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Design for Structural Adaptation in timber buildings: Industry perspectives and implementation roadmap for Sweden and Australia

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ABSTRACT

Extending the service life of timber structures can be connected to several circular economy (CE) values such as prolonged carbon storage, resource efficiency, and waste reduction. While the emerging CE strategy Design for Adaptation (DfA) is concerned with prolonging the service life of buildings, it is commonly focused on non-structural adaptability. This paper defines the concept Design for Structural Adaptation (DfSA) and investigates it from the perspective of the construction industries in Sweden and Australia. Existing knowledge on the topic was synthesized together with perspectives from stakeholders by combining a literature review with semi-structured interviews. A thematic analysis of the interviews was performed to analyze the perceived barriers, risks, and benefits of implementing DfSA for timber structures. Among the results are seven proposed characteristics of DfSA for timber, derived from a critical analysis of previous research works on adaptability and circularity strategies for timber. The thematic analysis of stakeholder interviews showed that the practitioners from both countries were unanimous in perceiving DfSA to be in line with national and global sustainability goals. The barriers to implementation, both found in literature and according to stakeholders, primarily concerned cost and technical solutions, followed by regulation and traceability. The study concludes that while the technical issues of DfSA for timber need to be studied further, research efforts are also needed to quantify the possible benefits of DfSA from a life cycle perspective. Lastly, the authors recommend investigations of common causes of demolition for different building types, to promote optimized and cost-efficient structural adaptability.

1. Introduction

As the construction industry is a major contributor to the world's greenhouse gas emissions, waste production, and resource consumption, transitioning the sector to a Circular Economy (CE) is often cited as crucial to achieving goals for sustainable development [1,2]. In World Economic Forum [3], the construction supply chain was identified as one of the eight supply chains responsible for more than 50 % of global emissions. The report states that approximately 40 % of these emissions could be abated with the

Abbreviations: BaU, Business-as-Usual; BIM, Building Information Model; CLT, Cross-Laminated Timber; DfA, Design for Adaptation; DfD, Design for Disassembly; DfNSA, Design for Non-Structural Adaptation; DfSA, Design for Structural Adaptation; DSM, Dependency Structure Matrix; SDG, Sustainable Development Goal.

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implementation of efficiency, renewable power, and circularity [3].

In transitioning the construction sector to CE, maintaining resources at a high-quality level by prolonging the service lives of buildings has been identified as an important step. Extending the service life of timber structures, specifically, adds the benefits of prolonged carbon storage and resource efficiency. One emerging strategy to enable prolonging the service life of buildings is Design for Adaptation (DfA), where a building is designed to be flexible in response to changing user demands. However, DfA efforts are often focused on non-structural adaptations only [4,5]. Moreover, it is typically only concerned with functional changes – e.g., moving partition walls in dwellings to accommodate for changing user needs – as opposed to repairability. In some cases, adaptability can be applied to the design of steel or prefabricated concrete [6–8], but modern timber structures are typically more complex for alteration in the use phase [9,10].

This paper defines the concept Design for Structural Adaptation (DfSA) and defines it as the design of a building to accommodate changes to its load-bearing structure, prompted by drastically changed user demands or structural damages. An example of the former is if the demand for office space is surpassed by a need for residential space, prompting a need for structural reconfigurations. An example of the latter is fire damage in a building, which is often complex and costly to repair in business-as-usual buildings. DfSA partly limits the scope of DfA by focusing exclusively on structural changes, and partly expands it by including non-functional changes such as repairability in its scope.

In this study, the concept of DfSA is applied to timber buildings. As can be seen in historical construction, traditional timber structures are inherently suitable for adaptations. Yet, while it is often claimed that modern timber construction offers similar possibilities for life extension, contemporary examples of adaptable timber buildings are scarce. The reason for this is likely the complexity of modern timber construction, where engineered wood products and high-performance steel connections limit the potential for structural adaptations. To facilitate such changes, the decisions made in the design phase are crucial [11–14]. However, due to the novelty of incorporating adaptability in the design of load-bearing timber, there is a lack of experience and guidance to refer to as a stakeholder. So far, no guidelines or technical solutions have been established in the field and, as a result, stakeholders may have a lack of motivation for implementing this novel concept. To increase incentives for DfSA in the design of timber buildings, there is a need to not only compile existing knowledge and experience but also identify and address the benefits and risks for the stakeholders involved. While previous studies in the field have been conducted with a focus on non-structural DfA, there is a lack of research within the concept of adaptable timber structures. A feasibility study that synthesizes previous research and input from practitioners and decision-makers can subsequently act as a foundation for the development of guidelines and technical solutions, which could promote the life extension of timber buildings.

This study aims to investigate the current status, barriers, benefits, and risks of implementing DfSA for timber buildings as an alternative to the business-as-usual way of design and construction. Two countries, with large timber industries: Sweden and Australia are in focus for the study. The two countries were chosen as representative case studies to promote the scalability of the results. While both countries have active timber markets, Sweden is self-sufficient in timber products whereas Australia relies partially on imports to meet its timber demand. Thus, Sweden can be seen as representative of countries with a positive supply-demand balance, e.g., northern European countries, Canada and Russia. Countries that import a significant share of their domestic timber consumption, such as the United Kingdom and France, are represented in this study by Australia. The two countries also show two different trends of structural systems within timber construction. While Sweden utilizes a wider range of structural strategies, including mass timber construction, Australia's construction sector is more uniform in its focus on light-frame and post-and-beam systems. One reason behind this difference is the availability of local technology and manufacturing, affecting the countries' industries. The two countries can therefore represent two differing industrial systems, which may influence the attitudes among practitioners towards DfSA for timber.

It is envisaged that an implementation of DfSA for timber in Sweden and Australia would be feasible and desirable, from the perspective of both the practitioners and society. In order to investigate this statement, this study poses three hypotheses: a) There can be a systemic approach to DfSA for timber. b) DfSA for timber is not yet implemented because of some barriers. c) Stakeholders have a vision and willingness to implement DfSA if the barriers can be overcome. To test the hypotheses, the authors pose three research questions (RQs) from the perspective of the two countries. The RQs, which also dictate the structure of the paper, are.

1. What are the key design features of a structurally adaptable timber building?
2. What are the barriers to implementing DfSA for timber buildings?
3. What are the benefits and risks of implementing DfSA for timber buildings?

To address the research questions, the authors conducted a literature review and semi-structured interviews with industry practitioners from both countries. In total, 22 participants were interviewed – 12 in Sweden and 10 in Australia. Purposive sampling was conducted to represent the entire value chain of building production and research in the pool of interviewees. The results of the interviews were evaluated using a thematic analysis. Corresponding to the three research questions, first, a set of characteristics was proposed for a DfSA strategy for timber buildings. Second, the barriers to implementing DfSA for timber buildings in the two countries were investigated. Last, the benefits and risks of implementing DfSA for timber buildings in the two countries were assessed. Based on the results, a set of actions to implement DfSA for timber is proposed. The paper concludes by summarizing the study and suggesting future research work to further advance efforts to prolong the service lives of timber structures.

2. Theory

CE is a multifaceted concept, including different strategies to move away from the linear "take-make-use-dispose" consumption model. The most frequent depictions of CE have been found to focus on three principles in order of priority: *reduce*, *reuse,* and *recycle* [15]. "The three Rs" have been expanded several times to include more principles within each theme [16,17]. To enable circularity, the decisions made in the initial design phase are crucial [16]. This is also true in the construction sector, where the initial design of a building is suggested to be the main determinant of its circularity [11–14]. Thus, designing for circularity has been a frequent topic in sustainable construction research. In reviewing such design strategies, Eberhardt et al. [12] identified three strategy themes: assembly/disassembly, material selection/substitution, and adaptability/flexibility. The two former themes are mainly focused on extending the service life of materials, components, and elements. Strategies related to adaptability/flexibility are instead concerned with extending the service life of entire buildings. The purpose is to both reduce the consumption associated with new construction and to reuse existing buildings.

To extend the service life of buildings, one should primarily investigate why buildings are typically demolished. A common notion is that buildings are demolished because they have become obsolete in some way [18–20]. Examples of such forms of obsolescence are aesthetic, functional, structural, or financial obsolescence [20]. Naturally, one form of obsolescence might cause another – e.g., structural obsolescence caused by damage or deterioration might cause a financial obsolescence, if the building can't be used as intended anymore. Obsolescence may lead to the demolition of structures long before their design life has passed. For instance, Swedish residential buildings commonly have a design life of at least 50 years. Despite this, almost 40 % of Swedish dwellings demolished in 1989–2021 were less than 40 years old, and approximately 15 % were younger than 30 years old at the time of demolition [21,22].

DfA is an emerging strategy to postpone building obsolescence and demolition. Though specific definitions of the concept vary, DfA generally aims to maximize the life span of buildings by facilitating changes [4,23,24]. The main motivation behind the concept is the unpredictability of factors that can affect a building in its lifetime [8,23]: The user needs might change, there might be some unforeseen damage to the building, or the climate might change resulting in new performance requirements. It is difficult, if not impossible, to anticipate for which specific reason a building might become obsolete before its design service life has passed. Furthermore, a building is not necessarily an entity made up of components that will expire at the same time or that have a finite life at all. Duffy [25] stated that a building can be seen as a collection of four somewhat independent layers with differing life spans. Brand [26] elaborated on the concept of system layers and expanded the list to six layers (ordered here from the longest life span to the shortest); *site*, *structure*, *skin*, *services*, *space plan,* and *stuff*. Altering or replacing a layer with a short life span (e.g., the furniture, labeled as *stuff*), typically does not affect the layers with longer life spans (e.g., the *structure*) [26]. From these insights, Graham [23] formulated two principal propositions of DfA; 1) a building is a dynamic system rather than a static object, and 2) a building is an assembly of constructed layers defined by their life spans.

Even for DfA buildings, the layer of the load-bearing structure is typically kept unaltered for the duration of the building's service life. This can be viewed as a reflection of Brand's [26] shearing layers, where the structure is the layer with the longest life span (surpassed only by the site, which is often presumed to be permanent). Altering the structure of a building is typically more costly and technically more complex than altering, for example, the space plan. Thus, this study proposes the following demarcation within the DfA concept.

- Design for Structural Adaptation (DfSA): Design that allows for change to the load-bearing structure of a building.
- Design for Non-Structural Adaptation (DfNSA): Design that allows for changes to a building's non-load bearing parts, e.g., its space plan, services, furniture, or façade.

It should be noted, though, that some strategies for DfNSA may facilitate DfSA. For instance, changes to a building's services can be necessary to perform certain structural adaptations.

Existing studies within the DfA concept can generally be classified as DfNSA research. It is commonly concerned with load-bearing frames that are designed to allow for changes to the non-load-bearing elements – e.g., structures where ceiling heights, live loads, and spans are increased in the initial design phase to allow for changes of usage [4,5]. This offers possibilities for flexible floor plans and functional changes, yet it is limited when extensive changes or structural repairs are needed. The authors of this study have instead chosen to focus on DfSA as a tool to avoid structural obsolescence, specifically in timber buildings.

Timber is often claimed to be a more sustainable choice of structural material for low-to midrise buildings. While several sustainability indicators can be found to support this claim, the common arguments lack some critical aspects. First, timber is commonly referred to as a renewable resource. However, a global rising demand for timber products has caused concerns about how to meet future timber needs while maintaining sustainable forestry [27,28]. While timber is renewable, mindful raw material extraction and timber resource efficiency are regarded as crucial to promoting biodiversity and carbon sequestration [29].

Second, timber captures carbon during growth and stores it in the use phase [30]. Sequestering and storing carbon are important tactics to mitigate climate change [3,28,31]. Yet, at the timber's end of life, the carbon is released into the atmosphere again. An extended use phase of timber ensures prolonged carbon storage, thereby reducing atmospheric greenhouse gas concentrations [30].

Third, timber is often claimed to have high reuse potential [32,33]. While a timber element can be used for several purposes throughout its life span, common reuse approaches will reduce the value and quality of the timber for each new use case [34]. A beam may be cut to a shorter beam, or it may be cascaded to a particle- or fiber-based product. High-quality timber products should be used for as long as possible before downcycling them into lower-quality products.

Despite the environmentally beneficial aspects of timber, today's timber structures do not promote service life extension and the associated preservation of high-quality timber products. If parts of a timber structure are damaged, e.g., by a local fire or by moisture, the entire building may be demolished since the conventional timber structure does not allow for extensive repairs. Similarly, drastically changed user demands may warrant a different structural system. The focus of DfA is often to avoid this issue by designing open-plan, post-and-beam structures with large spans and tall floor-to-floor heights. Still, such solutions are not always applicable for timber structures where serviceability requirements limit the floor and beam spans [35,36]. Moreover, increasing the spans and ceiling heights implies a higher material cost and decreased resource efficiency [37].

The complexity of altering a building's structure is particularly significant for modern timber buildings, for several reasons. First, modern multi-story timber structures are more complex for alteration in the use phase than traditional wood buildings [9]. Second, timber is a relatively cheap and low-carbon material, reducing the incentives to maximize its lifespan [9]. Third, though timber is often claimed to be an adaptable material, researchers argue that it lacks in this regard compared to steel [10]. This is due to lower rates of demountable connections, prefabrications, and reuse potential [10,38,39]. Fourth, modern timber structures are typically not designed to be adapted or even deconstructed. Consequently, adaptation attempts may face several problems. For instance, if an internal wall needs replacing, fitting the new wall or beam into place may not be possible due to the remaining structure. Furthermore, replacing a load-bearing wall or beam may be impossible to do without damaging the surrounding elements.

If, on the other hand, the building was designed with structural adaptation in mind, service life extension of the structure would be feasible. Rather than replacing a structurally obsolete building, it could be repaired or converted to have a new function. Thus, the motivations of DfSA fully align with circular economy values. If an entire building can be reused, materials and products are kept at a high-quality level and new construction can be prevented. However, due to the complexity of structural adaptability, examples of applied DfSA in timber buildings are scarce. This study aims to investigate how this new concept can be implemented, to further move the construction industry toward a circular economy.

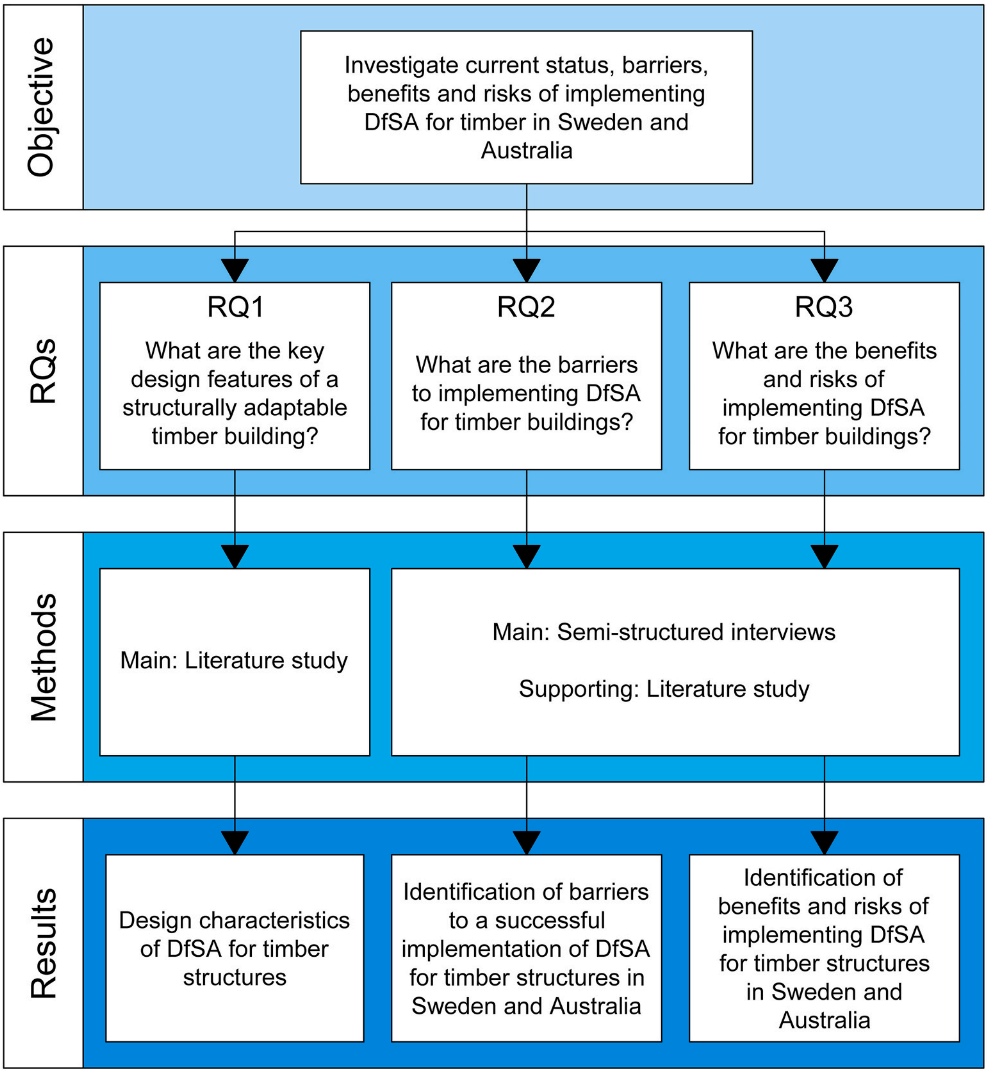

Fig. 1. Research overview.

3. Materials and methods

This chapter is divided with respect to the three research questions. Fig. 1 gives an overview of each RQ and its corresponding methods and results.

3.1. RQ1

To start with, the key design features of a structurally adaptable timber building are to be determined. As there is a lack of practiced or researched DfSA for timber, the chosen design features are based on a critical evaluation of previous research on general DfA strategies and timber-specific circularity strategies.

Representations of DfA in standards and regulations have been rare until recently. In 2020, a new ISO standard was published: ISO 20887 “Sustainability in buildings and civil engineering works – Design for disassembly and adaptability – Principles, requirements and guidance” [40]. The standard makes a distinction between specific and general adaptability, for expected and unexpected adaptations respectively. It further recommends careful consideration of which Design for Disassembly (DfD) and DfA principles to adopt for each construction project. The principles listed in ISO 20887 [40] to be considered for adaptability are.

- Versatility: Ability to accommodate changed functions with minor system changes.
- Convertibility: Ability to accommodate substantially changed functions by making building modifications.
- Expandability: Ability to accommodate substantially changed functions by facilitating building additions.

It should be noted that the adaptability principles of ISO 20887 are focused on accommodating functional change, and do not include repairability.

Since the notion of adaptable buildings emerged and gained popularity, a large number of studies have been carried out on the design of such buildings [6,8,26,41,42]. Several specific design strategies for DfA have been proposed in such studies. To investigate how the theoretical design strategies can be applied to real-world projects, Rockow et al. [4] collected common DfA strategies from the literature and analyzed them with the help of data from building adaptation projects from practice. As a result, they identified eight strategy themes.

- *Plans:* Accurate information, e.g., in documents, as-built drawings, and Building Information Models (BIM)
- *Reserve:* Increased capacity of the load-bearing structure.
- *Layer:* Separation of building system layers (based on Brand’s [26] shearing layers).
- *Open:* Open-plan spaces with limited obstructions.
- *Floor-to-floor height:* Increased floor-to-floor heights to accommodate for adaptation, for instance, a new function or added services.
- *Simple:* Simple design, such as repetitive and standardized elements.
- *Material:* Durable and high-quality materials that can last beyond the building’s design life.
- *Services:* High-quality services that are designed to accommodate both current and future needs.

The strategy themes can all be applicable for DfSA, except for the theme *Open*. The purpose of strategies within this theme is to minimize obstructions in the building’s two-dimensional layout and to allow for adaptations that do not require changes to the structure [4,6]. Using, for instance, a post-and-beam system with no internal structural walls can allow for non-structural functional changes [5]. As the aim is to avoid the need for structural adaptations, this strategy theme was deemed only applicable to DfNSA. However, applying such a strategy may reduce the need for DfSA and can thus be a valuable tactic for buildings that are not suitable for structural adaptations.

Furthermore, DfD and reversible connections in particular are generally considered to be enablers of DfA [6,23,40]. While Rockow et al. [4] recognize this, they exclude it from their list of strategy themes due to the lack of sufficient real-world examples of adaptation projects.

It should be noted that several researchers recommend a critical evaluation of DfA strategies. Schmidt and Austin [8] argue that universal adaptability is neither realistic nor desirable and that adaptability should be context-specific. Similarly, Fawcett [43] identified a need to optimize adaptability – to invest in a building’s ability to accommodate change, but not invest too much in case the

Table 1
Circularity strategies in timber engineering research, connected general DfA strategy themes.

Strategies for circularity in timber engineering research, compiled by Vandamme and Rinke [44]	Connection to general DfA strategy themes
Reversible connections	*DfD*
Avoiding chemical connections and non-compostable coatings and elements	*Material, DfD*
Protecting the timber from internal water damage	*Material*
Standardization and modularity	*Simple*
Sustainability certifications for circularity and reuse	–
Independent building envelopes	*Layer*
Durability, repairability, and replaceability	*Material, DfD*
Ability to carry increased loads	*Reserve*

expected change never occurs.

While the strategies described previously in this section can be considered non-material specific, researchers have also suggested circularity strategies specifically for structural timber. The main strategies for circularity in timber engineering research, as compiled by Vandamme and Rinke [44], are shown in Table 1. When applicable, a connection has been made to the strategy themes from Rockow et al. [4].

Based on Table 1 and the general DfA strategies from Rockow et al. [4], this study proposes seven characteristics of DfSA for timber buildings. The characteristics are: *Traceable*, *Targeted*, *Resilient, Layered*, *Simple*, *Durable,* and *Reversible*. A literature study was conducted to determine strategies, enablers and crucial aspects of these characteristics.

The proposed characteristics of DfSA were developed specifically for timber structures, but they can be applied to other materials and construction types. While some enablers described for the design characteristics are specific to timber, others are universal and not material-specific.

3.2. RQ2 and RQ3

While DfA as a general concept is gaining traction, DfSA is a rare concept both in research and in practice. To investigate this new and relatively unknown concept from the perspective of practitioners, an exploratory and qualitative research approach was applied as recommended by Fellows and Lui [45] and Creswell and Creswell [46]. To address the novelty of the topic, the authors chose to conduct semi-structured interviews with open-ended questions. This allowed the interviewees to reflect on the subjects more freely, compared to alternative methods such as questionnaires or structured interviews.

In Sweden, the interviews were held collectively in a focus group with 12 participants: one architect, three contractors/developers, two engineers/consultants, one timber manufacturing associate, two timber industry association representatives, and three researchers. In Australia, the interviews were held separately with 10 participants: three architects/housing providers, one contractor/developer, two engineers/consultants, one timber manufacturing associate, two timber industry association representatives, and one researcher.

Both collective and separate interviews have their respective benefits and drawbacks. Fellows and Liu [45] suggest that collective interviews may add the benefit of respondent interactions, leading to a richer consensus on the issue – though possibly at the loss of the detailed, individual input that separate interviews can provide. A common approach is to combine focus groups with other methods, such as individual interviews, for a triangulated methodology [45].

As the interview study had an exploratory approach to investigating a novel topic, the aim was primarily to gain an introductory understanding from key stakeholders. By having a smaller sample of interviewees, in-depth results could be collected from the stakeholders involved in the different phases of the construction process that DfSA might affect. As the primary aim was to interview the appropriate stakeholders, purposive sampling was used in the selection of interviewees. Bernard [47] recommends purposive sampling when the aim is to understand a specific social phenomenon from the perspective of key individuals. The interviewees were chosen with a focus on representation from architects, contractors, developers, engineers, consultants, timber manufacturers, timber industry associations, and research institutes. Interviewees were further chosen for the study based on their experience with timber building projects. Thus, a wide range of expertise from the entire value chain of timber construction was gathered.

Semi-structured interviews allow for rich results, but they also contain the risk of researcher bias. To reduce the risk of unconsciously leading the interviewee in some direction, e.g., by asking leading questions, the interviews all followed the same protocol which is described in the following.

Initially, DfA as a concept was introduced and defined, followed by a description of the study's aim to apply DfA to load-bearing timber structures. After that, the interviewees were asked to answer 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?

Follow-up questions were asked when applicable, such as when clarifications were necessary.

The input from the Swedish stakeholder group was written down during the focus group discussion. The interviews with Australian stakeholders were recorded, with the consent of interviewees, and transcribed. The answers to questions 1–3 were analyzed using thematic analysis, as it is a widely recognized analysis approach to find emerging themes from semi-structured interviews. The analysis was conducted iteratively, according to the process described by Braun and Clarke [48]. A mix of focused coding and in vivo coding was applied to the data. The former aimed to find the most prominent and relevant codes in relation to the research questions. The in vivo coding, i.e., the selection of direct quotes from participants, aimed to enrich and validate the identified themes. When the themes had been determined, they were re-evaluated and redefined if they were considered too vague or too similar to each other. If a found theme contradicted another theme it was not ignored – instead, the contradiction was explored. For instance, market competitiveness was found as a theme both when stakeholders were asked about benefits and risks. The reason for this was subsequently investigated based on the specific input points from stakeholders. The themes that were found are presented for questions 1-3 separately.

In RQ2, a substantial amount of research covering the barriers to implementing DfSA-related strategies was found. Thus, the input from practitioners regarding barriers could be connected to a research context. RQ3, on the other hand, concerns the perceived benefits and risks of implementing DfSA, which is yet to be implemented anywhere in the world. Thus, no previous research could be found to confirm or deny the potential benefits and risks identified by this study's interviewees. Furthermore, to the knowledge of the authors, there are no similar interview studies concerning the perceived benefits and risks of implementing DfA for timber structures.

4. Results

4.1. RQ1: characteristics of DfSA for timber buildings

To address RQ1, the proposed seven design characteristics of DfSA for timber are investigated in this section.

4.1.1. Traceable

Accurate information is crucial for DfA projects, to minimize uncertainties and ensure that adaptations can be carried out in accordance with the design [6,8,40]. Strategies to promote traceability for buildings include BIM [6,40], digital twins [49], and identification technology such as bar coding, Quick Response (QR) codes, or Radio Frequency Identification Device (RFID) tags [40]. Another example of information management for circular economy buildings is *material passports*, to allow for *buildings as material banks* [50]. Such documents or passports can cover entire buildings, or specific products and materials within a building [51]. For a DfA building, a material passport should not only document materials and quantities but also records of potential changes to the building and instructions for future adaptations [6,50]. For the load-bearing structure, in particular, such information could be crucial - showing information such as product dimensions, strengths, and reversibility of connections [52].

4.1.2. Targeted

While adaptability can grant long-term benefits, researchers have expressed the need to weigh such benefits against the initial increased cost and resource consumption that is associated with DfA [43,53]. Schmidt and Austin [8] further recommend that DfA should be context-specific. Such context, in a structural sense, could be that wet rooms are more prone to water damage than others, or that office buildings are sometimes replaced by residential buildings but not as often by warehouses. Aiming for universal adaptability could lead to overdesigned structures that are expensive to build and unattractive to clients and users [8]. Thus, there is a need for a risk-based approach to DfSA.

4.1.3. Resilient

Adapting a building can influence its load assumptions and load paths, and its requirements such as fire or moisture protection. To accommodate such changes, a well-recognized strategy within DfA is to incorporate reserve capacity in the early design stage [4,42]. Increasing the load-bearing structure's capacity could be performed as part of a DfSA strategy, for instance by preparing it for potential changes in load paths [6]. Increasing the resilience of other building layers could also facilitate DfSA. In the service layer, in particular, adaptability can be promoted by increasing the service capacity with potential future use in mind [54,55].

4.1.4. Layered

A common strategy for DfA is the layering of building systems, based on Brand's [26] shearing layers of change. The aim is to facilitate adaptation by separating elements, physically and functionally [6]. The strategy stems from the concept of *Open Building*, popularized in the 1960s by Habraken [56]. The idea behind the concept was to facilitate flexibility by separating a building's "permanent" parts, i.e., its structure, from its infill that could be easily changed according to the users' needs [56]. While the idea of the structure being permanent conflicts with DfSA, the strategy may still facilitate structural adaptations by minimizing obstructions and partial demolitions of other layers. For instance, avoiding ducts and cables embedded in the structure can make adaptations more feasible by minimizing the need for additional adaptations in the service layer [57].

To utilize a layered building for adaptations and deconstructions, traceability is, yet again, crucial. To aid in understanding the interdependencies of different layers and building systems, Schmidt and Austin [8] describe a Dependency Structure Matrix (DSM) (originally a Design Structure Matrix as coined by Steward [58]). The DSM is a square matrix that maps the relationships between elements. For instance, one can choose to map the physical dependencies, energy transfers, or information exchanges between different building parts.

4.1.5. Simple

Many researchers agree that DfA is enabled by the regularity and predictability of buildings, building systems, and elements [6,41,59,60]. Ross et al. [6] suggest that using repeating layouts and larger but fewer members in the structure can reduce uncertainty in the adaptation phase. Other strategies from Ross et al. [6] that can be included in this characteristic are *commonality* (repetitive use of component sizes and structural details) and *modularity* (standardization of element sizes and interfaces). Standardization and modularity are both widely recognized as adaptability enablers [61]. Though implementing such strategies can increase the initial investment cost of a project, they can simplify adaptation processes enough to provide cost savings in the long term [23,41].

4.1.6. Durable

Appropriate, durable materials and components that are possible to repair are important aspects of adaptability [9]. For instance, it is recommended to use materials of adequate durability in order to increase the longevity of the buildings. Robustness is a related aspect here, i.e. "the ability of a building to accommodate some kind of initial local damage without it propagating and causing disproportionate consequences" [62]. Hence, durability and robustness will increase the likelihood of a decision to adapt rather than demolish in case of obsolescence or increasing demands [63]. The owner's ability to maintain and refurbish the building is also of importance, as the building may otherwise be demolished because it is outdated or in poor condition. Lastly, Ross et al. [6] recommend avoiding both toxic or hazardous materials and composite materials since such qualities hinder both adaptation and reuse potential. For timber specifically, it is recommended to avoid glues and toxic coatings, while still keeping the timber protected from moisture [6, 64].

4.1.7. Reversible

Reversibility is primarily associated with DfD, but the connection between DfD strategies and building adaptability is nonetheless emphasized in many previous works [6,23,54,61,65]. Graham [23] proposes the following DfD strategies.

- *Independence*: keeping elements with different functions independent from one another.
- *Connections*: use mechanical connections, rather than chemical.
- *Sequencing*: consider in what order the building will be constructed and deconstructed, and place large or heavy elements where they can more easily be accessed for removal.
- *Documentation*: keep accurate records of construction and deconstruction available for the building's service life.

Independence, *sequencing,* and *documentation* are in line with previously described DfSA characteristics, namely *Layered* and *Traceable*. Mechanical connections, however, are more specific to DfD. DfD connections aim to retain an element or material's functional value after deconstruction, which is difficult to accomplish with glued connections [6,23]. Instead, the focus lies on reversible mechanical connections. An example of such a solution is the "hook connector" – for instance the Knapp Megant [66] – which consists of two parts that are fixed to the timber elements in prefabrication and that can be interlocked on site [67,68]. The

Table 2
Barriers to implementation of DfSA for timber buildings according to stakeholders.

Theme	Stakeholder group	
	Swedish stakeholders (focus group, February 2023)	Australian stakeholders (interview study, March 2023)
General barriers	• "Adaptability today and tomorrow might be different." – Engineer. • Difficult to create a general but useful design guide.	• It is difficult to predict what the adaptability needs will be. • DfSA conflicts with other resource-minimizing efforts – i.e., aiming for a lean design. • This new way of building requires training for designers, builders, inspectors, etc. • "To build something truly adaptable, you almost have to build it in a 3D grid […] What we found with this was it's very limited." – Architect.
Costs	• Design for Deconstruction is generally considered to be too costly and non-essential. DfA could face the same problem. • "How are financial aspects considered in the whole building process?" – Engineer.	• DfSA will demand a higher initial cost of the building project, an investment that might pay off down the line. But building projects are often on a tight budget where any non-essential feature will be removed. • "I would worry that something like adaptability, unless there was a really good argument for a long-term investment, that would be one of the first things that would be pulled out." – Architect.
Policy	• Building codes are not designed with adaptability in mind. They might be insufficient. • "Potential changes in the regulation and code in floor height, fire safety, acoustic performance, and other architectural parameters." – Contractor.	• "Standards are always behind the developments of industry and academia. You come up with these great ideas, but they need to be accepted by the regulatory bodies, by all the regulations, codes, building codes, and so on. If you decide to change what is standardized and very recognized on those standards … You will have a lot of obstacles" – Timber Industry Association. • If the adaptation is extensive enough, the building will have to conform to current building codes (possibly warranting further reconstructions or causing the developer to opt out of adaptation completely). • DfSA is not clearly incentivized.
Technical solutions	• "Connections are the challenge in buildings" – Contractor. • There is no guideline for connections that will allow for adaptability. • Extended service life of the building means prolonged maintenance of the non-structural building parts as well. • If a timber structure is designed to be adaptable, the service life of the building might instead be governed by its foundation or by long-term effects on timber, connections, glue lines, etc.	• Taking the load off an element while it is being replaced will potentially take a lot of work. • "I guess there are other issues around say service reticulation. In an office your services strategy is going to be quite different to what you would do in a residential building." – Engineer. • Different functions warrant different floor heights, but changing a building's floor height is not realistic.
Traceability	• The lack of a system to validate products for adaptive reuse.	• "If you're a builder and you buy a piece of timber that doesn't have the appropriate markings on it of what the standard is, you theoretically can be charged for using that piece of timber. […] [Some businesses] spray paint [markings] onto every single piece of timber. […] Now, that could get chopped off on-site by a builder. And then, where's the record?" -Timber industry association.

solution can be classified as reversible as it can be demounted again by simply detaching the two connector parts. Another example, developed specifically for timber panel structures, is the X-RAD connection system patented by Rothoblaas [69]. Like the hook connector, it consists of several parts that are installed in the separate timber elements at the factory, to be connected to each other on site. The X-RAD connection parts are installed in the panel corners and connect to neighboring panels with bolts via a connection plate [67–69]. The connection can be reversed by removing the bolts.

As DfD is an enabler of DfA, the reverse can be considered true as well; DfA can be an enabler of DfD [70,71]. However, Ross et al. [6] report that out of their eleven investigated design-based enablers for adaptability, experts rate DfD as the least effective one. They propose that this could be due to the lack of real-world examples of DfD as an adaptability enabler [6], a theory which Rockow [4] later find further support for. While DfD is mainly a strategy focused on the building's end of life, it is also a necessity for structural adaptations [71].

4.2. RQ2: barriers to a successful implementation of DfSA for timber

The second research question of this study concerned the barriers to an implementation of DfSA for timber buildings. This question is addressed in this section by summarizing and evaluating the results from the thematic analysis of the interview data regarding barriers. These results are subsequently connected to previous research works.

4.2.1. Overview of barriers according to stakeholders

Table 2 summarizes the input regarding barriers obtained from the interview study. Five themes were found in the thematic analysis: General barriers, Costs, Policy, Technical solutions, and Traceability. Some notable common concerns between Sweden and Australia were: a) difficulty in predicting adaptability needs, b) high initial investment costs, c) insufficient building codes, and d) building systems that hinder product traceability. While the technical solutions mentioned differed completely between the two groups, the participants expressed generally similar concerns within the remaining four themes.

The five themes found in the thematic analysis are connected to previous research works in the following sections.

4.2.2. General barriers

The need to incorporate prioritization in DfSA was brought up by several interviewees in the Australian stakeholder group. Despite being a design philosophy created to be a safety net for failed predictions, a 'one size fits all' approach to DfA is generally not considered to be appropriate [8]. Furthermore, as Australian interviewees pointed out, this would act in conflict with societal efforts toward resource efficiency. Optimizing structures to minimize new material demand, sometimes referred to as 'lean design' [72], is considered a staple of sustainable construction [73]. While DfA can be environmentally beneficial in the long term, there is a need to weigh those potential benefits against the lost opportunities for the short-term carbon savings associated with lean design [53].

Another concern within both stakeholder groups was informing and training practitioners on DfSA practices. This is echoed in ISO 20887 [40], where the importance of sufficient knowledge among all practitioners in the building process is emphasized.

4.2.3. Costs

Schmidt and Austin [8] stakeholder communication demonstrates a similar concern for costs as expressed by the stakeholders in this study. Incorporating adaptability in the design phase would, most likely, add an initial investment cost that might not be returned for decades [5,8]. Schmidt and Austin [8] further describe a 'circle of blame' regarding the lack of adaptable buildings produced; developers claiming that they would build adaptable if investors would pay for it, investors claiming a lack of demand for adaptability, owners and users pointing to a lack of available adaptable buildings, and designers and constructors claiming that no developers ask for adaptability.

The stakeholder communication results suggest that a well-demonstrated DfSA solution could motivate the increased initial cost to building owners. Similarly, existing research on implementing sustainability strategies in the construction sector has found stakeholder communication to be crucial [51,74].

4.2.4. Policy

The Swedish and Australian stakeholders shared similar sentiments on policy for DfSA. First, it was noted that building codes and standards are not designed with adaptability in mind, which can make implementation difficult. Similar notions can be found in literature, where regulation is suggested to play a vital role in the implementation potential of circular economy strategies [75–77]. Second, a possible barrier was the fact that in both countries, changing a certain area of an existing building can mean that the entire building must be updated according to current building codes. This may cause building owners to opt out of adaptations, rendering the DfSA efforts unnecessary. However, the DfSA characteristics defined in section 4.1 may facilitate such updates as they aim to design for multiple possible functions and requirements.

Another input, from an Australian interviewee, regarded the lack of incentives for DfSA. While the Australian government introduced a new regulatory CE framework in 2019, it is mainly concerned with waste recovery and recycling [78–80]. This is also the case for policy on the level of Australian states and territories, where the CE strategies and incentives have a clear focus on waste reduction [79]. Similar efforts can be found in Sweden, where by 2025 at least 70 % of C&D is to be recycled or prepared for recycling [81]. Additionally, a climate declaration of each new Swedish building (with a few exceptions) is required as of 2022 [82]. However, these initiatives are not likely to work as effective incentives to design for adaptation.

There are some indications of future regulatory incentives for circular economy principles in the European construction industry. In

2020, the European Commission introduced a "circular economy action plan" as part of the European Green Deal. In it, there are commitments to promote circular economy principles, such as durability and adaptability, for building design [83]. As of January 2024, no further details have been announced regarding this objective [84].

For the Australian construction industry, Iyer-Raniga et al. [79] identified a similar need as the existing policy is mainly concerned with end-of-pipe solutions. While recycling is important to the transition towards a circular economy, they argue that there is a need for regulatory frameworks based on higher-order, design-lead strategies [79].

4.2.5. Technical solutions

As discussed earlier in this paper, reversible connections are crucial for structural adaptability, but very rare in practical applications [4]. This sentiment seems to be shared by this study's stakeholders. In addition, there is concern for the complexity of supporting the surrounding structure while repairs are ongoing, the service reticulation for building conversions, and the longevity of non-adaptable building parts. These topics are all related to the defined characteristics of DfSA in section 4.1, though research on practical solutions and their execution is needed.

4.2.6. Traceability

Accurate information plays a crucial part in successfully implementing CE strategies in the construction industry, though Ahn et al. [85] find considerable research gaps on the subject. While BIM tools and Internet of Things technologies have great potential to aid in accurate information for CE projects, the research on applications in mass timber buildings, specifically, is found to be limited [85].

4.3. RQ3: benefits and risks of implementing DfSA for timber

The third research question of this study concerned the benefits and risks of implementing DfSA for timber buildings. This question is addressed in this section with the results of the thematic analysis regarding practitioners' perceived benefits and risks of implementing DfSA for timber in Sweden and Australia.

4.3.1. Benefits

Three themes within the perceived benefits were found, as can be seen in Table 3. The themes identified were *Sustainability and circularity*, *Market competitiveness*, and *Technical solutions*. A notable commonality between the two groups is found in the first category, where structural adaptability is perceived as in line with various sustainability goals. This is supported by the literature, where adaptability is frequently connected to environmental, social, and economic sustainability [4,86,87].

4.3.2. Risks

The thematic analysis of practitioners' perceived risks of implementing DfSA for timber resulted in four themes, as shown in Table 4. The themes found were *Sustainability and circularity*, *Market competitiveness*, *Technical solutions,* and *Building practice*. Several

Table 3
Benefits of implementing DfSA for timber buildings according to stakeholders.

Theme	Stakeholder group	
	Swedish stakeholders (focus group, February 2023)	Australian stakeholders (interview study, March 2023)
Sustainability and circularity	• In line with sustainability goals and EU taxonomy. • "From a fire safety perspective, this may decrease the demolition rate of buildings damaged by fire." – Engineer. • "The renovation rate needs to triple in Sweden." – Contractor.	• In line with growing demands for sustainable forest management and environmental conservation. • "Something that is going to be very common in the future because of the soil restrictions and less availability of soil in very dense urban areas is that you want to increase the capacity of buildings, and you want to add a couple of floors" – Timber industry association. • In southeast Queensland, available flatland to build on is becoming scarce. Thus, the demand to increase the capacity of buildings will be common in the future.
Market competitiveness	• If timber can be made adaptable, it can become a more competitive structural alternative. • It is often claimed that timber is easier to adapt and reuse [than other structural materials], but that is currently not always the case. • [On repairability] "Timber is often considered 'dangerous' due to moisture or fire." – Engineer.	• If the solutions are within reasonable limits and well justified to developers, they will increasingly see it as an investment rather than an unnecessary cost. • "We only meet about 70 % of our timber demand in Queensland. And similar nationally, so importing about 30 %. We're running around telling everyone to use more timber, but we haven't got enough. It's a big issue." – Timber Industry Association. • Timber is the preferred building material in Australia but there are not enough trees, processors, or manufacturers to meet the market demand. • "I think prefab itself has almost become a bit of a desirable aesthetic, so, perhaps there is the idea that it can be marketed to people down the track." – Architect.
Technical solutions	• "Standardization is very beneficial" – Timber industry association. • Good technical match with prefabrication technologies.	• "A lot of timber design lends itself to being designed for disassembly. Concrete is quite hard to deconstruct unless it's pre-cast." – Engineer.

input points can be connected to the proposed characteristics of DfSA for timber, listed in section 4.1. For instance, increased material demand and inbuilt details can be optimized and justified by targeting adaptability efforts. Incorporating durability in the DfSA strategy can affect the service life of the foundation, so it does not govern the building's life span. Lastly, simplicity and traceability can facilitate informed and safe adaptations by providing accurate documentation and predictable structural systems.

Other noteworthy input points do not have a direct connection to this study's defined DfSA characteristics. The most notable is the risk of decreased timber sales associated with resource efficiency. The interview results suggest that this is a more substantial concern in Sweden than in Australia. This may in part be caused by the difference in domestic timber production. Australia produces approximately 80 % of its annual consumption of sawn softwood and imports the remainder [88]. Sweden, on the other hand, is one of the world's leading exporters of timber products and more than meets the domestic demand [89]. Consequently, Swedish timber producers may have incentives that conflict with resource efficiency, while Australian producers are unlikely to face a demand shortage due to circular economy efforts.

5. Discussion

When investigating the Swedish and Australian construction systems and the practitioners' view of the topic, only a few differences were found. The most notable differences are likely to stem from the two distinguished timber industries. Sweden is more than self-sufficient in terms of timber products, whereas Australia relies partly on imports to meet the domestic demand [88,89]. Unsurprisingly, this affects both the portion of timber in load-bearing construction and the practitioners' view on resource efficiency in timber construction. First, Sweden utilizes and produces engineered wood products such as cross-laminated timber to a greater extent, while the focus of Australian timber construction mainly leans toward light-frame structures. Second, the idea of resource efficiency in the timber industry was seen as purely positive by most Australian industry stakeholders, while this was not the case for manufacturers in Sweden. This is likely because the domestic forest industry in Australia is not expecting a demand shortage even if the timber industry becomes vastly more resource efficient. Swedish timber producers, on the other hand, are stakeholders in one of the country's biggest export markets. In addition, Sweden has a large rate of energy usage from construction and demolition waste, which results in a market and rather high value for combustible demolition residues. Thus, Swedish producers might have fewer incentives to promote service life extension and reduced timber raw material consumption as an alternative to the current cascading process. The incentives for waste recovery and recycling in Australia, described in section 4.2.4, may be a marginally more effective driver for circular timber construction than similar Swedish initiatives. However, as neither country has implemented regulations that target building life extension specifically, the incentives for DfSA will likely be lacking for both industries.

The main barriers to implementation found, both in the literature study and the interview study, were centered around cost and technical solutions. Related to both issues is the approach of targeted DfSA. While designed adaptability emerged from the notion that predicting what will happen to a building is impossible, universal adaptability would neither be cost-effective, resource-efficient, or even technically possible [8,43]. The concept of targeting adaptability was found both in the literature study and the interview results. Several stakeholders suggested risk analyses for different building types, to investigate the probability of various damages or changed user needs together with the associated negative effects of not being able to adapt to them. This can serve both as a way to decide which

Table 4
Risks of implementing DfSA for timber buildings according to stakeholders.

Theme	Stakeholder group	
	Swedish stakeholders (focus group, February 2023)	Australian stakeholders (interview study, March 2023)
Sustainability and circularity	• Demand for too much, possibly unnecessary, material.	• "There's no accountability to how things are reused, repurposed or deconstructed, or recycled. Then you can implement all of these things for nothing and lose the gains to extend the life of a structure." – Engineer.
Market competitiveness	• One of the advantages of timber construction is the high prefabrication rates, resulting in quick on-site construction processes. A new solution should not prolong on-site construction as it can hurt timber competitiveness. • "Does DfSA make timber constructions less efficient considering time and cost? Not necessarily but it is a possibility." – Timber industry association. • Possibly decreasing timber sales.	• Timber producers always want to sell more cubic meters, even though the demand is much higher than domestic producers can provide. • "People make more money by creating more things. A lot of industries might go, 'Oh no, that's not great'. So, I see that as a potential barrier." – Timber Industry Association.
Technical solutions	• "Can the performance of the foundation in a prolonged time span be guaranteed? Even if the timber structure can last for a long time, the foundation might limit the lifespan still." – Engineer.	• "I see the potential risk in terms of this being complicated to implement." – Timber industry association.
Building practice	• "Unnecessary inbuilt details" – Architect.	• The knowledge of how to adapt the building might not be passed on, so in the future, it is either adapted in an unsafe way or simply demolished. • "It is difficult to ensure that builders will actually build [the structure] to be reversible." – Architect. • If the owner wants to adapt a building, they often need to upgrade it to meet modern codes. Sometimes that becomes too much work, causing the owner to opt out of adaptation.

type of adaptations are valuable to design for and as a way to motivate developers to accept the initial investment cost associated with DfSA. Naturally, there is still a risk that the type of obsolescence eventually occurring in the building is not one that was included in the designer's adaptability strategy. For instance, an office may have been designed to allow for a conversion to a residential building, while the risk for structural damage was considered low enough to not be included in the design strategy. If a fire occurs in the building, the designed adaptability may not sufficiently cover the needs for structural repair. Hence, practitioners should base their adaptability strategies not only on statistics but also on the specific scenarios they want to avoid for their project. For timber structures, stakeholders may be specifically cautious of fire or moisture damage and thus feel the need to invest in the building's ability to be repaired in such scenarios.

The identified barriers in study can be used as a guide to understand what is missing to enable an implementation of DfSA for timber. For instance, stakeholders' uncertainties about the cost of DfSA implies that an implementation is enabled by low-cost technical solutions, governmental incentives and well-communicated economic implications of the concept. Correspondingly, this study proposes seven actions to facilitate a successful implementation of DfSA for timber structures in Sweden and Australia. The steps are listed by order of importance below.

1. Development of reversible connection systems for adaptable timber structures, that are standardized, tested, and well-documented for practitioners.*E.g., reversible connection systems for CLT panels that allow for panels to be fully replaced.*
2. Implementation of governmental incentives and regulations to incorporate circularity strategies in the design process and the whole building life cycle.*E.g., financial incentives for adaptable building designs.*
3. Development of building codes and standards that incorporate reversibility and adaptations.*E.g., a more specific ISO standard with a focus on reversible building systems.*
4. Development of a system or technology for traceability, such as BIM and material passports, developed with a focus on adaptable load-bearing timber structures.*E.g., development of tools or add-ons for commonly used BIM software to aid in making buildings traceable.*
5. Quantification of the benefits of DfSA in relation to additional initial costs and material demands.*E.g., life cycle cost assessments in case studies of timber DfSA buildings that are adapted at some point in their service life.*
6. Communication with end-users, building owners, decision-makers, and other stakeholders to demonstrate the benefits of DfSA and to reduce uncertainty related to its application.*E.g., Demonstrations and mockups of reversible timber connection systems.*
7. Risk-based assessments of different building types to enable targeted DfSA, to motivate the additional initial cost and resource consumption.*E.g., surveys mapping the most common demolition causes for different building types in Sweden and Australia.*

The results of this study are generally in line with previous research on implementation of circularity strategies in the building sector. Similar studies have emphasized the need for regulatory incentives [75–77], accurate information [85], and stakeholder communication [51,74] in the implementation of sustainable and circular practices. This study reinforces these results while adding practical input regarding the implementation of one specific circularity strategy. The results of this study can act as a foundation for further research, which in turn can support the technical and economic feasibility of implementing DfSA for timber buildings. Designing buildings for longevity is a crucial part of reducing the construction sector's massive impact on global warming, resource consumption, and waste production. Building structures with timber rather than concrete or steel can be an important part of reducing this impact as well, but timber needs to be used mindfully. Keeping wood resource extraction at sustainable levels is essential in order to promote healthy forests and forest ecosystems. While Sweden's timber industry plays a major role in its economy, recent years have seen a growing public concern regarding deforestation. Similarly in Australia, there is widespread concern for loss of natural habitats and ecosystems due to industrial forestry. Thus, while multi-story timber construction is gaining popularity in both countries, resource efficiency and long-lasting structures are of public importance as well as vital for a sustainable development of the building sector.

As the two countries are seen as representatives of countries with growing timber industries but varying degrees of self-sufficiency, the results of this study are scalable. For instance, the perceived risk of decreasing timber sales due to resource efficiency, which was found among Swedish interviewees, could be assumed to also be present in other countries with high timber export rates. The collective concerns among this study's practitioners regarding investment cost and technical solutions are assumed to be reflected in any country with an active timber industry. Due to the scalability, the list of actions presented earlier in this section can be applicable to the worldwide timber industry, with a few exceptions. The two actions regarding governmental incentives and building codes are, to a certain extent, regionally bound. Furthermore, risk-based assessments of common demolition causes in timber buildings may vary on a regional basis. Because of this, such investigations ought to be conducted in each region or country where there is an interest in implementing DfSA.

It should be noted that this study is based on a relatively small, but carefully selected and representative pool of interviewees from the key actors in the timber and construction industry. The results from the interviews confirmed the findings from the literature while providing further important details and insights on the topic. Future research works may include in-depth interviews to further explore the insights found in this study. For instance, frequent input from the stakeholders of this study was that the cost of investing in a building's adaptability may cause decision-makers to opt-out. Thus, future interview initiatives may explore this by exclusively interviewing developers, clients, financial officers, and other decision-makers about the topic.

6. Conclusion

This study investigated the current status, benefits, risks, and barriers of implementing Design for Structural Adaptation for timber buildings in Sweden and Australia. Seven characteristics of DfSA for timber were proposed, and the effects of implementation on practitioners from different stakeholder groups were examined from the perspectives of both countries. In addition, the feasibility of implementing DfSA in Sweden and Australia was assessed by investigating barriers and how to overcome them.

Overall, DfSA was found to have many similarities with other concepts for building circularity, but with the added technical complexity of altering a structure without having to partially demolish the building. This complexity is reflected both in the results from the literature study and in the input from practitioners. The literature study and practitioners' input also showed the possible benefits of implementing DfSA for timber. The benefits were generally centered around environmental sustainability, but the results also suggest that DfSA can grant economic benefits. These benefits need to be put in relation to the increased initial investment cost that DfSA will likely bring. If timber DfSA can be risk-based, targeted, incentivized, well-documented, and communicated, such barriers may be overcome. In conclusion, there are clear benefits of implementing DfSA for timber structures, both from a societal and industrial perspective. Such an implementation could be feasible after further research and development has been conducted on several fronts, as detailed in the action plan in section 5.

This study contributes to the field of DfA research by addressing the gap concerning the application of DfA in load-bearing timber. Applying DfA to structures, and timber specifically, is shown to promote both ecological and economic sustainability. This study introduces and defines Design for Structural Adaptation, and subsequently investigates what is needed to implement it. Thus, it serves as an initial step in the roadmap towards designing timber structures for life extension. The input that is collected from practitioners is valuable not only to support further efforts to implement DfSA but also to any research concerning the implementation of circularity strategies and timber innovation. In the long term, this study can impact the construction industry by fostering development that reduces the need for new construction. Thus, the industry's impact on raw material consumption, waste production, and greenhouse gas emissions could be reduced.

The results of this study can be used as a guide for further research, as DfSA has been defined and the need for it has been established. The results mapping the barriers to implementation show where future efforts are needed. For such research works, the authors strongly recommend investigations into the common causes of demolition for timber buildings, considering variables such as location and building function. This information can assist in targeting DfSA strategies, thus optimizing the designed adaptability for cost- and resource efficiency. Furthermore, life cycle assessments and life cycle cost analyses are recommended to investigate the possible benefits of DfSA in timber buildings. The authors further suggest investigations of possible traceability technologies that can be applied to DfSA timber structures. Lastly, research and development of reversible timber connections for adaptability purposes is necessary to facilitate moving, removing, or replacing timber elements without damaging the remaining structure.

CRediT authorship contribution statement

Vera Öberg: Writing – original draft, Visualization, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Robert Jockwer:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Yutaka Goto:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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