quantify the costs and benefits of DfSA to contextualize the added realization cost and material demand.
3. Conduct risk-based assessments of different types of timber buildings to enable targeted and well-motivated adaptability strategies.
4. Implement governmental incentives and regulations for circularity strategies, both in the design process and from a life-cycle perspective.
5. Develop building codes and standards for reversibility and adaptability.
6. Develop solutions for traceability with a special focus on adaptable timber structures.
7. Set up and carry out communication with stakeholders, demonstrating the benefits of DfSA and reducing uncertainty regarding its application.

In the continued work described in this thesis, it was noted that to carry out several of the actions listed above, more information was needed. Specifically, action 2 was considered a key step. The actions described by this step are two-fold: justifying the monetary realization cost and justifying the potential environmental cost of increased material demand. The latter is dependent on the results of action 1, whereas the former was considered a necessary step before carrying out action 1. That is, to develop useful technical solutions for structural adaptability, one needs to know how important the monetary cost of a solution is for its probability of being used. By investigating the factors influencing the economic feasibility of DfSA, this importance could be determined. This investigation was also deemed important to describe in more specific terms how the feasibility of an implementation could be increased, as cost was one of the main barriers identified by stakeholders.

In order to address actions 5, 6, and 7, there was also an identified need to know the practical implications of implementing DfSA for timber. By mapping the process of adapting a DfSA timber structure, the need for standards and traceability solutions could be expressed in more detail. The potential benefits of DfSA could further be explored from an applied, practical perspective.

4.2 Study B – Practical implications

4.2.1 Adaptation process map

As an initial step in this part of Study B, the process of adapting a Swedish timber building with a D&C contractor was mapped from the perspective of the different involved actors. Thirteen phases were identified and described, based on stakeholder communication and literature, from problem identification to handover. An overview of these is shown in Table 3. The table's design follows a similar structure as in "The Mass Timber Insurance Playbook" [68] and the Swedish industry standard "ByggaF" [69].

In the following, a detailed description of each of the table´s phases is given, together with recounts of how the phases are typically carried out in Sweden. Whether the building was designed for adaptation or not can influence every phase except phase A, problem identification. The effect is described under each headline.

It should be noted that while some parts of the described process are unique to Sweden, other parts apply to other countries as well since they describe typical conduct within the building process.

Table 3: BaU action plan for adapting a Swedish timber building's structure in a project with a D&C contractor.

Stage / Actor	Project initiation	Concept design	Technical design	Construction	Closure
Developer or client*	A. Problem identification B. Assessment	C. Setting goals and budget D. Procurement of D&C contractor	G. Technical demand specification		M. Handover
D&C contractor		E. Tender offer development	H. Procurement of sub-contractors / suppliers I. Production of construction documents	K. Construction	L. Production of as-built documents M. Handover
Engineer, architect	B. Assessment	D. Procurement of D&C contractor F. Solution proposal	I. Production of construction documents		L. Production of as-built documents
Timber manufacturer			(I. Production of construction documents)	J. Manufacturing	

*Usually, the owner or property manager

A. Problem identification

This phase can either begin when a structural problem becomes evident, for example after a routine inspection, or when something causes doubts for the owner regarding the structural performance of the building. The doubts, alternatively the apparent structural problems, may result in a reassessment of the structure. The situations that can cause a need for structural reassessment can be sorted into three categories: potential ability changes, potential demand changes, and doubts about the initial structural design. Steiger [70] identified the following situations that can cause such a need, here sorted into the aforementioned categories:

- Potential ability changes:
    - The structure has not been inspected for a long time, leading to suspicions of degradation or hidden damages.
    - An unexpected event, for example, a fire or an earthquake, has caused an extreme load that may have damaged the structure.
    - A routine inspection has shown unexpected issues such as degradation, damage, or inadequate serviceability.

    - The structure is still needed after its design life has passed, so an ability assessment is needed.
- Potential demand changes:
    - There is increased loading (e.g., increased live loads due to changed usage, or new snow drift loads caused by additions to the structure).
    - There is a demand for increased reliability.
    - There is a need for structural modifications or strengthening due to changes in building use.
- Doubts about the initial structural design:
    - Similar structures are not performing as demanded.
    - A routine inspection has shown construction or design errors, or deviations from the original construction documents.
    - There is new knowledge or revised design codes.

If the property owner deems the problem to be significant enough to warrant a structural assessment, they can commission one.

B. Assessment

The assessment is performed in a series of increasingly detailed phases, where the number of phases needed is determined by the remaining level of doubt, the feasibility of an adaptation, and financial considerations [71]. The assessments are normally commissioned by the developer and carried out by engineers, possibly together with a team of specific experts [72].

The actions within each assessment phase are determined by the goal of the reassessment. Examples of methods to assess the structure's ability are visual inspection, mapping of cracks, timber moisture content measurements, and load tests [71]. If the problem identified is related to a change in demand, the assessment may primarily focus on the building's construction drawings and specifications, which can be complemented with some on-site structural assessment actions.

The assessment aims to decide whether to demolish, adapt, or continue to use the building in the same way (or, when applicable, whether to reduce the loads) [72,73]. Below is a list of questions to be taken into consideration by the engineer in this phase, based on Blaß [74], Baker and Moncaster [75], and Pintossi et al. [76].

1. What is the general condition of the structure? Are repairs needed?
2. Do the structural connections allow for the desired changes?
3. Is there enough accessibility to perform the adaptation? Can potential new elements be transported and fit into place?

4. Will the adaptation cause a need for service reticulation? How would that affect the structure?
5. Will the adaptation cause a need for additional protection of the structure? E.g., moisture or fire protection.
6. Are the floor-to-ceiling heights enough to accommodate a potential new building function?
7. How can the remaining structure be supported during the adaptation execution?
8. Will the adaptation itself cause a change in loads (e.g., from changed load paths or altered structural elements)? In that case, can the structure carry them, or are reinforcements needed?
9. Does the potential new building function affect the structure in terms of service class or load assumptions?

DfSA may affect such a process. As universal adaptability is generally seen as neither realistic nor desirable [12], the additional question for the developers and engineers becomes: was the structure designed for the specific kind of adaptation that is needed in this case? If not, the answer to questions 2-5 above might still be influenced if the building was designed for adaptation, as *reversible* and *layered* are proposed characteristics of DfSA. Likewise, the characteristic *reserved* can be connected to questions 6-9. Accurately *targeted* DfSA, however, can provide easy solutions to questions 2-9.

After the structural assessment, the developer performs a cost-benefit analysis to decide whether to move on to the concept design phase. In the analysis, the engineer's assessment is weighed against the expected loss due to the ability/demand imbalance [61,75]. As DfSA aims at facilitating cost-effective and simple adaptations, the cost-benefit analysis for such a project can be greatly improved.

C. Setting goals and budget

This phase is initiated in case a decision to adapt is reached in the previous phase. The developer will subsequently list the project demands and goals. Based on this, a budget for the adaptation project is to be set. This step involves substantial uncertainties as it is difficult to estimate how expensive adaptation projects will be [45]. If there is an early involvement agreement, this phase could be done together with a contractor which in turn might make cost predictions more accurate.

DfSA can directly affect the budget, as characteristics such as *layered*, *traceable*, *reversible*, and *simple* all aim at simplifying and facilitating cost-efficient and predictable adaptations.

D. Procurement of D&C contractor

For this phase, the developer will typically work with an architect to produce scope documents. The documents contain all the requirements, demands, needs, and desired outcomes of the project, and will serve as a basis for the decision to continue with the project. The documents are usually not detailed enough to be used for a building permit, but they are instead used as request documents to call for tender offers from different D&C contractors. Although a contractor could already be involved in the project, in the case of an early involvement agreement, the procured D&C contractor does not have to be the same one.

In the case of a DfSA building, the request documents should reflect the technical possibilities for adaptation together with any demands to incorporate adaptability into the potential new construction [48]. Material passports and other traceability enablers of DfSA could be significantly beneficial in this phase.

E. Tender offer development

When the request documents are sent out, interested contractors start assembling their tender offers. Based on the scope documents, the contractors can collect offers from service (e.g., HVAC) contractors and potential external engineers or architects. The collection of offers, along with calculated material and assembly costs, are then used to predict the cost of the project and develop an offer to send to the developer.

Although there is not enough industrial experience with DfSA to formulate the general tendency, offers to adapt a DfSA building are likely to be dependent on the type of designed adaptability and the contractor's experience with structural adaptations. Well-documented, open-source information about the building's DfSA strategies and technical solutions can motivate contractors with varying experience with DfSA to submit tender offers, given that the solutions are not dependent on proprietary technology.

F. Solution proposal

To propose a solution, the as-built documents need to be studied by architects and engineers. Some questions that need to be addressed are (based on stakeholder communication and Boverket [77]):

- What are the intended functions and geometries of the rooms in the finished building?
- Will the adaptation cause a change in fire protection, acoustics, energy, daylight, or waste management requirements?
- Will the adaptation cause architectural or engineering-related issues or changed demands?

- Which building codes were in place when the building was originally designed and built? Are there needs for conversions of structural capacities to align with current building codes?

To adapt a DfSA building, guidelines and specifications of the designed adaptability should be studied – e.g., disassembly plans and material passports.

After a satisfactory solution is proposed, the developer can choose to move on to the technical design phase.

G. Technical demand specification

This phase entails that the developer compiles a list of equipment needed. They also commission a room data sheet from the project group. Such a document describes the functions of the affected rooms and the various associated demands regarding space plan, interior design, equipment, services, and other technical requirements [78].

When adapting a DfSA building, the developer may have additional demands regarding the preservation of the building's adaptability. ISO 20887 [48] lists the following risks of adapting a DfA building that should be considered before construction:

- Refurbishments causing reduced flexibility, e.g., replacing a flexible element with a fixed one.
- Reduced capacity for expansions or conversions due to partial demolition.
- Reversible connections being covered or replaced by irreversible ones.
- Standardized elements being replaced by non-standardized ones.

To avoid these risks and allow for future adaptations, the developer may specify requirements such as using standardized elements and reversible connections.

H. Procurement of subcontractors and suppliers

Here, the contractor and designers determine the necessary technical systems and materials suitable for the project, based on the technical demands. Based on this, they produce documents to be used in the procurement of subcontractors and suppliers. The documents are also used to make a more accurate project budget. Such documents are called project planning documents, or "systemhandling", in Sweden. They can be described as more detailed versions of the scope documents from phase D.

For a DfSA adaptation, suitable subcontractors and suppliers with relevant technical solutions fitting the DfSA concept used must be identified and chosen by the procuring contractor. If the documentation of technical solutions and adaptation instructions are non-proprietary, the pool of suitable subcontractors and suppliers from which to select may increase.

I. Production of construction documents

The contractor, together with engineers, architects, and subcontractors, produces construction documents. The documents consist of production drawings and specifications or instructions for the builders. In some cases, the timber manufacturer is also involved in producing such documents.

For a DfSA building, instructions and specifications from the building's initial design phase should be followed in accordance with ISO 20887 [48].

J. Manufacturing

In this phase, the timber producer and suppliers manufacture the elements commissioned by the contractor. For DfSA buildings, the elements are designed to enable connections with the building's remaining timber elements. It is also crucial to design elements that can be physically transported into place in the existing building, considering factors such as the existing structure, elevator shafts, and floor-to-floor heights.

K. Construction

Here, the contractor performs the adaptations per the construction documents. Usually, the developer and the engineers will stay updated on the process and adjust the design in case of unforeseen circumstances.

The majority of the decisions regarding the adaptation of a DfSA project are assumed to take place in the design phase. However, in the construction phase, the contractor must have an ongoing discussion with the engineers regarding the designed adaptability and how to execute the adaptation [48].

L. Production of as-built documents

The D&C contractor, or the engineers and architects on behalf of the contractor, should produce as-built documents. If the adaptation was performed exactly as specified in the construction documents, they can simply be renamed as-built documents. Often, though, there will be small changes during the construction phase. For instance, the specified fasteners might be replaced by an equivalent alternative due to costs or availability. The as-built documents need to reflect such changes.

As-built documents and accurate information are especially important for DfSA buildings [36,48]. Traceability enablers such as BIM, digital twins, or identification technologies may be utilized to ensure that future adaptations and potential reuse efforts are possible.

M. Handover

In this phase, the contractor hands the project over to the developer together with potential warranties, maintenance instructions, ventilation inspection documents, fire safety documentation, environmental certifications, and energy performance certificates [77].

For DfSA projects, the contractor also needs to provide relevant design details, traceable inventories, and accessible component or product information about identification, warranty, and service life [48].

4.3 Study C – Economic implications

4.3.1 Cost-benefit analysis

The first run of the CBA calculation model was for the so-called baseline results. In this analysis, all factors were set to their baseline values. The results are shown in Figure 11, where the break-even point $x = 60$ years is noted. The y-axis of the chart represents the NPV of the two alternatives – i.e., the net value of costs and benefits, discounted to their present value. Thus, a higher NPV represents a more beneficial project. Note that the y-axis in the graph is not labeled, as the focus lies solely on the break-even point in the x-axis. The x-axis represents the interval at which structural obsolescence is assumed to occur. Hence, the break-even point reveals how often structural obsolescence would have to occur to make DfSA the more economically feasible option for the chosen scenario. According to these results, structural obsolescence would need to happen less often than every 60 years for DfSA to not be worth the investment. In other words, if one can assume that the need for structural adaptability will arise within the first 60 years of a building's service life, then DfSA could be considered a valuable investment.

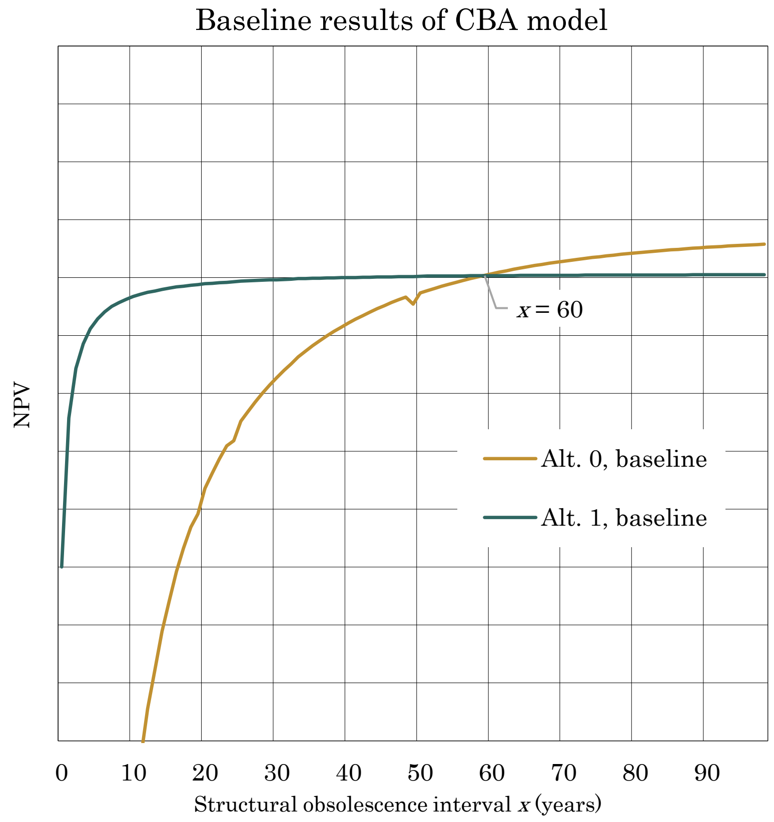


Figure 11: Baseline results of the CBA model, where Alt. 0 represents a BaU building that is replaced every x *years, and Alt. 1 represents a DfSA building that is adapted every* x *years.*

Naturally, as x approaches 0, the graph representing Alternative 0 plummets. For the low values of x, this model can be considered purely theoretical rather than a representation of a realistic scenario. For instance, when $x = 10$ years, the calculation model shows results for a BaU alternative that is demolished and replaced once every ten years. If the break-even point had been at $x = 10$ years, there would be slim chances of a return on investment for DfSA.

Looking at the graph for Alternative 0 in Figure 11, one may notice local minima at $x = 20$, 30, and 50 years. This is because the CBA model calculates the number of demolitions and replacements based on x. For $x = 49$ years, the BaU alternative has two building replacements within the 100-year period. First, at the time $t = 49$ years, and second, at the time $t = 98$ years. Thus, three buildings are included in this alternative: built at $t = 0$, $t = 49$ and $t = 98$. The third building is used beyond the 100-year mark, and a residual value is added to Alternative 0's NPV to represent the remaining 47 years.

This residual value is explained in Section 3.4.1. For $x = 50$ years, on the other hand, the second occurrence of structural obsolescence coincides with the 100-year mark. At this point, the building is simply demolished. There is no cost for new construction added, but neither is there a residual value of benefits after $t = 100$. Thus, the NPV of Alternative 0 in this scenario is lower than for $x = 49$. It is also lower than for $x = 51$, as this scenario also only includes two buildings – but two extra years of use benefits in the form of a residual value.

Though the baseline results paint a promising picture in favor of DfSA, it is important to note that it is based on example values. To obtain a well-rounded understanding of the issue, a sensitivity analysis is needed. Hence, the sensitivity analysis described in the following section addresses both RQ2 and RQ3b.

4.3.2 Sensitivity analysis of CBA

The sensitivity analysis was centered around the developed CBA model and the break-even point for the variable x. By varying one factor at a time, the effect that each factor has on the break-even point could be assessed. The results of this analysis are presented in Figures 12-14.

Figure 12a) shows that the building size does not affect the break-even point, even when the upper building size (15 000 m^2) is three times larger than the lower one (5 000 m^2). In turn, the construction cost (Figure 12b) has some effect on the break-even point – but not a large one.

Varying the DfSA realization cost, on the other hand, has an immense effect on the break-even point. As shown in Figure 12c), it ranges from 40 years up to 84 years, a span of 44 years. This can, in part, be explained by the fact that this cost only affects one of the two alternatives. An increased DfSA realization cost does not affect the BaU alternative, so when the NPV of Alternative 1 is lowered the break-even point decreases drastically. Similarly, when the DfSA cost is decreased, it only favors Alternative 1. The effect can also be explained by the vast range chosen for this variable, motivated by the uncertainty in predicting this cost.

Figure 13d) demonstrates the effects of varying the demolition cost. Though this factor mainly affects Alternative 0, it doesn't have the same effect as the DfSA realization cost. Demolition does occur once in the timeline of Alternative 1, but at $t = 100$ years. That entails 100 years of discounting, making the demolition cost a significantly less impactful cost than the DfSA realization cost. The latter occurs at $t = 0$, thus it is not discounted at all. The demolition cost also has a minor impact on Alternative 0 for any $x > 50$ years. If structural obsolescence occurs less often than every 50 years, demolition is only included twice in the model. Once, at $t = x$, and again at $t = 2x$. As $x >$

50 years, this second point occurs sometime after the 100-year mark, making this cost a residual value. These costs are discounted for x and $2x$ years respectively, decreasing their impact on the NPV of Alternative 0. For instance, the present value of a cost of €10m occurring in 50 years is only €1.3m (for a discount rate of 3.5%).

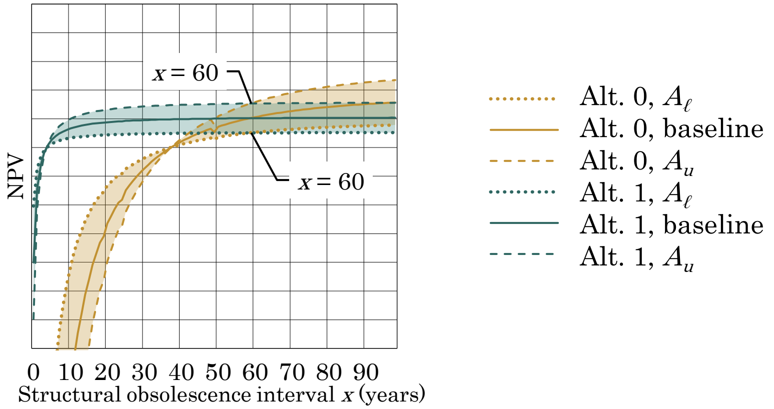
A similar situation can be found when investigating the cost of adapting a DfSA building. It only affects Alternative 1 and does so every x years. Similarly to the demolition cost variation, there is a minor difference in changing this variable for any $x > 50$ years. This cost is, in addition, assumed to be considerably smaller than the demolition cost. This led to a very small impact on the break-even point, shown in Figure 13e).

Due to the length of the studied period, the discount rate has a significant effect on the break-even point. This is shown in Figure 13f). The discount rate varied from 2% to 5%. To show the effect of varying the discount rate, consider the previous example of a cost of €10m occurring 50 years in the future. For a discount rate of 3,5%, the value recommended by the Swedish transport agency [79], the present value would be €1.8m. For a discount rate of 2%, the present value is €3.7m. If the discount rate is 5%, the present value is as low as €0.9m. This rate is, however, not something that can be affected by the development of DfSA.

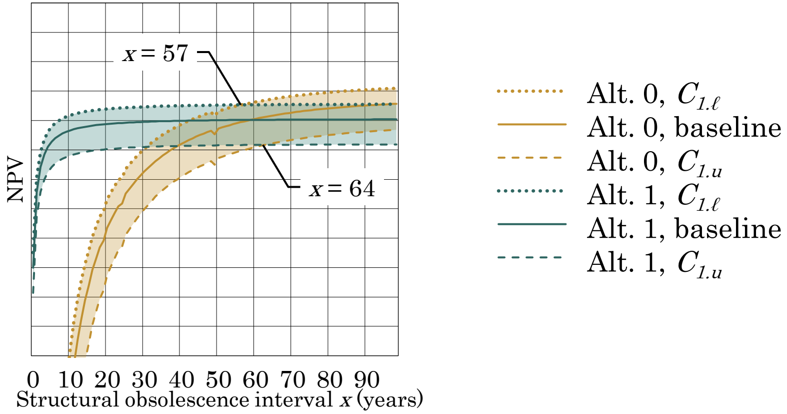
Figure 14g) shows the effect of varying the monetary benefits of building use. While the effect of the NPV of a single alternative is immensely affected by this, it has a small effect on the break-even point. This can be explained by the fact that the baseline for the value depreciation rate is 0%, meaning that the buildings do not lose value over time. For a value depreciation rate above 0, the BaU alternative would be favored by a higher building value as every building replacement would result in a return to the peak value. The DfSA building would, on the other hand, decrease in value for its entire service life of 100 years.

The effect of an increasing depreciation rate is shown in Figure 14h). At 0%, all values are at their baselines and the break-even point is at $x = 60$ years. As the depreciation rate is increased, the BaU alternative is favored, and the break-even point is lowered. At a 2.0% depreciation rate, the break-even point is at $x = 49$ years.

a) Building size variation



b) Construction cost variation



c) DfSA realization cost variation

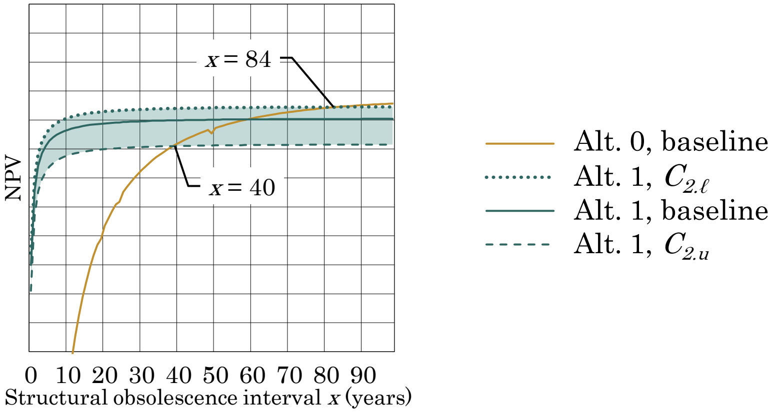
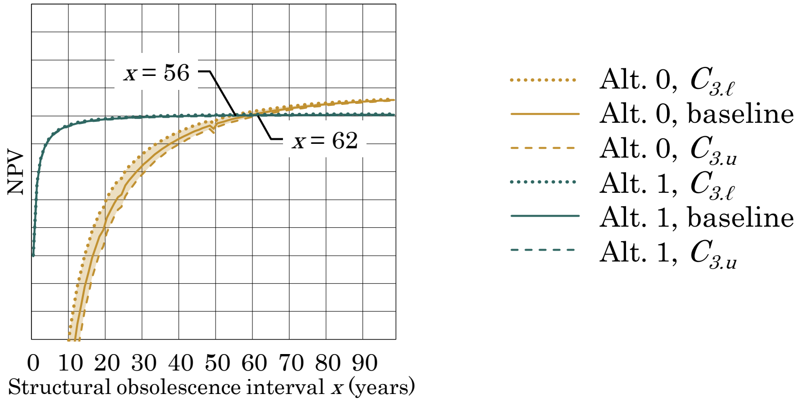


Figure 12: Results of the OFAT analysis for the factors a) building size, b) construction cost, and c) DfSA realization cost.

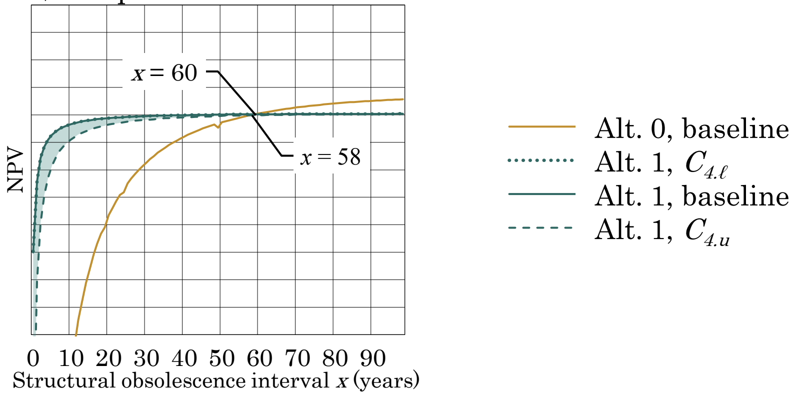
Alt. 0 represents a BaU building that is replaced every x *years.*

Alt. 1 represents a DfSA building that is adapted every x *years.*

d) Demolition cost variation



e) Adaptation cost variation



f) Discount rate variation

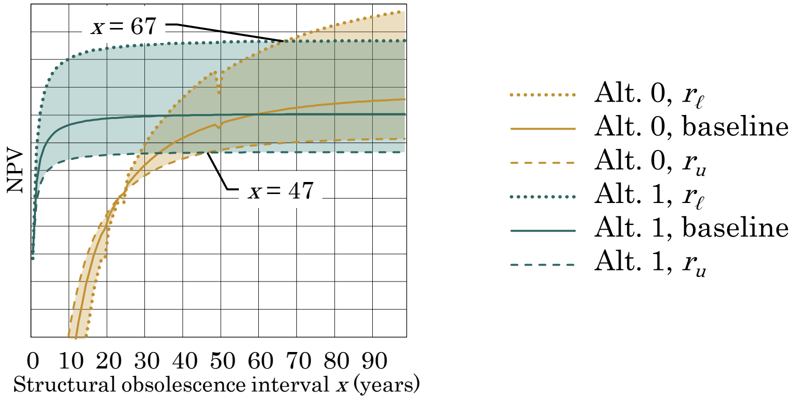
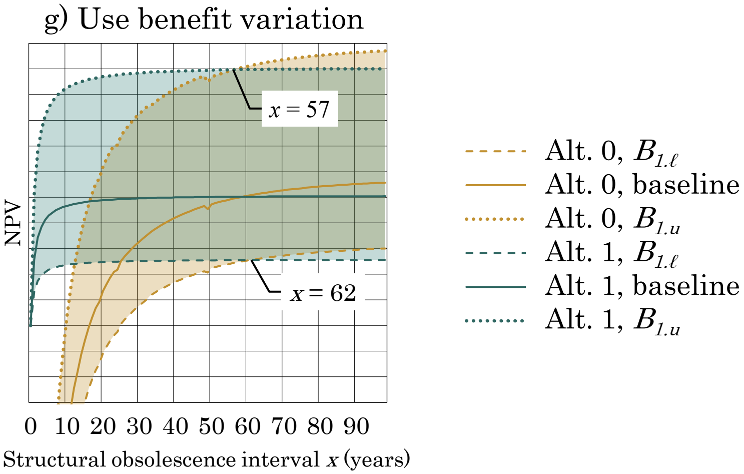


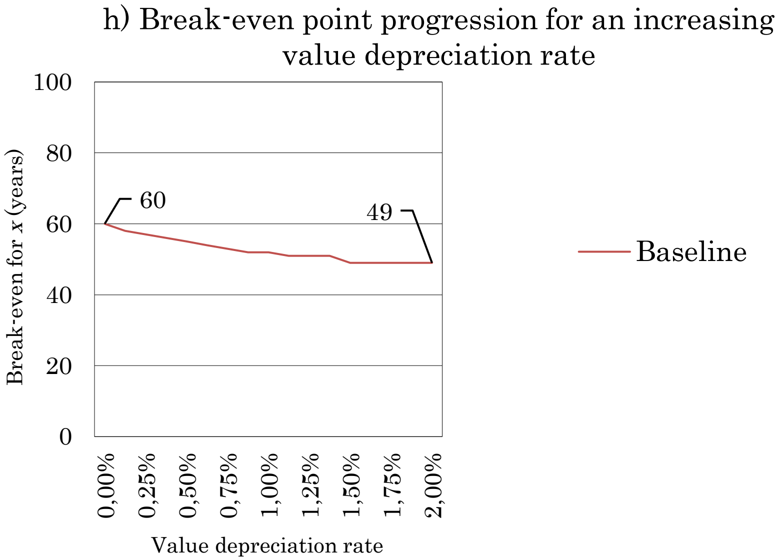
Figure 13: Results of the OFAT analysis for the factors d) demolition cost, e) adaptation cost, and f) discount rate.

Alt. 0 represents a BaU building that is replaced every x *years.*

Alt. 1 represents a DfSA building that is adapted every x *years.*



g) Use benefit variation



h) Break-even point progression for an increasing value depreciation rate

Figure 14: Results of the OFAT analysis for the factors g) use benefit and h) value depreciation rate.

Alt. 0 represents a BaU building that is replaced every x *years.*

Alt. 1 represents a DfSA building that is adapted every x *years.*

The break-even point intervals for each factor are shown in Figure 15. As the baseline result was a break-even point of $x = 60$ years, all results are anchored around this point. It is clear from these results that the DfSA realization cost has the most significant impact on the break-even point for x.

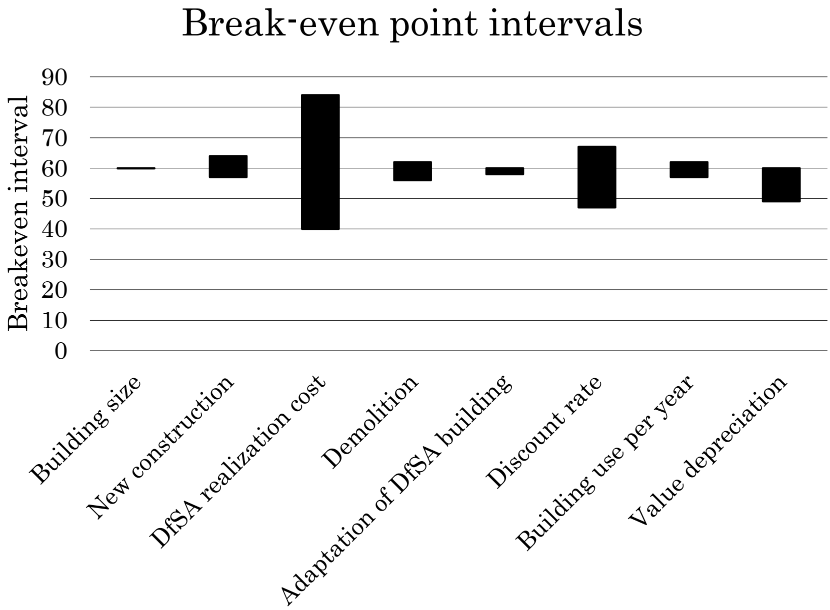


Figure 15: Break-even intervals from the OFAT analysis.

4.4 Research method reflection

The interviews in Study A differed between the two stakeholder groups. In Australia, the interviews were held separately, where they were recorded and transcribed. This generated an immense volume of results, as each interview typically lasted for 1-1.5 hours. In Sweden, a focus group was held as one collective interview. While the amount of raw material generated from this focus group was less than that of the interviews in Australia, the collective approach had its own benefits. By allowing discussion between participants, a "brainstorming" effect occurred where stakeholders could build on each other's ideas. The participants also had access to the notes taken during the meeting. They could disagree if they thought the note-taker was misinterpreting their point and add their own notes during the meeting. This minimized the risk of misunderstanding the stakeholders' input.

Mixing individual and collective interviews is a common approach for methodology triangulation [80]. One thing that should be pointed out, though, is that only one interview approach was used per stakeholder group. None of the individual interviews of this study were held with Swedish stakeholders, and no collective interview was held with Australian stakeholders. There is a possibility that Australian stakeholders could brainstorm new ideas and arrive at new conclusions if a focus group had been held with them. Likewise, individual interviews with Swedish stakeholders may have resulted in richer results from each participant. While this is an important notion, it should also be noted that Study A was an exploratory study of a novel topic. It aimed at finding general perceptions and predictions for this concept that has yet to be developed. It is the author's conviction that on this level, the differences between the Swedish and Australian timber industries would not lead to vastly different results if the methods were mirrored. Certainly, there are differences in resource availability and local policy. These differences were represented in the results of the interview study. Yet, for applying a circular economy concept to timber buildings in general – that is, without specifying any specific structural systems – the two countries are similar in their growing timber industries and ambitions for sustainable construction. For potential future studies that delve deeper into technical details of DfSA for timber, however, there would be value in separate interview studies with a triangulated methodology. This is because the two countries have slightly different approaches to structural systems within timber construction. Though the use of panel construction with CLT has increased in Australia in recent years, the progress of adopting it has been slower than in Europe [81,82]. Sweden, on the other hand, is one of the world's leading countries in the production and use of CLT [82]. Thus, a DfSA strategy in Sweden might focus on CLT, while this might not be an appropriate focus for Australia. In this initial study, though, no structural system was specified. Hence, the regional differences were assumed to be sufficiently covered with the chosen methodology.

In Study B, the conclusions drawn from the literature study regarding the adaptation process in Sweden were only confirmed by communication with one stakeholder. These results may have been strengthened by expanding the number of stakeholders. Yet, the author would like to emphasize that the aim of the stakeholder communication in Study B was not to collect opinions or reflections. Instead, the purpose was to confirm that the conclusions drawn from the literature aligned with industry norms. Because of this, communication with one expert on the subject was deemed sufficient.

In Study C, DfSA was compared to a BaU alternative in a CBA model. CBA is typically used to measure the effect a project has on society, rather than the individual investor. The alternative, which focuses solely on that investor, would be a cost-revenue analysis.

While the CBA model described in this thesis could technically be called a cost-revenue analysis, these typically have a shorter studied period. For a studied period of 100 years, it is unlikely that the investor is the same actor as the owner at the 100-year mark. During this time, the building or lot could be sold several times. The idea was that the revenue received for selling the DfSA building would reflect its future possibilities for life extension. But to be able to reflect this on a global scale, it was not deemed suitable to focus on one single investor who sells the building after some years. The comparison to a BaU scenario, where the owner may change for each new building, would not be suitable in such an analysis either. Instead, the model was developed from a societal point of view. It should be noted, though, that “society” in this context is limited to the industry of building investors and developers. This limitation was based on the results of Study A, where investment cost was one of the main concerns among stakeholders. The calculation model does, however, allow for externalities to be added. Thus, it can be used in future studies where the scope is expanded to investigate the societal and environmental benefits of DfSA. In such studies, one could add costs for environmental loads such as resource consumption, carbon emissions, and waste production. The results of such studies would be useful in achieving actions 2 and 4 in the roadmap towards implementation, described in Section 4.1.3.

Lastly, another alternative to the CBA model would be to instead choose a life-cycle cost (LCC) approach. While this approach is useful for assessing the total costs of a project, it was deemed preferable to include monetary benefits in the model. In addition, the comparative CBA enabled the exclusion of some costs that were seen as equivalent between the alternative. For instance, the land property cost and operational costs were disregarded as they were assumed to be equivalent. Disregarding major costs in this way in an LCC model was considered misleading, as the result would not reflect the actual life-cycle cost of the projects.

Chapter 5

5 Conclusions and future research

5.1 Conclusions

The aim of the research work presented in this thesis was to explore the industry potential to implement DfSA for timber buildings. First, stakeholder benefits and barriers to an implementation were investigated. Second, the potential to overcome the identified barriers was assessed and key actions to facilitate an implementation were identified. Lastly, the practical and economic implications of applying DfSA to a specific timber building project were investigated.

The following sections provide conclusions to the three research questions one by one. This is followed by a section stipulating the overall conclusions reached from this work.

5.1.1 RQ1: Benefits and barriers

- *RQ1: What are the stakeholder benefits and barriers to an implementation of DfSA for timber?*

The results of Study A suggest that the main perceived stakeholder benefits of DfSA are centered around environmental sustainability. This could be perceived as a societal benefit rather than a technical or economic benefit affecting the construction industry stakeholders. Still, a connection to local governmental sustainability objectives was identified in both Sweden and Australia. Economic activities that align with such objectives can be beneficial for stakeholders, either for marketing purposes or for economic subsidies.

Other identified benefits of an implementation of DfSA for timber were mainly dependent on the assumption that effective technical solutions can be found. If so, the stakeholders saw benefits in market competitiveness for timber as a structural material. Resource efficiency was also identified as especially attractive among

Australian stakeholders, as they rely partly on imports to supply their domestic timber demand.

The identified barriers to an implementation of DfSA for timber were categorized into five themes: *general barriers*, *cost*, *policy*, *technical solutions,* and *traceability*. The most prominent of the five themes were *cost* and *technical solutions*. Stakeholders saw the assumed DfSA realization cost as a significant barrier, as building projects often are on a tight budget and non-essential features are deprioritized. Regarding technical solutions, several barriers were identified. For instance, stakeholders saw potential difficulties concerning connection design, supporting the structure during the adaptation work, adhering to changed building requirements for functional adaptations, and ensuring the longevity of a building's non-structural parts.

5.1.2 RQ2: Increasing implementation feasibility

- *RQ2: How can the feasibility of a successful implementation of DfSA for timber be increased?*

In Study A, a roadmap towards implementation was developed. This roadmap consisted of seven actions that, in turn, were designed to overcome the barriers found in the study of RQ1. The actions can be summarized as steps to ensure that the DfSA for timber is risk-based, relevant, incentivized, well-documented, and communicated.

The second research question was further investigated in Study B and C, with a special focus on how to improve the practical and economic feasibility of DfSA for timber. Study B can be concluded by stating that DfSA increases the demands for accurate building information and stakeholder communication. Development is needed in terms of effective solutions for traceability. Moreover, future technical solutions should be well-documented and available for early adopters.

Study C concluded that the DfSA realization cost is the single most influential factor in determining this economic feasibility. If low-cost solutions can be found, DfSA could be considered a valuable investment even if the need for structural adaptation only arises once within 84 years. This result is based on the lowest assumed DfSA realization cost, namely 2% of the original building cost. Certainly, this can be considered a conservative lowest cost – as 2% of the total cost of designing and constructing a building is still quite a considerable sum. As DfSA for timber is developed, this percentage may be smaller still. It was, however, considered important in Study C to not underestimate the DfSA realization cost and risk painting an overly optimistic picture. It should also be noted that the initial phase of an implementation tends to involve higher costs due to inexperience among designers and builders.

5.1.3 RQ3: Practical and economic implications

- *RQ3: What are the practical and economic implications of applying DfSA to a specific timber building project?*

DfSA was found to have a significant impact in most phases of the practical process of adapting a timber building. First, there is an increased demand for documentation of the adaptability strategy and building information. Accurate information from the original design and construction phase is crucial in the adaptation process. To enable potential future adaptations, it is also imperative to keep precise records of the performed adaptation work. This increased demand for traceability can benefit the building in other ways as well – for instance, facilitating non-structural adaptations or reuse of building parts after the building's end of life. Second, the designed adaptability should significantly reduce uncertainties in the adaptation process regarding cost or technical feasibility. Third, DfSA may limit the options in the procurement of contractors, subcontractors, and suppliers. The cost of these contracts will be influenced by the procured actors' previous experience, competence, and available solutions for structural adaptability. The results from RQ2 on overcoming barriers are relevant here. If DfSA can be incentivized and well-documented, with low-cost technical solutions, this added cost may be mitigated.

The long-term economic implications of implementing DfSA for timber showed possibilities for economic feasibility. Even with a very conservative DfSA realization cost as the baseline – 14% of the original construction cost – the results showed a break-even point at $x = 60$ years. This entails that if structural obsolescence is assumed to occur more often than every 60 years, DfSA could be an economically feasible investment.

5.1.4 Overall conclusions

The research work described in this thesis serves as an initial step in the effort to implement adaptable structural design for timber buildings. The insights gained from the conducted research work can act as a foundation for the further development of the concept of DfSA, as crucial considerations to facilitate an implementation are determined.

While there are environmental advantages of DfSA that may indirectly benefit stakeholders, there are also possibilities for more direct benefits. If DfSA for timber is developed with the following conclusions of this thesis in mind, economic and practical feasibility could be reached. Important considerations for the future development of the concept include:

- The structural engineering development of the concept needs to have a particular focus on low-cost technical solutions, to facilitate economic feasibility.

- Solutions for traceability are crucial for when an adaptation is eventually performed. These solutions also need to be cost-effective as they contribute to the DfSA realization cost.

- The solution for DfSA for timber should be well-documented and communicated to end-users and other stakeholders, to decrease cost and complexity and increase the likelihood of early adopters.

5.2 Future research

For the continued development of the concept of DfSA for timber, several research needs have been identified. The suggestions for future research efforts are listed below.

- The first part of this study was centered around Sweden and Australia, whereas Study B and C only focused on Sweden. Applying the methods of Study B and C to an Australian context would enhance the scalability of the conclusions on the practical and economic implications of DfSA for timber.

- The main conclusions of this thesis are not limited to a specific structural system for timber buildings. Yet, the choice of structural system is highly central in the development of technical solutions. Moreover, potential adaptation needs and risks of structural obsolescence should be investigated for different structural systems. For instance, as CLT tends to be used for larger structures, the potential adaptation needs may differ from smaller, light-frame timber structures. A DfSA strategy should adhere to this.

- On a similar note, the possible adaptation needs and structural obsolescence risks should be investigated for different building functions. This would enable targeted adaptability strategies to avoid unnecessary costs and material demand.

- The societal and environmental benefits of DfSA for timber should be quantified and demonstrated to promote governmental incentives and standards for adaptability. From the societal perspective, the CBA model of this thesis can be expanded to include social externalities. From the environmental perspective, life-cycle analysis (LCA) applications are recommended.

- To facilitate DfSA for timber, technical solutions for reversible connection systems need to be developed. This development should consider potential adaptability needs for the investigated structural system, the logistics of replacing structural elements, and the solution’s prefabrication degree, standardization potential, and cost.

References

[1] R. Becqué, E. Mackres, J. Layke, N. Aden, S. Liu, K. Managan, C. Nesler, S. Mazur-Stommen, K. Petrichenko, P. Graham, Accelerating Building Efficiency: Eight Actions for Urban Leaders, World Resources Institute, Washington, DC, 2016. https://www.wri.org/research/accelerating-building-efficiency (accessed October 18, 2023).

[2] United Nations Environment Programme, 2022 Global Status Report for Buildings and Construction: Towards a Zero-emission, Efficient and Resilient Buildings and Construction Sector, Nairobi, 2022. https://www.unep.org/resources/publication/2022-global-status-report-buildings-and-construction (accessed October 18, 2023).

[3] C.E. Andersen, A. Garnow, C. Grau Sørensen, A. Wittchen, L. Kristensen Stranddorf, E. Hoxha, F. Nygaard Rasmussen, H. Birgisdóttir, Whole Life Carbon Impact of: 45 Timber Buildings, Department of the Built Environment, Aalborg University, 2023.

[4] Y. Niu, K. Rasi, M. Hughes, M. Halme, G. Fink, Prolonging life cycles of construction materials and combating climate change by cascading: The case of reusing timber in Finland, Resources, Conservation and Recycling 170 (2021) 105555. https://doi.org/10.1016/j.resconrec.2021.105555.

[5] P. Graham, Design for Adaptability — An Introduction to the Principles and Basic Strategies, (2005) 13.

[6] G. Kelly, R. Schmidt III, A. Dainty, V. Story, Improving the design of adaptable buildings though effective feedback in use, in: Proceedings of 2011 CIB Management and Innovation for a Sustainable Built Environment International Conference, Amsterdam, Netherlands, 2011.

[7] Z.R. Rockow, B.E. Ross, A.K. Becker, Comparison of Building Adaptation Projects and Design for Adaptability Strategies, J. Archit. Eng. 27 (2021) 04021022. https://doi.org/10.1061/(ASCE)AE.1943-5568.0000481.

[8] R. Jockwer, Y. Goto, E. Scharn, K. Crona, Design for adaption – making timber buildings ready for circular use and extended

service life, IOP Conf. Ser.: Earth Environ. Sci. 588 (2020) 052025. https://doi.org/10.1088/1755-1315/588/5/052025.

[9] O. Akinade, L. Oyedele, A. Oyedele, J.M. Davila Delgado, M. Bilal, L. Akanbi, A. Ajayi, H. Owolabi, Design for deconstruction using a circular economy approach: barriers and strategies for improvement, Production Planning & Control 31 (2020) 829–840. https://doi.org/10.1080/09537287.2019.1695006.

[10] W. Debacker, S. Manshoven, D1 Synthesis of the state-of-the-art: Key barriers and opportunities for Materials Passports and Reversible Building Design in the current system, BAMB - Buildings As Material Banks, 2016.

[11] A. Kręt-Grześkowiak, M. Baborska-Narożny, Guidelines for disassembly and adaptation in architectural design compared to circular economy goals - A literature review, Sustainable Production and Consumption 39 (2023) 1–12. https://doi.org/10.1016/j.spc.2023.04.020.

[12] R. Schmidt III, S. Austin, Adaptable Architecture, Routledge, Abingdon, 2016.

[13] Skogsindustrierna, Produktion och konsumtion, (2023). https://www.skogsindustrierna.se/om-skogsindustrin/branschstatistik/produktion-och-konsumtion/ (accessed October 12, 2023).

[14] Statistics Sweden, Demolition of dwellings in multi-dwelling buildings by region, type of ownership, period of construction, size of dwelling and reason for demolition. Year 1989-2019., (2023). https://www.statistikdatabasen.scb.se/pxweb/en/ssd/START__BO__BO0101__BO0101F/LagenhetRivAkBpLtRAr/.

[15] Statistics Sweden, Demolition of dwellings in multi-dwelling buildings by region, type of ownership, period of construction, size of dwelling and reason for demolition. Year 2020 - 2022, (2023). https://www.statistikdatabasen.scb.se/pxweb/en/ssd/START__BO__BO0101__BO0101F/LagenhRivAkBpLtRArN/.

[16] J. O’Connor, Survey on actual service lives for North American buildings, (n.d.).

[17] T. Osaragi, Factors leading to buildings being demolished and probability of remainder, (2004).

[18] J. Kirchherr, D. Reike, M. Hekkert, Conceptualizing the circular economy: An analysis of 114 definitions, Resources, Conservation and Recycling 127 (2017) 221–232. https://doi.org/10.1016/j.resconrec.2017.09.005.

[19] J. Cramer, The Raw Materials Transition in the Amsterdam Metropolitan Area: Added Value for the Economy, Well-Being, and the Environment, Environment: Science and Policy for Sustainable Development 59 (2017) 14–21. https://doi.org/10.1080/00139157.2017.1301167.

[20] Circle Economy Foundation, The Circularity Gap Report 2023, 2023. https://www.circularity-gap.world/2023#download (accessed August 16, 2024).

[21] N.M.P. Bocken, I. De Pauw, C. Bakker, B. Van Der Grinten, Product design and business model strategies for a circular economy, Journal of Industrial and Production Engineering 33 (2016) 308–320. https://doi.org/10.1080/21681015.2016.1172124.

[22] Ellen MacArthur Foundation, 2013.

[23] M. Risse, G. Weber-Blaschke, K. Richter, Eco-efficiency analysis of recycling recovered solid wood from construction into laminated timber products, Science of The Total Environment 661 (2019) 107–119. https://doi.org/10.1016/j.scitotenv.2019.01.117.

[24] Y. Sandin, G. Sandin, C. Cristescu, J. Olsson, Kunskapsläge kring byggnader med stomme av trä: teknik, hållbarhet och cirkulär materialanvändning, (n.d.) 154.

[25] C. Goldhahn, E. Cabane, M. Chanana, Sustainability in wood materials science: an opinion about current material development techniques and the end of lifetime perspectives, Phil. Trans. R. Soc. A. 379 (2021) 20200339. https://doi.org/10.1098/rsta.2020.0339.

[26] O. Eriksson, G. Finnveden, T. Ekvall, A. Björklund, Life cycle assessment of fuels for district heating: A comparison of waste incineration, biomass- and natural gas combustion, Energy Policy 35 (2007) 1346–1362. https://doi.org/10.1016/j.enpol.2006.04.005.

[27] G.M. Winder, A. Bobar, Responses to stimulate substitution and cascade use of wood within a wood use system: Experience from Bavaria, Germany, Applied Geography 90 (2018) 350–359. https://doi.org/10.1016/j.apgeog.2016.09.003.

[28] F. Ximenes, C. Björdal, A. Cowie, M. Barlaz, The decay of wood in landfills in contrasting climates in Australia, Waste Management 41 (2015) 101–110. https://doi.org/10.1016/j.wasman.2015.03.032.

[29] F.A. Ximenes, W.D. Gardner, A.L. Cowie, The decomposition of wood products in landfills in Sydney, Australia, Waste Management 28 (2008) 2344–2354. https://doi.org/10.1016/j.wasman.2007.11.006.

[30] D. Müller, D. Moser, Rückbau und Wiederverwendung von Holzbauten, PIRMIN JUNG Schweiz AG, 2022.

[31] C. Cristescu, D. Honfi, K. Sandberg, Y. Sandin, E. Shotton, S.J. Walsh, M. Cramer, D. Ridley, M. Risse, R. Ivanica, A. Harte, C. Uí, M.D. Arana-Fernández, D.F. Llana, M.G. Barbero, B. Nasiri, Design for deconstruction and reuse of timber structures – state of the art review, (2020).

[32] O.O. Akinade, L.O. Oyedele, M. Bilal, S.O. Ajayi, H.A. Owolabi, H.A. Alaka, S.A. Bello, Waste minimisation through deconstruction: A BIM based Deconstructability Assessment Score (BIM-DAS), Resources, Conservation and Recycling 105 (2015) 167–176. https://doi.org/10.1016/j.resconrec.2015.10.018.

[33] A. Kręt-Grześkowiak, S. Bruhn, A.A.V. Jensen, M. Birkved, Quantifying the environmental impact of structural timber across multiple future lifecycles, Discov Appl Sci 6 (2024) 197. https://doi.org/10.1007/s42452-024-05860-y.

[34] Nationale Informationsstelle zum Kulturerbe (NIKE), Abfall ist Rohstoff, NIKE Bulletin 6 (2011). https://www.nike-kulturerbe.ch/fileadmin/user_upload/Bulletin/2011/06/PDF/Rohstoff.pdf (accessed September 5, 2024).

[35] F. Nakib, Toward an adaptable architecture guidelines to integrate adaptability in building, in: Salford Quays, 2010.

[36] B.E. Ross, D.A. Chen, S. Conejos, A. Khademi, Enabling Adaptable Buildings: Results of a Preliminary Expert Survey,

Procedia Engineering 145 (2016) 420–427. https://doi.org/10.1016/j.proeng.2016.04.009.

[37] O. Heidrich, J. Kamara, S. Maltese, F. Re Cecconi, M.C. Dejaco, A critical review of the developments in building adaptability, IJBPA 35 (2017) 284–303. https://doi.org/10.1108/IJBPA-03-2017-0018.

[38] D.G. Iselin, A.C. Lemer, The fourth dimension in building: strategies for minimizing obsolescence, National Academy Press, Washington, DC, 1993.

[39] A. Thomsen, K. Van Der Flier, Understanding obsolescence: a conceptual model for buildings, Building Research & Information 39 (2011) 352–362. https://doi.org/10.1080/09613218.2011.576328.

[40] S.J. Wilkinson, H. Remøy, C. Langston, Sustainable Building Adaptation: Innovations in Decision-Making, John Wiley & Sons, Incorporated, Somerset, 2014.

[41] P. Bullen, P. Love, A new future for the past: a model for adaptive reuse decision-making, Built Environment Project and Asset Management 1 (2011) 32–44. https://doi.org/10.1108/20441241111143768.

[42] R. Jockwer, V. Öberg, L.-M. Ottenhaus, P. Leardini, Y. Goto, Towards Adaptability and Circularity of Timber Buildings, in: World Conference on Timber Engineering (WCTE 2023), World Conference on Timber Engineering (WCTE 2023), Oslo, Norway, 2023: pp. 1497–1505. https://doi.org/10.52202/069179-0203.

[43] Viola, Diano, Repurposing the Built Environment: Emerging Challenges and Key Entry Points for Future Research, Sustainability 11 (2019) 4669. https://doi.org/10.3390/su11174669.

[44] J. Douglas, Building Adaptation, Butterworth-Heinemann, Oxford, 2002.

[45] P.A. Bullen, Adaptive reuse and sustainability of commercial buildings, Facilities 25 (2007) 20–31. https://doi.org/10.1108/02632770710716911.

[46] R.D.F. Bromley, A.R. Tallon, C.J. Thomas, City Centre Regeneration through Residential Development: Contributing to

Sustainability, Urban Studies 42 (2005) 2407–2429. https://doi.org/10.1080/00420980500379537.

[47] J. Brigante, B.E. Ross, M. Bladow, Costs of Implementing Design for Adaptability Strategies in Wood-Framed Multifamily Housing, J. Archit. Eng. 29 (2023) 05022013. https://doi.org/10.1061/JAEIED.AEENG-1357.

[48] ISO 20887, ISO 20887:2020 Sustainability in buildings and civil engineering works — Design for disassembly and adaptability — Principles, requirements and guidance, (2020).

[49] W. Fawcett, Investing in flexibility: The lifecycle options synthesis, Projections 10 (2011) 13–29.

[50] H. Watt, B. Davison, P. Hodgson, C. Kitching, D.T. Danielle's, What should an adaptable building look like?, Resources, Conservation & Recycling Advances 18 (2023) 200158. https://doi.org/10.1016/j.rcradv.2023.200158.

[51] S. Brand, How buildings learn: What happens after they're built, Viking, New York, 1994.

[52] R. Askar, L. Bragança, H. Gervásio, Adaptability of Buildings: A Critical Review on the Concept Evolution, Applied Sciences 11 (2021) 4483. https://doi.org/10.3390/app11104483.

[53] E.S. Slaughter, Design strategies to increase building flexibility, Building Research & Information 29 (2001) 208–217. https://doi.org/10.1080/09613210010027693.

[54] J. Gosling, P. Sassi, M. Naim, R. Lark, Adaptable buildings: A systems approach, Sustainable Cities and Society 7 (2013) 44–51. https://doi.org/10.1016/j.scs.2012.11.002.

[55] P. Russell, S. Moffatt, IEA Annex 31 Energy-Related Environmental Impact of Buildings, (2001). https://www.iea-ebc.org/Data/publications/EBC_Annex_31_Assessing_Building.pdf.

[56] R. Schmidt III, T. Eguchi, S. Austin, A. Gibb, What is the Meaning of Adaptability in the Building Industry?, (2010) 10.

[57] A. Leaman, B. Bordass, S. Cassels, Flexibility and Adaptability in Buildings: the "killer" variables, (1998).

[58] L. Kuiri, P. Leardini, Design for Adaptability and Disassembly: Towards Zero Construction Waste in the Australian Housing Sector, (2022).

[59] S. Shahi, M. Esnaashary Esfahani, C. Bachmann, C. Haas, A definition framework for building adaptation projects, Sustainable Cities and Society 63 (2020) 102345. https://doi.org/10.1016/j.scs.2020.102345.

[60] M. Caruso, R. Pinho, F. Bianchi, F. Cavalieri, M.T. Lemmo, A Life Cycle Framework for the Identification of Optimal Building Renovation Strategies Considering Economic and Environmental Impacts, Sustainability 12 (2020) 10221. https://doi.org/10.3390/su122310221.

[61] C.-K. Chiu, F.-P. Hsiao, W.-Y. Jean, A novel lifetime cost-benefit analysis method for seismic retrofitting of low-rise reinforced concrete buildings, Structure and Infrastructure Engineering 9 (2013) 891–902. https://doi.org/10.1080/15732479.2011.631114.

[62] R.J. Williams, P. Gardoni, J.M. Bracci, Decision analysis for seismic retrofit of structures, Structural Safety 31 (2009) 188–196. https://doi.org/10.1016/j.strusafe.2008.06.017.

[63] R. Askar, L. Bragança, H. Gervásio, Design for Adaptability (DfA)—Frameworks and Assessment Models for Enhanced Circularity in Buildings, ASI 5 (2022) 24. https://doi.org/10.3390/asi5010024.

[64] O.O. Akinade, L.O. Oyedele, S.O. Ajayi, M. Bilal, H.A. Alaka, H.A. Owolabi, S.A. Bello, B.E. Jaiyeoba, K.O. Kadiri, Design for Deconstruction (DfD): Critical success factors for diverting end-of-life waste from landfills, Waste Management 60 (2017) 3–13. https://doi.org/10.1016/j.wasman.2016.08.017.

[65] M.D. Alba-Rodríguez, A. Martínez-Rocamora, P. González-Vallejo, A. Ferreira-Sánchez, M. Marrero, Building rehabilitation versus demolition and new construction: Economic and environmental assessment, Environmental Impact Assessment Review 66 (2017) 115–126. https://doi.org/10.1016/j.eiar.2017.06.002.

[66] European Parliament, Council of the European Union, Regulation (EU) 2020/852 of the European Parliament and of the Council of 18 June 2020 on the establishment of a framework to facilitate sustainable investment, and amending

Regulation (EU) 2019/2088, (2020). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:32020R0852 (accessed September 6, 2024).

[67] B. Feng, Y. Zhang, R. Bourke, Urbanization impacts on flood risks based on urban growth data and coupled flood models, Nat Hazards 106 (2021) 613–627. https://doi.org/10.1007/s11069-020-04480-0.

[68] C.P. Callow, J. Glockling, The Mass Timber Insurance Playbook: A guide to insuring mass timber buildings, (n.d.).

[69] Fuktcentrum, Industry standard ByggaF - method for moisture safety of the construction process, (2013). https://www.fuktcentrum.lth.se/fileadmin/fuktcentrum/PDF-filer/ByggaF_Branschstandard/1_ByggaF_branschstandard.pdf (accessed September 19, 2023).

[70] R. Steiger, Development of New Swiss Standards for the Assessment of Existing Load Bearing Structures, (2008).

[71] P. Dietsch, H. Kreuzinger, Guideline on the assessment of timber structures: Summary, Engineering Structures 33 (2011) 2983–2986. https://doi.org/10.1016/j.engstruct.2011.02.027.

[72] D. Diamantidis, Probabilistic Assessment of Existing Structures - A publication of The Joint Committee on Structural Safety (JCSS), RILEM Publications S.A.R.L., 2001.

[73] A. Feio, J.S. Machado, In-situ assessment of timber structural members: Combining information from visual strength grading and NDT/SDT methods – A review, Construction and Building Materials 101 (2015) 1157–1165. https://doi.org/10.1016/j.conbuildmat.2015.05.123.

[74] H.J. Blaß, H. Brüninghoff, H. Kreuzinger, B. Radović, S. Winter, Guideline for a first evaluation of large-span timber roof structures, (n.d.).

[75] H. Baker, A. Moncaster, Adaptation and Demolition in a Masterplan Context., (2018). https://doi.org/10.1002/9781119231455.ch4.

[76] N. Pintossi, D. Ikiz Kaya, A. Pereira Roders, Assessing Cultural Heritage Adaptive Reuse Practices: Multi-Scale Challenges and

Solutions in Rijeka, Sustainability 13 (2021) 3603. https://doi.org/10.3390/su13073603.

[77] Boverket, En byggnads liv, (n.d.). https://enbyggnadsliv.boverket.se/post-list/index.html (accessed September 21, 2023).

[78] LU Byggnad, Byggprocessen i nio steg, (2019). https://www.konstnarliga.lu.se/sites/konstnarliga.lu.se/files/2021-01/Byggprocessen%20i%20nio%20steg.pdf (accessed September 22, 2023).

[79] Trafikverket, Analysmetod och samhällsekonomiska kalkylvärden för transportsektorn, Trafikverket, 2024. https://bransch.trafikverket.se/asek (accessed September 11, 2024).

[80] R. Fellows, A. Liu, Research Methods for Construction, 4th ed., John Wiley & Sons, Ltd, Newark, 2015.

[81] B. Gilbert, M. Skitmore, Y. Ali, J. Gray, Key considerations of cross-laminated timber (CLT) for high-rise construction in Australia: A review, NICMAR Journal of Construction Management 35 (2020) 70–81.

[82] M. Wieruszewski, B. Mazela, Cross Laminated Timber (CLT) as an Alternative Form of Construction Wood, Drvna Ind. 68 (2017) 359–367. https://doi.org/10.5552/drind.2017.1728.