COST Action CA 20139
Holistic design of taller timber buildings (HELEN)

Design for robustness, adaptability, disassembly and reuse, and repairability of taller timber buildings: a state of the art report

Edited by

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General info

This report comprises documents written within the scope of Working Group 1 of COST Action CA20139 Holistic Design of Taller Timber Buildings (HELEN).

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The sole responsibility of the content of the various contributions lies with their authors.

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Impressum

Design for robustness, adaptability, disassembly and reuse, and repairability of taller timber buidlings: a state of the art report.ban

COST Action CA20139 – Holistic Design of Taller Timber Buildings (HELEN).

Working Group (WG) 1 – Design for robustness, adaptability, disassembly and reuse, and repairability.

WG 1 and its subgroups (SGs) are coordinated by Pedro Palma, Maria Felicita, Kristina Kröll, Lisa-Mareike Ottenhaus, Felipe Riola-Parada, Gerhard Fink, José Manuel Cabrero, Reinhard Brandner, and Robert Jockwer.

December 2022

Foreword

Working Group (WG) 1 of COST Action CA 20139 HELEN deals with aspects related to design for **robustness**, **adaptability**, **disassembly and reuse**, and **repairability** in taller timber buildings.

As of October 2022, WG 1 has 102 registered members from 40 different countries. About 80% of the members are also members of other WGs, 35% of which are also members of WG 4 and 25% are members of all other WGs. This shows the broad scope and interdisciplinary nature of the topics addressed in WG 1.

After the 1st WG 1 meeting[1] in Izola (SI), on 24-25.05.2022, WG 1 was organised into one Sub-Group (SG) on robustness and disproportionate damages:

- SG Robustness, coordinated by Pedro Palma (Empa, Switzerland) and Maria Felicita (TU Delft, The Netherlands)

and three subgroups (SG) related to the circular economy:

- SG Adaptability, coordinated by Kristina Kröll (University of Wuppertal, Germany), Lisa-Mareike Ottenhaus (The University of Queensland, Australia), and Felipe Riola-Parada (City University of Applied Sciences Bremen, Germany);
- SG Design for disassembly and reuse, coordinated by Gerhard Fink (Aalto University, Finland) and José Manuel Cabrero (Navarra University, Spain);
- SG Repairability and maintenance, coordianted by Robert Jockwer (Chalmers University, Sweden).

The documents collated in this publication were written within the scope of the various SGs and were revised based on comments received during and after the 2nd CA 20139 Plenary Meeting[2] in Gothenburg (SE), on 04-05.10.2022.

The objective of these documents is to give an introduction to the topics of WG 1 and to motivate other members to identify possible collaborations and actively participate in the work of WG 1.

1 Draft minutes and presentations of the 1st WG 1 meeting, in Izola (SI), temporarily available online at https://polybox.ethz.ch/index.php/s/lOmpX9G8YJ89asb.

2 Draft minutes and presentations of the WG 1 Session during Gothenburg's Plenary Meeting temporarily available online at https://polybox.ethz.ch/index.php/s/zUUgZntlYw6jEsC.

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SG Robustness

This SG deals with the topics of resistance to disproportionate damages, including structural and non-structural robustness and resistance to progressive collapse. The documents in this section include a short introduction to robustness and related terminology, a description of the stakeholders and design framework for resistance to disproportionate collapse, and case studies of strategies against disproportionate collapse in modern taller timber buildings:

- **Robustness – Introduction and terminology** 9
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- **Robustness – Importance for design of tall timber buildings** 12
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- **Structural robustness – Case studies of strategies against disproportionate collapse in multi-storey timber buildings** 22
  Pedro Palma (Empa, Switzerland) and Maria Felicita (TU Delft, The Netherlands).

SG Adaptability

This SG deals with topics related to changes in the functional use of buildings, how the design of tall timber buildings can account for adaptability-related requirements (e.g. versatility, convertibility, expandability), and with the interactions between these and other requirements (e.g. robustness, durability). The documents in this section are:

- **Adaptability – Introduction and terminology** 26
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This SG addresses the topics of design for disassembly and reusability in the context of tall timber buildings. This includes the design of new timber buildings taking into account future needs of disassembly and maximising reuse possibilities, but also the reuse of reclaimed materials in new buildings. The documents in this section are:

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- **Properties of salvaged structural timber components:**
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- **Barriers to design for disassembly and reuse of timber and**
  lifecycle potential of service time expansion 84
  Rafael Novais Passarelli (Hasselt University, Belgium).

SG Repairability and maintenance

This SG deals with issues of maintenance of the building stock during its planned service life and of restoring the original conditions in case of damages. It aims at studying: i) maintenance strategies for tall timber buildings; ii) the design of new buildings taking into account eventual need for repairs; iii) repair strategies for tall timber buildings; and iv) how to hold the materials' grey energy within the building stock and prevent unnecessary consumption of new resources and energy. The documents in this section are:

- **Repairability and Maintenance of Timber Buildings – A need for future timber buildings** 88
  R. Jockwer (Chalmers University, Sweden); and
- **(P)Re-paring taller wooden buildings: Building enclosure detailing importance in durability of non-transparent envelope** 92
  Slobodan Peulić (University of Banja Luka, Bosnia & Herzegovina) and Darija Gajić (University of Banja Luka, Bosnia & Herzegovina).

Horizontal topics

These contributions cover topics that intersect and are of interest for several SGs. The documents in this section are:

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- **Structural robustness – Stakeholders** 14
  Pedro Palma (Empa, Switzerland),
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- **Structural robustness – Case studies of strategies against disproportionate collapse in multi-storey timber buildings** 22
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  Maria Felicita (TU Delft, The Netherlands)

Robustness – Introduction and terminology

Pedro Palma, Empa – Materials Science and Technology (Switzerland);
Maria Felicita, Delft University of Technology (The Netherlands)

1 Robustness and disproportionate consequences

The term *robustness* is often used to describe the ability of a building to accommodate some kind of *initial local damage* without it propagating and causing *disproportionate* consequences. Robustness therefore assumes that a hazardous event has occurred and that the building was locally affected by it (Figure 1) and is, therefore, one aspect of the resistance to disproportional consequences.

When the triggering hazardous event (e.g. malicious or unintentional actions, fire, decay, overloading) can be reliably known in advance, specific measures can be adopted. However, it is often the case that the initial local damage is caused by unforeseen or even unforeseeable events that cannot be explicitly accounted for in the design and use of the building. This makes *robustness* a prominent aspect in avoiding consequences that are *disproportionate* to the original hazardous event or damage. The disproportionality of the consequences can only be assessed in relation to predefined requirements or expectations (e.g. area that is allowed to collapse in case a load-carrying column is severely damaged, construction elements that are expected to be replaced after a fire in a compartment). However, specifying these requirements is not actually an engineering problem and can even be more challenging (Starossek 2018), since it must reflect the will of the owner, the concerns of other stakeholders that might be affected by the potential disproportionate consequences (e.g. civil authorities, insurance companies, neighbours), and even public opinion. Therefore, agreeing on acceptable direct and indirect consequences might require administrative or even political decisions.

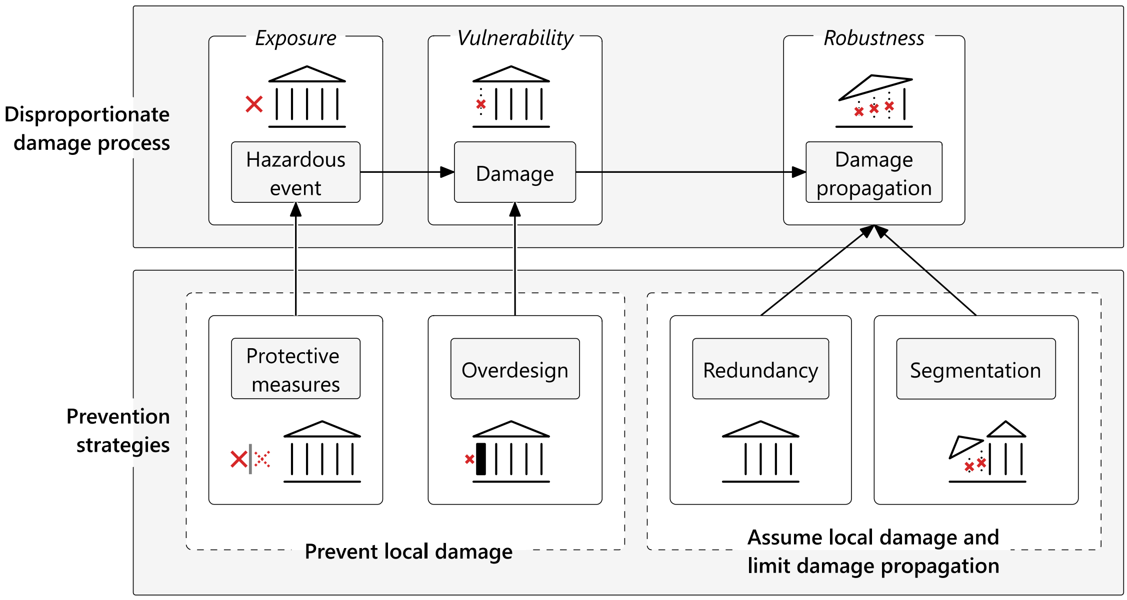

Figure 1: Disproportionate damage process and corresponding prevention strategies, based on Starossek and Haberland (2010), Palma et al. (2019), and Mpidi Bita et al. (2022)

2 Design strategies

Design strategies against disproportionate consequences commonly fall into one of the following categories (Figure 1).

1) *Prevent local damage:*
    a) *protection measures* aimed at reducing the probability of occurrence of the hazardous event (e.g. barriers against vehicle impact, active fire protection systems, water and damp proofing);
    b) *overdesign measures* aimed that reducing the vulnerability of *key elements* of the building, in case a hazardous event happens (e.g. overdesign load-carrying columns to withstand vehicle impacts, use materials less prone to deterioration, use effective firestops).
2) Assume initial local damage and *limit damage propagation:*
    c) *robustness measures* aimed at limiting damage propagation through:
        i) *redundancy* (e.g. design beams to carry vertical loads through catenary action in case a supporting load-carrying column is damaged, therefore creating an alternative load path); and/or
        ii) *segmentation* (e.g. design a fire compartment for full burnout, thus isolating it from its surroundings).
3) *Prescriptive rules*.

The effectiveness of i) *protection* or ii) *overdesign* strategies depends on how reliably the hazardous events can be foreseen and characterised. Since these are usually events with a very low-probability of occurring, the effectiveness of such measures can be very difficult to assess and to ensure for larger or complex buildings.

Strategies based on verifying or increasing iii) *robustness* require the definition of initial local damages and, therefore, also requires the identification of *key elements*, whose failure would result in unacceptable consequences. The design is then made assuming that these components are damaged. *Redundancy* strategies are based on providing alternative ways to fulfil the performance requirements by bypassing the damaged component. *Segmentation* strategies are based on isolating the damaged areas, either through weak fuse elements (e.g control joints) or strong isolating elements (e.g. fire walls between adjacent buildings).

The application of prescriptive design rules should be limited to buildings of minor importance, since their effectiveness is often unclear.

3 Quantifying robustness

Robustness is better achieved when considered from the early stages of conceptual design. Nevertheless, quantitative measures of robustness can be useful in some situations, such as when verifying explicit requirements or optimising the design (e.g. to assess the cost effectiveness of different strategies).

Quantitative measures of robustness are mostly based on comparing some measure of the damaged and undamaged systems or on assessing the response of the system to some initial damage (André and Faber 2019). Since different types of buildings are prone to different types of damages and damage propagation, there is no single "best" quantification of robustness (e.g. energy-based measures of structural robustness are better suited to assess impact-type progressive collapses, such as pancake-type collapses, whereas measures based on reserve load-carrying capacity are often suitable to assess redistribution-type progressive collapses and alternative load paths) (Starossek 2018). In any case, the crucial aspects of a robustness assessment are (Maes et al. 2006) a clear definition of the system being assessed, the identification of specific performance requirements; the identification of specific hazards, and the analysis of the consequences of damage within the system.

In the case of structural robustness, various quantification methods have been proposed, mostly through deterministic, reliability, and risk-based robustness indexes (Sørensen 2011; Chen Yong-Liang et al. 2016). These indexes, however, are not easily determined (except maybe for deterministic-based indexes) and, as all single-value indexes that summarise complex systems, only reveal the susceptibility of the structure to disproportionate collapse to some extent. In addition, they are also mostly not applicable in ordinary design practice. Target reference values for robustness indexes (e.g. like the target values for the reliability index β provided in prEN 1990:2021) against which the calculated indexes could be compared are also not available, making the indexes only useful for comparisons between not very dissimilar alternatives (i.e. same structure but different initial damage or different connectivity between elements) (Palma et al. 2019).

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Robustness – Importance for design of tall timber buildings

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1 Structural robustness

The main goal of structural robustness is to prevent disproportionate collapse caused by errors in design and construction, lack of maintenance, and unforeseeable events (Kirkegaard et al. 2010). Structural robustness is a requirement in most major design building codes in the world, such as Eurocodes (prEN 1990:2021); however, detailed implementation guidance is not common. Existing design guidelines that address the prevention of disproportionate collapse through structural robustness are based on research and practical experience from traditional construction materials such as steel and concrete (Mpidi Bita et al. 2022). The most common methods for incorporating structural robustness into the design of a building are design for redundancy through alternative load paths (ALPs) and overdesign of key elements. ALP methods rely on the redistribution of loads across the structure, where the structural elements and connections must be designed to maintain their strength through large deformations and load reversals, and allow controlled load redistribution during local collapse (Ellingwood et al. 2007).

2 Robustness of tall timber buildings

The increasing popularity of engineered wood products has led to the development of larger, taller, and more complex timber structures than ever before. Moreover, European Union policies on transitioning to a bio-based circular economy has made the structural timber industry grow at an unprecedented pace, with the world's tallest timber building title having been broken many times since the mid 2010s ("List of tallest wooden buildings" 2022; Voulpiotis et al. 2021). The novelty and accelerated growth of these structures has led to uncertainties in terms of structural robustness, such as the susceptibility of such structures to disproportionate collapse and their ability to redistribute loads through ductile mechanisms within the structural members and connections.

The following characteristics of timber increase the potential of unexpected risks when scaling up to new heights:

- Brittle failure modes in timber members: Timber members fail mostly in a brittle manner, which makes timber connections a critical component in load redistribution.
- Low weight: Timber used in construction is approximately 5 times less dense than reinforced concrete and 15 times less dense than structural steel. The direct advantage of lighter building has a pitfall of being much more sensitive to horizontal actions (e.g. wind) and vibrations as the height of the building increases.
- Low connection stiffness: The often limited stiffness of most common timber connections becomes critical in taller buildings, namely for horizontal loads.
- Durability: The cumulative decay of wood by fungi and the migration of wood-boring beetles and termites due to warmer winters is a significant risk for taller buildings, in which repairs might be more complicated.
- Moisture-dependency: Timber is a naturally grown, hygroscopic material, with strength and stiffness negatively influenced by increased moisture.

- Combustibility: Large timber cross sections have some inherent fire resistance, but also contribute to the fire load and external charring and pyrolysis inside the cross sections can continue even after the cooling phase of a fire.
- Time effects: Timber creeps with time, even more so under wet conditions and wet-dry cycles, which can be critical on heavily loaded structures like tall timber buildings.
- Studies on the susceptibility of tall timber buildings to disproportionate collapse are limited (Mpidi Bita et al. 2022). Load redistributions within a structure in case of local failure is usually achieved through catenary/membrane action given that it allows the structure to maintain high load carrying capacities and deformations. However, such mechanisms required sufficient tensile capacity in the members, lateral stiffness, and strength of adjacent members, as well as rotational ductility of the connections, which is usually not implicit in timber structures. The brittleness of timber and the extreme importance of timber connections must be considered when designing for accommodating load redistributions within a structure, especially tall buildings.

For a brittle material such as timber, large deformations need to be accommodated through metal connectors to achieve ductility. Tests in novel connections have proven that timber assemblies can achieve the same mechanisms as reinforced concrete and steel buildings when sufficient ductility is provided (Mpidi Bita and Tannert 2019). However, this is not implied for standard metal connectors usually implemented in timber structures, for which the behaviour under high deformations and combined axial and bending loads is not well established. Design strategies based on overdesigning key elements seem to be popular, mostly because they are straightforward to design for, but do not directly contribute to increased capacity for load redistribution (Palma et al. 2019). The lack of reference projects, design guidance and requirements may impede the expansion of tall timber structures.

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Structural robustness – Stakeholders

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1 Importance of designing for resistance to disproportionate collapse

Given the relative novelty of taller timber buildings and the limited experience on their behaviour, resistance to disproportionate collapse should be considered by the stakeholders, also because of the symbolism of these structures and the media exposure that they tend to receive. Disproportionate collapse resistance is particularly relevant for tall timber buildings, given the current interest in their construction and ongoing "race" for the tallest timber building. The requirements set by civil and building authorities and insurance companies tend to reflect the current state of knowledge and experience, which are still limited, and the regulatory consequences of damages disproportionate to their inception in a tall timber building could be severe and long-lasting.

Decisions on robustness-related issues often require dealing with:

i) very-low probability and even unforeseeable hazardous events;
ii) planning mitigation strategies; and
iii) defining acceptable levels of damage.

The first two aspects can be particularly challenging, and are mostly engineering problems. The third aspect, however, is not something that can be decided by the structural design team alone and should be decided at the project stakeholder level. The definition of acceptable levels of total damage, i.e. the specification of performance requirements and the corresponding verification methods in case of an initial local damage can be even more challenging than the other aspects (Starossek 2018). It must reflect the will of the owner of the building, the concerns of all stakeholders, including the public who might be directly or indirectly affected by the damages. Therefore, it might require administrative or even political decisions (Starossek and Haberland 2010), hopefully supported by cost-benefit analyses for example.

2 Stakeholders

In scope of resistance to disproportionate collapse, stakeholders are not only the promoters and owners of the structure, but also those directly or indirectly affected by such a collapse, such as, e.g., users, civil and building authorities, the structural design team, insurance companies, the police, fire brigade, nearby hospitals, schools and other neighbours. Table 1 indicates roles and tasks in a typical tall timber building project.

The *promoters and owners* are naturally interested in optimising monetary costs of safety measures (e.g. fire safety and resistance to disproportionate collapse) and in reducing downtime in case of damages, namely downtime needed for repairs and the corresponding economic losses including associated reputational risk and losses. Promoters and owners often have no incentive to avoid externalising consequences (e.g. spill of hazardous materials into the environment after a collapse) and it is often up to the civil and building authorities to mitigate any consequences of such incidents.

Civil and building authorities must take the wider public interest into account and must be responsible for the specification of some performance objectives, in particular the acceptable levels of damage. The interests of an owner should obviously be taken into account, but it is the responsibility of the public authorities to ensure that the risk of a disproportionate collapse remains below/within acceptable levels. *Civil and building authorities* are often accused of being slow in allowing for new building technologies to be implemented at a large scale, but they have to consider many more aspects, including public opinion, in their decisions.

The *structural design team* is obviously interested in achieving a safe and economical design, preferably by following rational and well-established design frameworks, in which their responsibilities are clearly defined. If relevant, the structural designer must account for resistance to disproportionate collapse from the early stages of conceptual design and develop a design strategy (e.g. prevent local damage, limit damage propagation) and the corresponding verification procedures. This should take into account the owner's preferences and the requirements set by the authorities regarding acceptable levels of damage.

The design scenarios might represent exceptional situations (e.g. a sudden removal of a load-carrying element) and the design strategy might be based on non-standard load-carrying processes (e.g. catenary action, impact loading, very high deformations), well-established analysis and verification procedures might not be available or might be too conservative. Therefore, there can be a tendency to focus on simply overdesigning key structural elements, which might indirectly lead to some increase in robustness, but does not ensure nor prevent damage propagation. Therefore, civil and building authorities must be involved in approving the verification procedures envisaged by the design team, particularly for high-risk structures and even require independent design checks.

Amongst *insurance companies* there is a clear need for a better understanding of the performance of tall timber structures exposed to hazardous events (Giddings n.d.), namely fire, water damage, or other events that might trigger a disproportionate collapse. Following a well-defined design procedures and having more standardised, appropriate and relevant verification methods would surely increase the confidence to insure tall timber buildings.

Neighbours to a tall timber building are also a stakeholder. They are interested in short construction times, limited disruption, noise, and pollution, including possible increase in wind speed around a tall timber building. Timber buildings have significant competitive advantage in this regard, given the high degree of prefabrication and low weight, which often leads to faster and cleaner construction with relatively small teams. Timber buildings currently benefit from very good public opinion, but this can quickly change if they are perceived as unsafe, e.g. regarding fire hazards or disproportionate partial collapses, or if their lack of durability requires continuous repairs.

Table 1: RACI matrix (R = Responsible, A = Accountable, C = consulted, I = Informed).

Construction Phase	Promoter or owner	Consultant	Contractor	Other stakeholders
Feasibility stage / conceptual design	R	A	I	C
Option selection	A	R	C	I
Detailed design for single option	R	A	C	I
Independent project review	R	C	I	A
Construction	R	C	A	I
Verification	I	C	R	A
Post construction (maintenance, renewals)	A	C	R	I

3 Conclusions

The current popularity and positive sustainable impact of timber construction encourages the building of larger, taller, and more complex buildings. However, this incentive also puts these buildings in the public eye, which makes these buildings particularly susceptible to a strong pushback in case of their performance fails to meet the public's expectations, namely if they are perceived as unsafe or not durable. Given the relative novelty of tall timber buildings and the limited medium andlonger-term experience, stakeholders have the duty to keep the current positive public perception of timber buildings by adoptingcarefully devised teams, roles and tasks including a well-established design frameworks.

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Structural robustness – Design framework for resistance to disproportionate collapse

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1 Overview

The design framework for resistance to disproportionate collapse presented in his document (Figure 1) is based on the Starossek (2018) and comprise the following main parts:

i) risk assessment/classification of the structure;
ii) specification of hazard scenarios;
iii) specification of performance objectives;
iv) development of design strategies and corresponding verification procedures.

The level of *design requirements* should be based on the risk assessment of building and this can be achieved by undertaking the risk assessment and building classification frameworks described in Section 2. The specification of *hazardous scenario*s, such as threat-specific (e.g. impact of a car in a ground-floor column) or non-threat-specific events (e.g. notional damage such as a sudden removal of a structural component), and *performance objectives* (i.e. the acceptable level of damage/consequences) should involve other stakeholders besides the owner and the design team, namely the relevant civil and building authorities and an insurance company. For major projects, the specification of hazardous scenarios requires some experience, since the creation of general rules is difficult because of many possible scenarios and project-specific nature of many of them. Once the hazard scenarios are considered and the performance objectives are set, the structural design team then selects the *design strategies* (e.g. protection or overdesign measures to prevent local damage, robustness measures to limit damage propagation) and the *design verification procedures* (e.g. based on structural analysis models or even testing). A schematic overview of this design framework for resistance to disproportionate collapse is given in Figure 1.

For buildings with low importance and exposure it should be possible to achieve an adequate level of resistance to disproportionate collapse without any explicit design verifications, but increasingly complex verification are often required for buildings of high importance and/or exposure. For special structures, project-related criteria might even be required and this will involve not only the owner and the structural design team, but also stakeholders (e.g. civil and building authorities, insurance companies).

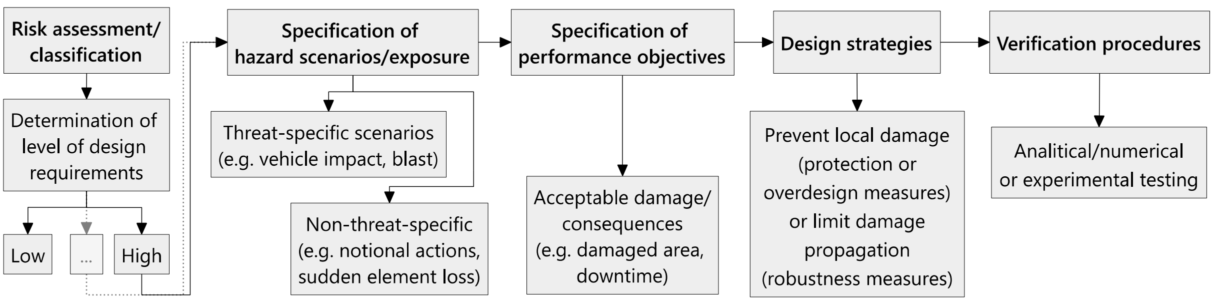

Figure 1: Design framework for resistance to disproportionate collapse, based on Starossek (2018).

2 Risk assessment and classification of buildings

The first step in defining robustness-related requirements is to assess the *importance* of the building, i.e. the *direct* and *indirect* risks or consequences of a collapse, and its *exposure*, i.e. the probability of occurrence of a hazardous event (e.g. accident, malicious or unintentional actions). In some cases, the *indirect* risks or consequences of a collapse (e.g. debris damaging infrastructure adjacent to the building, income losses due to halted activity, spread of hazardous materials, damage to public morale) can have a greater impact on the importance of the structure.

For these purpose of classification of buildings, the European structural design standard prEN 1990:2021 establishes five consequence classes, based on an indicative qualification of consequences (loss of human life or personal injury and economic, social or environmental consequences). The exposure of the structure, i.e. the level of threat, is not explicitly accounted for (or it is assumed proportional to the importance of the building). Different indicative design methods for enhancing the resistance to disproportionate collapse are given for the various consequences classes. The North American GSA (2013) establishes five facility security levels, based on the level of threat (i.e. the *exposure* of the structure) and the *importance* or significance (i.e. risks or consequences of collapse). These levels are assessed using evaluation factors that include criticality, symbolism (e.g. the US Capitol is assigned very high symbolism, whereas small offices in leased commercial buildings are assigned low symbolism), facility population, facility size and threat. Design requirements are then specified depending on the facility security level and number of storeys. The also North American UFC 4-023-03 for military buildings establishes four risk categories, defined based on the number of occupants, function of the building, and consequences of collapse. The *exposure* of the structure is, therefore, also not directly accounted for. Design requirements are specified for the different risk categories (Perhaps we should add the reference here too).

3 Specification of hazard scenarios / exposure

Hazardous events are abnormal actions that can occur during the construction and service life of the building. These are the design scenarios for which the performance objectives / level of damaged of the structure should be evaluated.

Threat-specific scenarios can be foreseen (e.g. impact of a vehicle, far-field blast) and the corresponding actions on the structure might even be reasonably well estimated. However, given that it is effectively impossible to identify and quantify all hazards, it is clear that the list of identified scenarios is incomplete and the corresponding actions have a significant uncertainty. Threat-specific scenarios are mostly project-specific (e.g. the probability and characteristics of the impact of a vehicle depends on the location and access to the building) and it is not always straightforward to prescribe general rules. These scenarios allow for design strategies against disproportionate collapse based on preventing local damage (protection measures to reduce the probability of occurrence of a hazardous event and overdesign measures to reduce the probability of damage in case of a hazardous event). The specification of threat-specific scenarios should be complemented with threat-independent scenarios.

Threat-independent scenarios assume an initial notional damage or action (e.g. sudden removal of a load-carrying member), independently of a specific triggering event. These scenarios assume that damage has occurred and the design strategies against disproportionate collapse must be focused on limiting damage propagation (robustness-related measures), namely redundancy and/or segmentation.

4 Specification of performance objectives / acceptable level of damage

The performance objectives or acceptable level of damage must reflect the promoter's or owner's brief and requirements, but also the concerns of other stakeholders, who might be affected by a disproportionate collapse (e.g. civil and building authorities, insurance companies, neighbours). In some cases, agreeing acceptable *direct damages* (e.g. collapsed area) will mostly involve the owner and the insurance company, but depending on the use of the building, civil and building authorities might also impose limitations on the acceptable level of damage (e.g. the acceptable collapsed area will be different for a retail building than for a remote and mostly unoccupied storage warehouse).

Indirect damages are not directly related to the material damage of the collapse, but arise from the impact of the collapse in the interests or economical activities of stakeholders (e.g. downtime in manufacturing during structural repairs, obstruction of public roads, damage of public infrastructure) and even in the public opinion. Therefore, specification of acceptable levels of indirect damages is made by civil and building authorities, who have the duty to protect public interest. The assessment of indirect damages in terms of costs is not always straight forward (e.g. spread of a hazardous material to the environment) and so it is not always straightforward to sum direct and indirect damages.

5 Specification of design strategies

Resistance to disproportionate collapse can be achieved at different levels.

- Preventing local failures by
    - adopting protective measures (to reduce the probability, extent or mitigate the exposure of the structure to abnormal events), or by
    - overdesigning key elements (to reduce the probability of damage in case of a hazardous event, i.e. reduce the vulnerability of key elements and increase safety against initial failure).
- Assuming local failure and limiting damage propagation (robustness-related measures to increase insensitivity to initial damage), through
    - redundancy (e.g. design beams to carry vertical loads through catenary action in case a supporting load-carrying column is damaged, therefore creating an alternative load path); and/or
    - segmentation (e.g. design a fire compartment for full burnout, thus isolating it from its surroundings).

Design strategies based on adopting *protective measures* often fall outside the scope of structural design (e.g. vehicle barriers, access control, active fire protection). Strategies based on *overdesigning key elements* should be a last resort (Arup 2011; Hewson 2016; Huber et al. 2018), used only in cases where other alternatives are not viable or too costly. Design of key elements follows the common design procedure, even if the considered actions are anything but common, and the corresponding structural design can often be done in accordance with available guidance (Palma et al. 2019).

The *redundancy* strategy is based on providing an alternative load path (ALP) for the forces not transmitted anymore through failed components. It is based on assessing the behaviour of the remaining structure after an initial notional damage. A commonly assumed initial damage is the notional removal of one (or several) components of the structure and a so-called *element-removal analysis* is then performed, with the objective of evaluating if the remaining structure is able to accommodate the damage. Redundancy on its own might not be suitable to avoid disproportionate collapse. In the case of repetitive structures, systematic design or execution errors can compromise the ability of a structure to redistribute loads and lead to progressive collapse (Munch-Andersen and Dietsch 2011), as the alternative load paths are all affected by a common-cause failure.

In these cases, *segmentation* can be an adequate design strategy. The objective of this strategy is to compartmentalise the structure in a way that collapse progression after an initial damage is halted at predefined locations, either through fuse-type elements or by having control joints at which the segments are physically separated. Most common solutions for *vertical segmentation* rely on providing shock-absorbing zones with high energy dissipation capacity. Examples of vertical segmentation are scarce, however, the 14-storey timber building “Treet”, in Norway, includes a paradigmatic example (Abrahamsen and Malo 2014): this building has two “power storeys” that carry a prefabricated concrete slab on top of which four levels of residential modules are stacked; these “power storeys” should be able to halt a progressive collapse of the stacked residential modules, limiting the extent of collapse.

6 Verification procedures

The verification procedures should allow evaluating that adopted design strategies specified performance objectives / acceptable levels of damage are met for the various hazard scenarios. The verification procedures usually comprise analytical or numerical models of the structure that are able to adequately capture the most relevant phenomena. Simplified analyses can be based on linear quasi-static structural models with dynamic amplification factors (Mpidi Bita and Tannert 2022) or nonlinear quasi-static (pushover) analyses (Huber et al. 2020, 2021), but more advanced non-linear dynamic analyses are also possible (Mpidi Bita and Tannert 2019; Cao et al. 2021). The main issue with the modelling of timber buildings under these scenarios is the current lack of experimental validation. Therefore, experimental testing should be required for high-risk buildings. In any case, verification procedures should be approved by the civil and building authorities and/or independent external entity. The verification procedure should be a check of all relevant project-specific designs as well as correct construction and installation.

7 Conclusions

Resistance against disproportionate collapse has to be seen in a broader design framework, which comprises the risk assessment/classification of the structure, followed by the corresponding specification of relevant exposures, design strategies, and verification procedures. Resistance against disproportionate collapse is not at all limited to the use of more or less advanced structural analysis techniques, which is the impression that is often given, and, when required, has to be taken into account from the initial stages of conceptual design.

The current popularity of timber construction encourages the construction of larger, taller, and more complex buildings. However, this incentive also puts these buildings in the public eye, which makes them particularly susceptible to a strong pushback in case their performance fails to meet the public's expectations, namely if they are perceived as unsafe or not durable. Given the relative novelty of tall timber buildings and the limited medium- long-term experience, stakeholders have the duty to keep the current positive public perception of timber buildings by adopting carefully devised design procedures based on well-established design frameworks has the one presented above.

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Structural robustness – Case studies of strategies against disproportionate collapse in multi-storey timber buildings

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Maria Felicita, Delft University of Technology (The Netherlands)

Foreword

The case studies presented in this document are mostly based on the publication "Prevention of Disproportionate Collapse for Multistory Mass Timber Buildings: Review of Current Practices and Recent Research", by Mpidi Bita et al. (2022).

1 Case studies

1.1 Stadthaus apartment building

The Stadthaus is a nine-storey apartment building in London, UK, that was completed in 2009 (Wells 2011). It is a platform-type construction with cross laminated timber (CLT) floor panels on CLT walls. The design strategy against disproportionate collapse was based on the alternative load path (ALP) approach in EN 1991-7:2006. The load-carrying walls are laid out in both directions and have small tributary loading areas. The floor panels were designed to act as cantilevers or span in two directions above damaged zones and the walls to act as deep beams.

1.2 Treet building

The fourteen-story Treet building in Bergen, Norway, was built in 2015 and was the tallest timber truss construction in the world. The structure consist of massive vertical glued laminated timber (GLT) trusses and intermediate concrete storeys, on which prefabricated apartment modules are stacked. Analyses were performed to check that main structural members and connections can undergo large deformations in case a members of the main trusses is damaged. The concrete storeys were designed to withstand failures in the prefabricated modules and the design of other secondary members also accounted for debris loading (Abrahamsen and Malo 2014; Malo et al. 2016).

1.3 Redstone Arsenal hotel

The four-story Redstone Arsenal hotel in Huntsville, USA, was constructed in 2016. CLT panels were used all internal and exterior walls, floors, and roof. Like the Stadthaus, the highly redundant layout of the CLT walls provides some redundancy for load redistribution. The structure was designed for the force and deformation demands obtained from a linear-elastic element-removal analysis in accordance with GSA (2013) and UFC 4-023-03 guidelines (Steimle 2016).

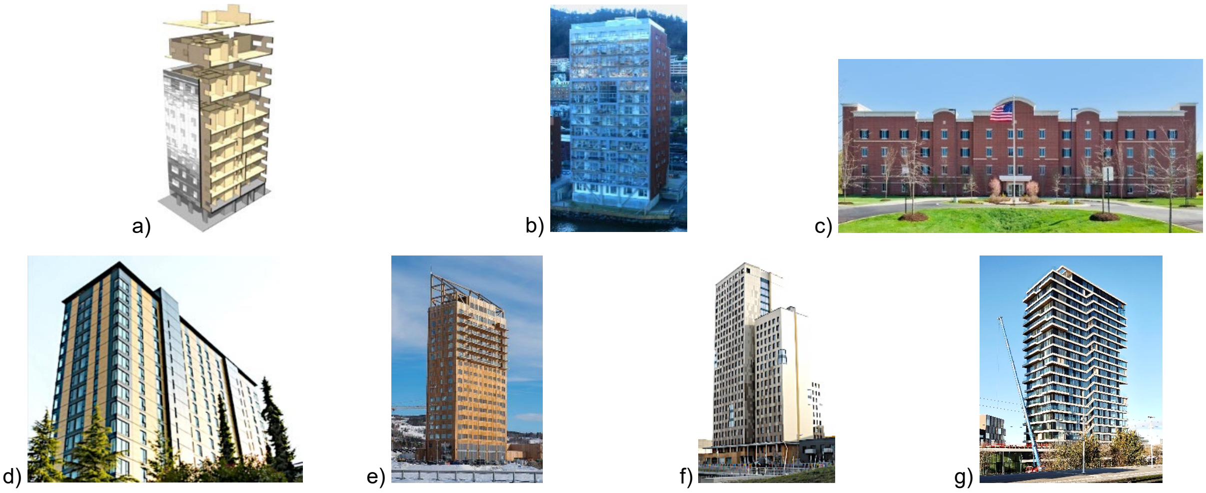

Figure 1: Case studies: a) Stadthaus apartment building; b) Treet; c) Redstone Arsenal hotel; d) Brock Commons; e) Mjøstårnet; f) HoHo: g) HAUT.

Sources: a) https://commons.wikimedia.org/wiki/File:Murray_Grove_Cross-Section.jpeg; b) https://commons.wikimedia.org/wiki/File:Treet_(Bergen)_011.jpg; c) https://digital.ihg.com/is/image/ihg/candlewood-suites---military-huntsville-4439365680-2x1; d) https://www.flickr.com/photos/ubcpublicaffairs/36357661945; e) https://commons.wikimedia.org/wiki/File:Mj%C3%B8st%C3%A5rnet.jpg; f) https://commons.wikimedia.org/wiki/File:HoHo_Wien_Vienna_19-20_IMG_2225.jpg; g) https://commons.wikimedia.org/wiki/File:HAUT_Amsterdam2.jpg.

1.4 Brock Commons building

The Brock Commons is an eighteen-storey building in Vancouver, Canada, and was the tallest timber building when completed in 2017. The structural system comprises a concrete core and CLT floor panels point-supported on timber columns (Poirier et al. 2021). Design followed the element removal approach of EN 1991-1-7. The multi-span CLT floor panels were designed for two-way action and cantilevering in the case of loss of a column and the column-to-column connections were design to carry tension forces and hold the floor below (Fast and Jackson 2017).

1.5 Mjøstårnet building

The Mjøstårnet is an 18-storey building in Brumunddal, Norway, and was the tallest timber building at its completion in 2019. The structure comprises a GLT framed truss and CLT floors. Concrete floors were used in the upper storeys to reduce wind-induced vibrations. The columns were overdesigned to resist a pressure of 34 kPa, based on EN 1991-1-7:2006. The connections between the GLT elements were designed to exhibit a ductile failure mode and the structure was designed to withstand the impact of a falling concrete floor (Huber et al. 2018).

1.6 HoHo Wien

The HoHo Wien is a 24-storey hybrid concrete-timber building in Vienna, Austria. As in the Brock Commons building, the column-to-column connections were design to carry tension forces and hold the floor below in case of column loss. Horizontal and vertical ties were used to provide alternative load paths: the vertical ties consisted of glued-in steel rods connected to the concrete beams; the horizontal ties consisted of on-site casted reinforcement bars between concrete beams and floors (Woschitz and Zotter 2017).

1.7 HAUT

The HAUT is a 21-storey hybrid concrete-timber building in Amsterdam, Netherlands. The lateral stability is provided by a concrete core and two CLT shear walls. The transfer of the vertical loads is given by load bearing CLT walls, which support TCC floors spanning in one direction. Wherever the floor edges are not supported by a load bearing wall, glulam down stand beams are introduced. These beams double as a tension ring around the perimeter of the floor acting as a structural tie (Verhaegh et al. 2020).

2 Conclusions

The examples above show that various design approaches against disproportionate collapse have been used in different types of multi-storey timber buildings. Robustness-related aspects were explicitly considered from the early conceptual design process and formed the adopted structural solutions and detailing. The design strategies against disproportionate collapse included: providing ALPs based on floor panels acting as cantilevers, spanning in two directions, and walls above removed elements acting as a deep beams; designing columns to carry tension forces and hold the floors below; designing ductile connections; and vertically segmenting the building using strong floors.

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Adaptability – Introduction and terminology

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1 Definition of adaptability

Adaptability can be defined as a built-in ability of buildings to adapt to change by accommodating different uses, different spatial and functional configurations without significantly affecting the building, ongoing activities or the environment (Kronenburg, 2007). On this basis, adaptability plays an important role in improving the sustainable performance of a building. The ability to withstand the test of time as the spaces and components of the building continue to change opens up many possibilities, including each pillar of sustainable development (Nakib, 2009)

The so-called great acceleration (Steffen et al. 2015) of current socio-economic processes, mainly driven by the continuous growth of the world population and consumption, has relevant effects on the functional requirements for the changeability of buildings. Innovative technical solutions and new spatial structures are needed to be investigated seeking for the highest degree of interaction, flexibility and adaptability enabling sustainable adjustments of architectural forms according to socio-cultural and climate needs over time. In this context, the consideration of the life cycle of a building is not only reduced to its conception and realisation, but extends to the type and duration of its use. The temporal component is therefore considered an indispensable parameter of the architectural process, in which the concepts of "adaptability" and "flexibility" play a major role. Both concepts have often and erroneously been used as synonyms. However, adaptability refers to use-neutral spaces that can be adapted to different social purposes without changing their physical form. Flexibility defines the fitting capacity of a building through easy and uncomplicated physical changes, what means that the building concept should allow for an eventual ability to change by connecting, dividing, enlarging and merging spaces without great effort (Groák, 1992). The hypothesis of this paper is that adaptable buildings result from an interaction between space, construction and use and formulate the following questions:

- Which spatial structures and constructions allow for the highest degree of interaction, flexibility and adaptability?
- How many different levels of flexibility and adaptability can be defined in a building and which are their requirements?
- How adaptable and flexible structures affect other parameters? Which conflicts must be considered? How can those be solved?

2 Types of adaptability

To make a building adaptable, the questions are: what changes can occur & how can they be managed? Brand defines six shearing layers of change, which are site, structure, skin, services, space plan and stuff for describing the expected life cycle of building components (Brand, 1995). Later, the book "Adaptable Architecture" (2016) by Schmidt and Austin describes six different types of adaptability. The purpose of these types is to illustrate the kind of adaptability that is desired. The typification thereby addresses the question: What types of adaptability can occur? How can these be taken into account?

In the following, these types are summed up to give an overview of the possible changes in a building:

- **Adjustable – change of task/user**: e.g. furniture, furnishings, appliances
- **Versatile – change of space**: e.g. the layout of the rooms
- **Refitable – change of performance**: e.g. change in the performance of a building due to a change in the space, services or building envelope
- **Convertible – change of use**: e.g. change in the performance of a building due to a change in the space, services or building envelope
- **Scalable – change of size**: e.g. enabling horizontal and vertical extension
- **Movable – change of location**: e.g. by enabling easy assembly and disassembly, more suitable for temporary structures (Schmidt and Austin, 2016)

With regard to the planning of a multi-storey timber building, as envisaged by this COST Action, the adaptability types "Versatile", "Refitable", "Convertible", "Scalable" are particularly important. Against this background, the next chapter will classify multi-storey timber buildings into categories of adaptability.

3 Case studies

The following projects have been selected to be analysed in regard to their adaptability type and the solutions implemented.

- Oxley Woods (UK 2008) Rogers Stirk Harbour and Partners
- Z8 (Germany 2018) ASUNA / Hüls Engineers
- Walden 48 (Germany 2020) Scharabi + Raupach / IFB
- Collegium Academicum IBA (Germany 2022) DGJ Architektur / Pirmin Jung
- Illwerke Zentrum Montafon, IZM (Austria 2013) Hermann Kaufmann Architects / Merz Kley Partner

Table 1: Summary of Case Study Projects

Project	Adaptability type	Implemented system	Outcome
Oxley Woods	Adjustable, Refitable, Scalable	Timber frame and panels	Different combination of rooms Adding additional storey with add-on pieces Change of perfomance
Z8	Versatile, Convertible	Post and beam	Combination of use Different flats configurations
Walden 48	Adjustable, Refitable, Versatile	Cross-wall load-bearing CLT walls with long-span slabs	Open living space Different housing units
Collegium Academicum IBA	Versatile	Non load-bearing inner walls with a modular approach and detachable timber-timber joints	Flexible use of apartments Adaptability over time
ZM - Illwerke Zentrum Montafon	Convertible, Adjustabl	Timber-concrete rib decks on a central steel beam	Big spans in the central axis and thickness reduction

4 Conflicts and Design Strategies

4.1 Conflicts

- **Conflicts (01)**: in the case of adaptable spaces and flexible buildings, many times the strategy for allowing different uses (or allowing a change of configuration without changing use, like changing the configuration of housing units) leads to the use of structural systems with **medium/big spans**, with the objective of creating bigger spaces free of load-bearing elements (study cases: Walden 48, IZM). These structures are more demanding and costlier and therefore they originate bigger initial investments. An advantageous cost-balance can be achieved only taking into account the whole life-cycle of the building and the potential of savings in the future cases of uncomplicated physical changes.
- **Conflicts (02)**: design for flexibility assumes that "future cases of uncomplicated physical changes" should be expected. In order to achieve this, the conceptual design of connections takes a relevant role and the use of **reversible joints** appears as desirable. This adds a task to be performed by the connections themselves: they do not only have to perform properly after being installed, they also have to allow elements being removed and connected again, and this ideally for several cycles until the final recovery. This extra performance and robustness can add complexity and cost to the joints.
- **Conflicts (03)**: design for flexibility can conflict with the run of **building installations** as usual, where building installations have to be integrated for a particular final solution. The possible "future cases of uncomplicated physical changes" have to be anticipated and planned for allowing them from the very beginning.

4.2 Design strategies

- **Design strategies (01) - Hybridization**: the use of timber **hybrid structures** appears as a common strategy in order to achieve the goals and propose solutions to the conflicts stated in the previous point. Timber-concrete decks (*study cases:*

Walden 48, IZM) or the combination of timber structures with steel elements (*study cases: IZM*) can be used for achieving bigger free spans

- **Design strategies (02) - Detachable Joints**: the use of robust **detachable joints** able to withstand several cycles of assembly and disassembly appears as desirable. Properly designed steel connectors can fulfil this function and in the case of timber-timber connection the use of stronger hardwoods at these points appears as an alternative (*study cases: Collegium Academicum IBA*) (Drexler, 2021)
- **Design strategies (03) - Building Services**: a modular and combinatorial spatial approach can be used for defining the possible run of building services. A clear definition of **installation cores and main shafts** is necessary for serving and defining the differents combination of spaces anticipated in the design (*study cases: Collegium Academicum IBA*)

Links for the Case Studies:

Project	Link
Oxley Woods	http://www.oxleywoods.com/
Z8	https://www.asuna-leipzig.de/zz8
Walden 48	http://www.anneraupach.com/portfolio-items/walden-48/ https://scharabi.de/walden-48/
Collegium Academicum IBA	https://dgj.eu/portfolio/dgj223-iba-collegium-academicum/
ZM - Illwerke Zentrum Montafon	https://www.hkarchitekten.at/de/projekt/izm-illwerke-zentrum-montafon/

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Working definitions of ‘adaptability’ and ‘flexibility’ for use in research on buildings designed for change

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1 Introduction

This paper introduces a working definition for flexibility and adaptability in housing design, that has been developed from a state-of-the-art literature review of Design for Adaptability for research with a focus on the design of timber buildings. The themes of flexibility, adaptability, and principles of Circular Design that underpin the research are relevant for adaptable building design of taller buildings and designing adaptable buildings in urban and suburban contexts.

For this paper, it is understood that building construction internationally needs to transition from the linear ‘take-make-model’ to the alternative Circular Economy (CE) (Ellen Macarthur Foundation, 2015). Literature about designing buildings towards a CE has expanded significantly in the last few years (Munaro et al., 2020) and Design for Adaptability (DfA) has become a growing area of research (Askar et al., 2022; Askar et al., 2021; Aziz et al., 2020; Geldermans et al., 2019; Geldermans, 2016). This paper will refer to building design for a CE as it is otherwise known as Circular Design (CD) (Baker-Brown, 2017; Cheshire, 2016).

2 Definitions for Flexibility and Adaptability

In the CD literature a key approach to increasing building longevity is to design buildings that are flexible and adaptable to the changing needs of their occupants and contexts (ARUP and Ellen Macarthur Foundation, 2020; Cheshire, 2016; Cimen, 2021; Manohar, 2017). Yet in the literature, both terms ‘flexible’ and ‘adaptable’ buildings, are used and sometimes interchanged in meaning (Askar et al., 2021). To clarify the difference between the two adjectives, their use in the English language can be referred to. The *Oxford English Dictionary* (OED, 2021) has meanings of the adjective ‘flexible’ that can be applied to buildings:

> Flexible, *adj. n*. 1.a. *adj.* Capable of being bent, admitting of change in figure without breaking; yielding to pressure, pliable, pliant. 3.a. That can be ‘bent’, inclined, or rendered favourable to. 4.a. Susceptible of modification or adaptation to various purposes or uses; pliant, supple.

Using these meanings literally, a flexible building allows changes of use to occur by the building having the capacity to allow change without ‘breaking’, or parts of the building can be easily modified or ‘bent’, such as an interior with movable screens.

Likewise, referring to dictionary meanings of the adjective ‘adaptable’ applied to buildings:

> Adaptable, *adj.* ‘1. Capable of being applied or used in different conditions or contexts: capable of being modified or amended, especially so as to be put to a new use or serve a new purpose. 2. Able to adjust to new conditions or situations, or to change in one’s environment. (OED, 2021)

When these capabilities are used to describe an adaptable building, changes to the physical fabric of the building are usually required. For a building to facilitate new functions different to the functions which it was originally designed for, the building undergoes a process of change. To enable buildings to adapt to change without damaging the materials that they are constructed from, they need to be designed for future change (Friedman, 1997; Kronenburg, 2007; Schmidt & Austin, 2016; Schneider & Till, 2007a).

One important theory that enables change in buildings, is Brand's concept of a building as 'shearing layers of change'; with the inner layers acknowledged as having shorter lifespans to enable change or replacement without affecting the integrity of the outer layers (Brand, 1995). In this paper, Brand's layers of change are used to define parts of the building that change in either adaptable or flexible buildings, as noted in Fig.1 below.

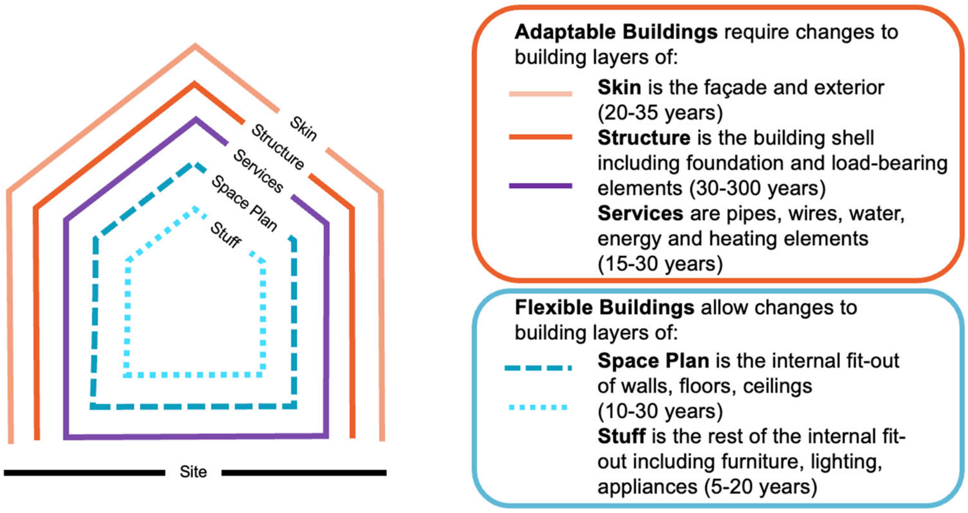

Figure 1 Brand's Shearing Layers of Change with Flexible and Adaptable Building Layers

Another important work in the DfA literature is Schmidt and Austin's (2016) comprehensive theory for adaptable buildings; through analysis of 290 buildings designed for change they defined six levels of adaptability, in order of increasing change to the building: adjustable, versatile, refitable, convertible, scalable and movable (Fig. 2) (Schmidt & Austin, 2016). Levels of 'adjustable' and 'versatile' usually occur within the building interior and can be modified by occupants themselves with little change to the building; in this research these levels are regarded as 'flexible' buildings. The adaptability levels of 'refitable' - to change the services, 'scalable' - to change the size of the building, 'convertible' - to change the use and 'movable' – change of location, are regarded as truly 'adaptable' buildings.

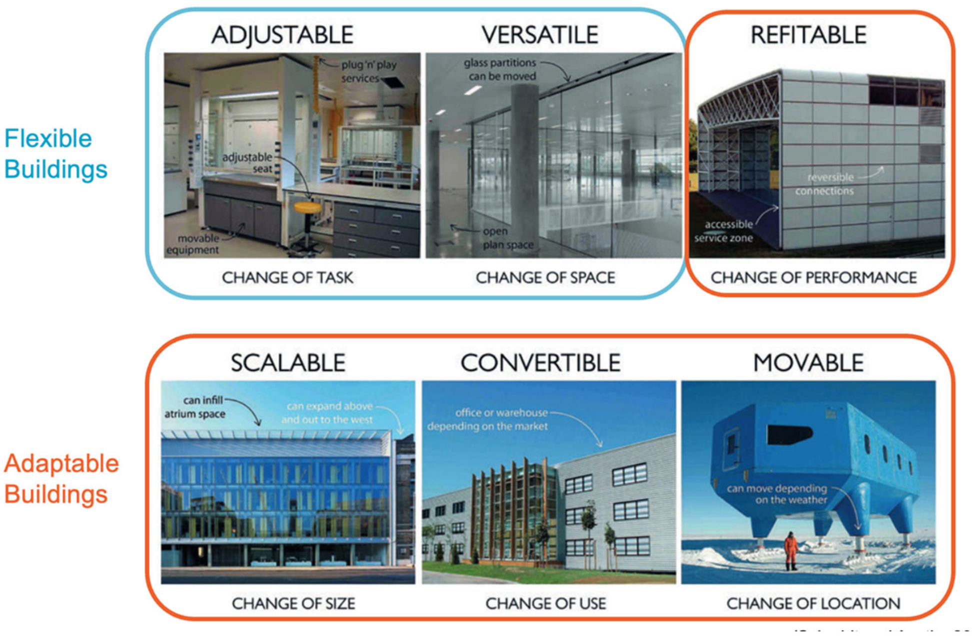

Figure 2 Six Levels of Adaptability by Schmidt and Austin 2016

3 Design for Flexibility and Adaptability

Schneider and Till extensively researched flexible housing projects from 1850 to 2006 located mostly in Europe, the more important of these included as 160 case studies in their book *Flexible Housing* (Schneider & Till, 2007a). They categorised the design of flexible housing into 'soft' or 'hard' types, soft referring to "tactics which allow a certain indeterminacy, whereas hard refers to elements that more specifically determine the way the design may be used" (Schneider & Till, 2007a, p.7). In the soft types, the user can adapt the plan configuration according to their needs, through a more relaxed approach to planning that provides more space and some spatial redundancy, whereas, in the hard types, the architect or designer is in control by designing the dwelling with an intention for its use, for example by providing sliding doors. The authors observed that housing driven by construction technologies was unyielding to change of use other than what it had been designed for (Schneider & Till, 2006, 2007b). Preferring the soft strategies over hard, they discussed a variety of easier-to-implement interventions, such as vertical additions in the roof space, communal circulation space used for other purposes, slack space that can be taken over by residents, functionally neutral rooms, joining two units to make a larger unit, dividing up a unit to make two smaller units, sharing a room between units, positioning of the service core to increase room configurations, and provision of raw space (unfinished space) for residents to finish and customise to their needs (Schneider & Till, 2007a).

Adaptable architecture in the literature has also been referred to by authors as 'loose fit', that allows buildings to change (Lifschutz, 2017), 'hybrid', when it adapts over time (Pelsmakers et al., 2020), 'rhythmic buildings' in a conceptual framework combining the three sustainability pillars of society, environment and economy (Ellen et al., 2022), and resilient housing with creative dwellers (Krokfors, 2017).

But perhaps the most successful architectural movement that provides flexibility for occupants in tall building design is the Open Building movement. An Open Building is designed in two parts: the outer building *support*, or base building, comprising of structural walls, floors, and roof that has a longer life span (100 years); while the non-structural *infill*, which suits the needs of the occupier, has a shorter life span (10-20 years) and can be removed without damaging the base building (Kendall, 2010). This concept aligns with Brand's shearing layers of change discussed earlier (Brand, 1995). The concepts of 'supports' and 'infill' were pioneered by John Habraken and others in the Stichting Architecten Research (SAR) group in the Netherlands, as an alternative approach to the homogenous and inflexible mass housing apartment buildings built after the second world war (Habraken, 1972; Habraken et al., 1976), and in Japan as 'skeleton and infill', by Utida and Tatusumi, in the design of Kodan Experimental Housing Project (KEP) (Ikeda & Amino, 2000) and Century Housing Project (Kendall & Techier, 2000; Minami, 2016). SAR designed a system for dwelling plans in row housing and apartment buildings comprising of fixed structural walls and floors for the perimeter of each dwelling and specific zones for bathrooms/kitchens and living/bedroom areas, which could vary in size according to prescribed incremental dimensions. The architects developed rules for how the rooms could vary in size and function, and created various unit layouts to suit occupant types; however, in early built projects, occupants modified the units in ways not imagined by the architects (Habraken et al., 1976). Consequently, in later Open Building projects, the architects involved end-users in the design process (Kendall & Techier, 2000). More flexibility was achieved in the KEP housing project, where a movable partition wall system allowed occupants to modify the interior - even though some partitions became stiff with age (Minami, 2016).

Contemporary residential Open Building projects are *NEXT21* in Osaka, Japan (Osaka Gas Co, 2013), *Superlofts* in the Netherlands (Habraken, 2017) and 'raw space' housing in *Tila,* Helsinki (Franke, 2014; Koehler, 2022). In *NEXT21* a coordinating architect kept the building skeleton and façade under control by rules stipulating cladding materials and their proportions, without compromising on diversity of apartment sizes, styles and types of households in the building designed by thirteen interior architects for the eighteen infill dwellings (Kendall, 2006; Osaka Gas Co, 2013). Built in 1993, some apartments have already undergone change without any damage to the base building, demonstrating the flexibility of the design approach. In both Superlofts and Tila, the base building has a mostly unfinished double floor apartment space with a bathroom and kitchen finished in Superlofts and only a bathroom in Tila. These three projects are progressive examples of Open Building, an approach that suits the scale of apartment buildings with multiple owners. In all these examples though, flexibility is implemented within fixed perimeter walls and footprint, which may imply high initial construction costs for underutilised.

4 Incremental or Scalable Housing

An alternative approach that plans for future extension of the dwelling is incremental housing, which has precedents in vernacular housing types (Rashid & Ara, 2015). The concept is to build a minimum core as a starter home which is then added on later by the owner as self-builder when household needs change as demonstrated in *Quinta Monroy* and *Villa Verde* by Elemental (Aravena & Iacobelli, 2020). Both housing projects provide a minimum core and space for growth through an organising concept of modular masses and adjacent voids, at the scale of terrace houses of up to three storeys. The owners choose the materials of built-in rooms based on availability and affordability. Each dwelling gains unique appearances providing identity; although the risk exists of lacking consistency, which may result in a haphazard aesthetic.

At the scale of tall buildings, there has been an incremental skeleton-infill approach planned for apartments for low-income families in Malaysia, as discussed in a report (Wook & Mahdzar, 2016). The first phase apartments are designed with adjacent vacant incremental zones that are gradually filled in later; to control the building quality, self-builders are required to use standardised components of partitions, windows, and doors as specified by the architects. Components are designed in module sizes of 1000x2700mm with connection joints that can be attached and detached from their positions, making the components interchangeable (Wook & Mahdzar, 2016).

5 The potential of DfA combined with Design for Disassembly

Increasing on-site adaptability of a building could potentially be achieved by combining DfA with the emerging technology of Design for Disassembly (DfD). DfD could facilitate greater flexibility and adaptability of tall buildings and the CE principles of reducing waste and keeping materials in loops of use. Prefabrication construction has the potential to integrate reversible connections, as the nature of prefabrication is to construct modular, standardised components mostly off-site for assembly of near-finished components on-site (Aitchison, 2018; Geldermans, 2016; Smith, 2010). With reversible connections, building components could be added to and reconfigured on site or at the end of one building's service life, deconstructed and reassembled in another location. However, there is need for research in this still largely unexplored combined field of design for disassembly and design for adaptability of timber buildings.

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Socioeconomic factors for higher adaptability

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1 Introduction

The design of taller timber buildings should be performed with intensive collaboration among the various teams and their members. At present, this makes Circular Economy-aligned, taller timber buildings more demanding than their more traditional concrete and steel counterparts. Unfortunately, the list of design collisions is very long. Here we concentrate on collisions that complicate scalability of funding.

2 Evaluation methods

How do we know if timber buildings retain their value and is there a premium potential?

Historically, both commercial and residential real assets offer attractive risk-return profiles. For timber multi-storey buildings, the historical datasets that would offer the foresight of expected returns are yet to be collected. On the property market, the focus of investor's convenient analysis methods lays with developing, maintaining and improving the rental income as opposed to cost reduction or energy efficiency (Christersson et al. 2015), while discounting effect gives less weight to potential delayed cash flow gains of adaptable solutions (Vimpari 2016). Therefore, the work needs to be done with the investors to bring specific design-related information about physical properties of the adaptable assets (such as lightweight) to the focal point of the investor's decision-making (Vimpari and Junnila 2016).

In the following we give a brief overview of alternative strategies (Figure 1):

- Developing availability of long-term performance data of timber buildings
- Optimizing and aggregating siloed solutions via interdisciplinary collaboration
- Extending learning capabilities and intensifying feedback
- Including finance and insurance in interdisciplinary collaborative optimization

3 Interdisciplinary design collaboration

How do we have one single point of responsibility in interdisciplinary timber design process?

Most building design professionals recognize the benefits of interdisciplinary collaboration for iterative improvement of initial siloed solutions and achieving holistically optimized results. Conversely, the customer is usually faced with a novelty and sometimes wonders who is responsible for the decisions and ultimately the integrity of the timber design. Procurement frameworks exist that enable interdisciplinary collaboration in intra- or interfirm domains. However, the ability to reap benefits of the interdisciplinary collaboration is limited by the availability of the dynamic project leadership expertise in client capacity (Brady and Davies 2010). Such expertise can be educated uniformly to municipal and private sector clients and applied to projects with diverse needs, backgrounds, and timber-based systems (Rodionova 2021). Alternatively, professional construction client, bearing long-term responsibility for the integration of project deliveries and technical property management, can represent a novel single assess point connecting investment professionals and securitizable assets.

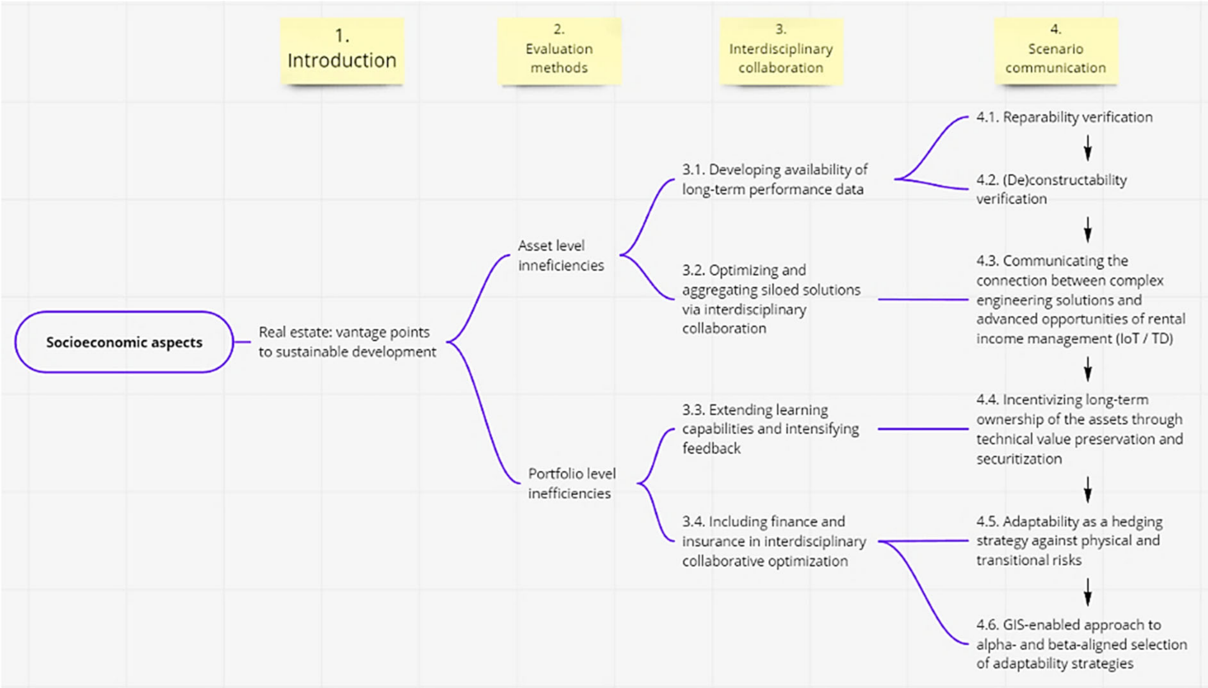

Figure 1: A Mind-Map supporting the report structure.

In the crux of the dynamic project leadership, there is work culture that appreciates the importance of risk recognition and trains project personnel to come forward with the problems identified, as well as offers instructions on how to prevent the threat or take advantage of the opportunity (Davies et al. 2016). While the literature provides guidelines for training teams and members in risk recognition and processing in organizations (Chaleff 2017), developing dedicated training for construction professionals could enhance accurate and efficient risks and opportunities (R&O) communication in projects.

The cultural aspect is augmented with toolsets, including those serving real-time detailed verification of the personnel competence (VTT 2021) and ongoing quality of decision-making, including risk appreciation across the project team (French 2020, Mark et al. 2018, Resolex n.d.). Finally, the incentives and resources should be aligned to support the problem solving. Processes should be put in place to subsidize the innovation emerging from the uncovered issues of the integrated project delivery (and maintenance) through agile cost shifting (Hall et al. 2014).

Development directions in this domain may include standardization of dynamic risk management procedures (Rodionova 2021); including finance and insurance contributions into iterative collaborative optimization (Acharya et al. 2020); and extending learning capabilities and scope of the management from AEC to O&M processes, thus bridging the gap between DfMA and DfD/A workflows (Rodionova 2021).

4 Scenario communication across financial and technical lifecycle design

What is the practical value of Circular Economy solutions and functional adaptability of the timber multi-storey buildings?

As opposed to linear extrapolation or planning found in the conventional asset appraisal methods and overlooking multiple novel sources of volatility (Hirsch et al. 2015, Blundell et al.

2005, Szumilo et al. 2016), scenario planning addresses volatility on two levels. Predictive scenarios consider the iterative nature of built environment projects, while surprising scenarios contribute to the robustness of the general strategy, uncovering hidden vulnerabilities (Galle et al. 2017). We identified following directions of asset and portfolio level research for extended interdisciplinary collaboration between design, finance and insurance professionals. The aim of the proposed framework is establishing dedicated green investment vehicle for multi-storey timber buildings.

Repairability: How do you ensure that your building's bottom line value can be preserved?

- Technical Due Diligence (TDD) of new built projects, evaluating fullness, transparency and validity of the design documentation for the needs of future renovation.

(De)constructability: How to validate adaptability potential of the new design?

- Complementing the above with evaluation framework for obtaining detailed information on individual parts and adaptability routines during O&M stage.

Adaptability: How to best communicate the connection between complex engineering solutions and advanced opportunities of rental income management?

- Digital twin solutions aggregating the complex technical information presented above and allowing for competitive bidding using several alternative use scenarios.

Finder keeper mindset: Is there alternative portfolio enhancement strategies to asset rotation?

- Developing robust long-term asset data management and adaptability strategies towards bundling and securitization of the assets (Eeva 2019).

Transitional and physical risks: How adaptability can help in safeguarding your portfolio against the surprising scenarios of socioeconomic and climate change?

- Due to the volatile nature of the emerging climate and socioeconomic scenarios, different locations have different profiles as related to user profiles and profitability in short-, middle- and long-term. Engineered adaptability can be seen as a way to preserve significant proportion of the assets' physical value even in surprising scenarios.

Diversification of the portfolio: How to define optimal adaptability and green construction scenarios for different locations?

- GIS-enabled analytical approach can augment the selection of appropriate construction technologies, including ratio and location of long-term and interchangeable building components and material bank functionality.

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Designing timber buildings for adaptability

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1 Introduction

Design for Adaptability (DfA) enables buildings to adapt to the changing needs of their occupants and variable conditions of their contexts, thereby keeping them, and their construction materials, in use for longer (ARUP & Ellen MacArthur Foundation, 2018, 2020; Cheshire, 2016; Geldermans, 2016) - while theoretically reducing global warming potential by almost 50% compared to conventional buildings (Rasmussen et al., 2020). Key to DfA is Brand's concept of a building as "shearing layers of change" (Figure 1), which acknowledges different lifespans of building components (Brand, 1994; Nordby, 2009). This concept can be effectively stretched from the functional components of a building to its technological components, where each part, or layer, can be accessed and replaced, for maintenance or spatial re-functionalisation.

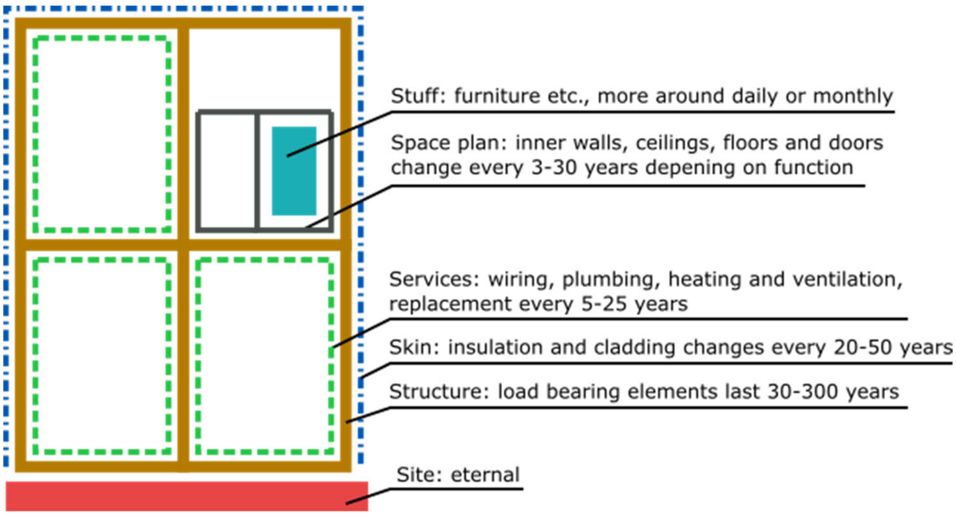

Figure 1. Shearing layers based on (Brand, 1994)*.* (Ottenhaus, 2022)*.*

While DfA has recently gained popularity in literature, it is quite an old concept as buildings have been adapted or repurposed for different uses for thousands of years, including building extensions (Jaksch et al., 2016), modular kit homes used by settlers (Li et al., 2017), as well as relocatable caravans. High-performance adaptability is a more recent concept, where adaptations meet both functional and structural requirements, and the extent of material change required to accommodate functional change may vary significantly.

2 Defining adaptability

Kuiri and Leardini (2022) help clarify the difference between 'flexible' buildings, which allow changes of use to occur without affecting the structure and skin, and 'adaptable' buildings, which require more substantial changes to their physical fabric. Schmidt and Austin (2016) defined six increasing levels of change to the building: from flexible buildings that can be modified by occupants themselves, with little change to the building fabric (adjustable, versatile, refitable), to adaptable buildings, ranging from changing parts or changing the size of the building, to moving the building entirely to another location (convertible, scalable and movable). Therefore, adaptability requires a novel approach to design and construction in the context of a circular economy, to design out waste and keep resources in use. DfA provides framework and strategies to implement reversible changes in buildings.

DfA is enabled by Design for Manufacture and Assembly (DfMA) in combination with Design for Disassembly / Deconstruction (DfD). Modular, prefabricated components with reversible connections allow for partial deconstruction and replacement (conversion, maintenance, and repair), building extensions (scaling), and disassembly and reassembly of entire buildings in a different configuration or location (adaptation, reconfiguration, and relocation) (Akinade et al., 2017; Geldermans, 2016; Nordby, 2009). While past literature has focused on challenges facing taller timber buildings (Buchanan, 2016; Moroder et al., 2018), and the benefits of DfMA (Woodard & Jones, 2020), little research is available on adaptable timber buildings, let alone adaptability of taller timber buildings. According to (Ahn et al., 2022) indeed, most studies focus on environmental benefits of mass timber buildings from cradle to gate, disregarding their circularity potential at the end of life through DfA.

3 Designing timber buildings for adaptability

Working backwards through the adaptability definitions of Schmidt and Austin (2016), the literature on movable timber buildings is mostly focused on low-rise construction, ranging from tiny houses (Calluari & Alonso-Marroquín, 2017), and small-scale demonstration projects (Finch et al., 2020; Roggeri et al., 2021; Smith, Carradine, et al., 2011; Smith, Wong, et al., 2011; Wu et al., 2018; Yan et al., 2022), to temporary accommodation or emergency housing (Badergruber et al., 2016; Baixas & Ubilla, 2016). In addition, some built examples of removable public buildings such as schools, offices and hospitals exist (Kyrö et al., 2019; Newton et al., 2018; Winter et al., 2017). It is also worth noting that while open source building systems such as WikiHouse (Dangel, 2018), Sim[PLY] (Albright et al., 2021), or SE-structure (Montagnana & Fukuta, 2016) allow for disassembly and reassembly in principle, deconstruction can be labour intensive (Boyd et al., 2012; Farrar, 2019), unless disassembly is considered in the initial design (Chisholm, 2012; Walsh & Shotton, 2021).

Scalability of timber buildings is generally only treated in the context of building extensions or urban infill (Dind et al., 2018; Jaksch et al., 2016; Lehmann, 2012), or in the context of single-family homes that can “grow and shrink” in relation to a typical family lifecycle (Milwicz & Nowotarski, 2015; Phillips et al., 2016). Milwicz and Nowotarski (2015) present growing and shrinking homes as a solution to housing affordability, but do not consider the cost of the building site (which is often substantial). Phillips et al. (2016) centre their research around questionnaire results regarding flexible and growing homes in a Brisbane (Australia) context, recommending modern construction technology (such as offsite manufacture) to facilitate changes (such as additions).

Silva et al. (2020) explore case studies of different materiality on movability, scalability, and more permanent internal adjustability. They also propose conceptual architectural solutions for adaptable timber buildings: a shelf structure, where wooden modules can be plugged in and out, a tower prototype that allows internal changes, and a demountable system. Interestingly, while the 14-storey building ‘Treet’ in principle followed the shelf approach with prefabricated modules stacked on “power storeys” (Abrahamsen & Malo, 2014), the external Glulam truss system does not allow for adaptations.

Jockwer et al. (2020) and Walker and Norman (2021) address adaptability in timber construction more broadly. Jockwer et al. (2020) state that the most effective ways to implement circularity in construction are: 1) extension of the service life of both structures and building materials; 2) retention of the quality of materials (durability / longevity of high-quality materials); 3) recycling and repurposing of building parts and materials that no longer meet demands. Adaptability is introduced as a tool to extend the service life of buildings by maximising their use life cycles as shown in Figure 2. This approach is supported by Walker and Norman (2021) who found that highly sustainable (timber) buildings had been "demolished after just 2- years due to a lock of flexibility". They make recommendations to achieve flexibility / adaptability, by keeping the design simple with regular grids, making services accessible and designing for maintenance and repair. They also suggest a similar approach to Silva et al. (2020), where internal walls can be moved by being non-loadbearing. However, this approach would rather fall in the 'flexibility' category according to Schmidt and Austin (2016).

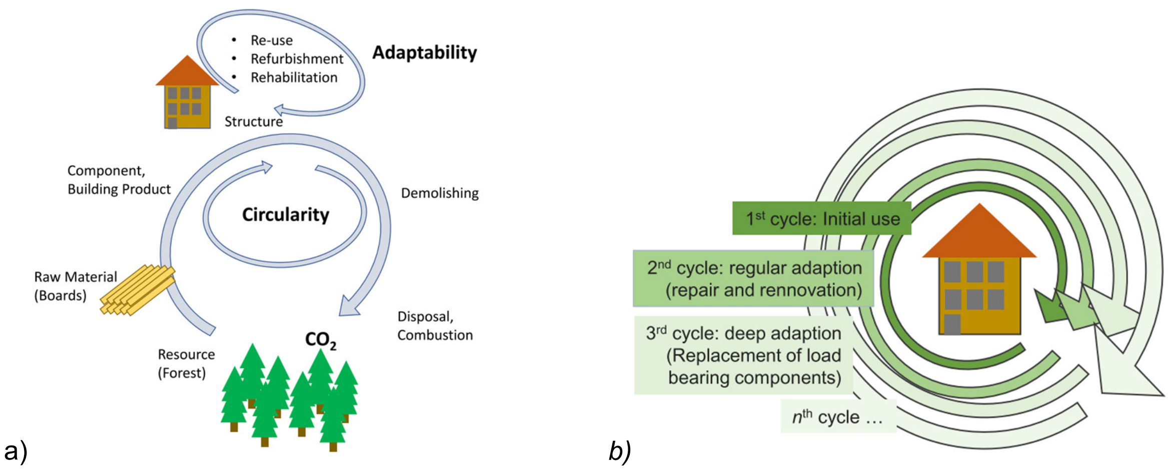

Figure 2. a) Illustration of the concepts of adaptability and circularity. b) Illustration of extension of service life through multiple use-cycles (reproduced with permission from Jockwer et al., 2020).

Jockwer et al. (2020) conclude that DfA allows for buildings to adapt to changing functional requirements, thereby extending their service life, which provides economic, social, and environmental benefits. The authors sum up the idea stating that "[t]he most sustainable building is the building that is not teared down" (Jockwer et al., 2020).

4 Adaptable Taller Timber Buildings: Challenges and Outlook

One of the key barriers to adaptability of taller timber buildings is the lack of reversible connections; mass timber construction commonly relies on a great amount of non-reversible screw fixings. While the connector XRAD allows for structural movability and scalability of cross laminated timber buildings (Bhandari et al., 2021; Pianegonda et al., 2021), all other layers and building requirements are neglected, including hygrothermal performance. Other reversible connectors allow for disassembly of post-and-beam structures (Kowal & Augustin, 2016), however, these systems are not suited for panelised construction (Yan et al., 2022).

Another challenge, and a barrier to implementing adaptability, is the lack of standardisation (Jockwer et al., 2020; Walker & Norman, 2021), since taller timber buildings are currently designed as "one-off" projects (Curtis, 2020). Lack of standardisation also affects reusability of components (ARUP, 2016; Nordby, 2009).

Furthermore, a common 50-year service life means that end-of-life strategies of disassembly, reuse and adaptation are rarely considered during initial design (Geldermans, 2016; Jockwer et al., 2020); this would be an issue for timber buildings and other buildings, alike.

Changing environmental demands due to climate change present a further challenge for taller (timber) buildings, since refitting of the envelope can be difficult (Defo et al., 2018).

Finally, reliable assessment of the remaining service life and performance of salvaged structural members has not been sufficiently developed (Crews et al., 2008; Jockwer et al., 2020; Nakajima & Nakagawa, 2010). This presents a challenge for both scalability and movability of buildings, especially once they have served their initial intended service life.

Addressing these gaps in the literature, current research at Chalmers University of Technology (Sweden) explores adaptable mass timber buildings allowing for change of use and repair of local damages (Bergås & Lundgren, 2020; Ljunge & Silfverhjelm, 2022). Aligned and complementary research at the University of Queensland (Australia) addresses spatial and climate adaptive design of light timber framed construction, with full-scale prototyping (Yan et al., 2022).

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Influential parameters on adaptability of taller timber buildings

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1 Introduction

Timber buildings are becoming more interesting for engineers over the last decade for their multiple benefits in off-site construction, better quality audit, usual modular or simple composition, healthy indoor living environment, low environment impact and other. The basic spatial structure hinders not only communication and productivity but also the adaptability and flexibility from construction point of view to make it possible to continue using the building even if needs have changed (Hegger et al., 2008). If it is a goal to design buildings for long-term usage, it is also possible to expect that functional needs could change through time and that some parts of the building should be replaced. According to Jockwer et al. adaptability can be explained as the possibility to replace or adjust load bearing and other components in buildings in the case of local damages or the change of functional demand. Here two set of parameters can be defined – structural and sociological. First ones are connected to the structural possibilities of the building to adapt – types of joints, elements disposition and relation to envelope, layout etc. and second one to the user demands occurring through usage lifespan.

Before adaption of certain building it is necessary to set series of parameters needed to be assessed in order to make analysis whether a building can be adapted. This set of rules can be bases on occupants reports, layout possibilities (determination by building soft skills and disposition of construction elements, installation shafts, partitions), quality check marks (water leakage, mould growth, infiltration, potential emission of hazard elements done with thermal imaging and air infiltration tests), composition of façade layers, disposition of openings, disposition of HVAC elements and other. Thus, adaptability measures can improve functional organization, structural robustness, aesthetical appearance, and architecture comfort; and can prolong overall life cycle of the building with reducing amount of the waste in construction land fields, reduce energy needed for demolition and transportation.

This paper shows an overview of how different parameters and causes influence on the service life of the building, thus, necessity to adaption and changes in functional and construction properties. It tackles the basis of architecture design principles/ limitations that influence or guide adaptability processes in certain direction.

2 Classification of taller wooden building elements

Adaptability of the building is limited with structural system, envelope system and architectural mass. Each listed item cannot be considered individually, even some of them contain the others, and that is, they permeate each other. According to Green & Tagart, 2017, structural composition of the buildings is categorized into:

- Horizontal and vertical construction element;
    - frame system, in which loads are carried by system of beams and columns, mostly suitable for building programs that require larger and more flexible interior spaces

  - panel system in which vertical and horizontal loads are carried by a series of regularly spaced solid wall panels arranged in two directions in plan. Panel systems are generally better suited to residential programs, where occupant needs are more fixed
  - hybrid system
- Building core (Ilgın et al., 2022);
  - centrally located – with advantages in structural contribution, compactness, enabling openness of the spaces on the exterior façade for light and views, and better safety performance for fire escape;
  - peripheral - low efficiency in space use, challenging fire escape distances;
- Podium (the lower portion of a building which is distinct from the building mass of the tower) – usual made in concrete, this podium can provide many benefits such as housing services at ground level, providing high clearances in public spaces and large openings, and generating fireproof areas for large mechanical and electrical services and equipment;
- Design of structural system (etc. exposed columns and beams) (Kuzmanovska et al., 2018);

Envelope system depends of structural system, transparency, prefabrication level and architectural expression. The performance of the envelope and the durability of the building are affected by the choice of materials; details of assemblies which must control thermal bridges, the movement of air, vapour and moisture; and quality control of the manufacturing and construction processes, to ensure that the integrity of the envelope is maintained throughout the life of the building. Facades can be categorized as load bearing or non-load bearing. The selection of it is highly connected to both structural strategy and construction sequence. They are divided into three main groups, according to their opaque/transparent ratio degree – (1) opaque walls with punched windows, (2) completely glazed and (3) façade systems with alternating elements either fully transparent or fully opaque. The use of mobile or fixed scaffolding was noted, in order to infer the system's degree of prefabrication of facade. If no action is required from outside during the installation of the façade, the prefabricated envelope system can be defined as factory finished. However, when external access to the façade is necessary the external wall elements can be defined as be semi-finished assemblies. Spatial configuration and architectural mass of tall buildings is tied to the structural strategy; shape, size and location of the core and primary horizontal circulation. Therefore, factors taken into account are (1) building volume (overall geometric strategies such as rectilinear or irregular plan, and regular or irregular extrusion), (2) balcony strategy (wide range of configurations from protruding balcony to no balcony at all, as well as the use of timber as a finish) and (3) circulation (ventilation - central and peripheral, cross ventilation with circulation spaces: totally airtight or with some degree of natural ventilation).

3 Challenges on adapting existing building

The design of today's sustainable building requires integral thinking, where Integral Design process (IDP) enables alternative approaches to be evaluated at the schematic design stage, allows conflicts to be resolved, tracked and approved with help of virtual models. The areas of design expertise overlap and systems within a building perform multiple functions (Green & Tagart, 2017). For instance, size and placement of windows on the façade is not only architectural design concern but it represents engineering task to calculate amount of light it passes through, to calculate potential glare and track infiltration loses on the linear joints between frame and glass, to calculate thermal transmittance and heat loses, develop details of connections, etc. Also, there is a potential conflict with other installation systems such as HVAC, plumbing or electrical networks – the larger glass volume is, less space for building services on the envelope. Today, three-dimensional image of the building makes it possible to identify potential collisions between of any functional and technical elements (Bali et al., 2018) thus make it easier to avoid them. Quality parameters can be considered as sets of rules needed to be accomplished by building for it to be healthy and responsible for the tenants. These parameters are sometimes personal, where users show their own subjective feel of variety of comforts. However, in order to achieve higher standard of built environment they are defined by national or international legislative. Dynamic changes in legislative are also parameter that defines conditions necessary to be fulfilled by the building.

Functional adaptability is determined by microclimate conditions (primarily sun insolation) and technical limitations from architecture practice – structural elements, building services, adaptability of the envelope in accordance with specific needs from the inner space or obsolescence of the materials/joints. Building enclosure acts as environmental separator between inside and outside, and serves to maintain comfortable thermal, visual and acoustic environment within a building. The durability of building itself is determined by the selection of materials, which must be designed for the required service life as well as be compatible with one another in the ensemble. To ensure the integrity of the envelope and long service life of building and facade, the detailing is crucial whereas engineers can control thermal bridging, air, vapour and moisture movement. (Green & Tagart, 2017)

There are several key points that define the level of adaptability of an object. All of them are in some way dependent on each other, but in order to enter the process of change, it is necessary to analyse the existing documentation, the condition of the building and the possibilities of performing interventions. Key factors of adaptability are presented below:

- Building orientation according to properties of micro location (primarily insolation and dominant wind flows) influence on whether floor layout can be adjusted. These limitations are stricter and more visible in the southern regions of Europe with very warm summers, and very cold winters; and they are less visible in the facilities with controlled indoor environment;
- Structural limitations – each type of structure behaves differently. Panel systems are most rigid while skeletal systems enable more adjustments in the floor plans;
- Building services - they present very rigid system of pipes and new connections are determined on distances between utility elements and vertical installation shafts;
- Soft skills – they present potential of the building to adapt to new needs;
- Potential vs. capabilities. Not all good measures for adoption are optimal. Economic parameters are as equally important as others - structural principles, equipment needed, amount of personnel, duration of works, influence on inhabitants and environment impact.

4 Comparing adaptability potential through different case studies

The following chapter presents good practice example where emphasis is given to the parameters which influence the adaptability potential. Student dormitory towers in Trondheim, Norway are made of CLT panels that serve as both partitions and structural elements. Intentionally, this example is chosen because it is not designed with specific necessity for later adaption or changes. It is interesting to question whether present buildings can be adapted in future and to see how functional requirements in early design stages influence the choice of construction that later that determines possibility of adapting the building with regard to function, structure and envelope and the installation systems in the building (whether it is open or hidden arrangement).

This example is determined by both primary structure and the envelope, which are load-bearing elements. As the main purpose is student housing which required small individual rooms, they are divided by CLT panels as load-bearing element. In that case, adaptability (in this sense flexibility to) is only possible by making new openings in the panels what can weaken the structure. Adaptability potential of the buildings which are built with CLT panel system is not great, since they have not been designed with that purpose. Joining two unites to one bigger apartment will potentially be possible, however, that will demand significant efforts of load redistribution and joining two separate bathrooms will demand different arrangement of installation systems.

Building installations (air conditioning, plumbing and electrical in some parts) are put beneath ceiling (noticeable from ground floor common areas) making them easily reachable for repairs. This type of installation allows for horizontal pipes to be rearranged/redirected without compromising structural integrity of the floor slabs.

Figure 1. Open installation management system in Moholt tower – ease of access, maintenance and rearrangement potential (photos by S. Slobodan Peulić).

5 Conclusion

This paper showed brief set of parameters needed to be evaluated when adaptability is analysed. Its contribution is in promotion of the building adaptive skills and emphases that a building can be adaptable mostly if it has been thought/ designed as such. Moholt example is taken due to very precise function, heavy usage and different social structure. This is good example of timber structure that has peaks in usage during semester and that is empty during summer and winter breaks. Trends are moving towards column and beam/slab systems despite the program; a shift towards the hybridization of constructive materials; increasing the articulation and expression of wooden structural elements and wooden ceilings; increasing use of non-wearable sheath systems; an increase in the use of fully glazed facades and, potentially, a move towards increased prefabrication of the envelope. Further analysis could investigate comfort quality within the building and analyse adaptability from more detailed point of view looking into details and whether rearrangement of interior and exterior elements can be achieved.

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Parameters for wooden adaptive facades

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1 Introduction

Requirements for the envelopes of buildings being built in the 21st century include that the envelopes be made of materials that are not harmful to the environment or human health, and that the production and construction processes be with low energy requirements and minimized emissions. It is important that they provide the necessary functionality and comfort of living in the building, and that they have a long lifespan that finds adaptability to the various and diverse changes that occur throughout the building's lifetime.

The adaptability of building envelopes can be considered from different aspects, and accordingly, different parameters for design and assessment can be established. For the design of facades in general, and thus wooden facades, several parameters can be recognized in terms of adaptability:

- adaptability to annual and daily cycles, i.e. changes,
- adaptability to new technologies, especially the integration of energy production technologies into facade structures,
- adaptability to the needs of improvement of spatial comfort, the possibility of removing and replacing non-load-bearing parts of the facade and adding new structures in order to expand the existing interior space or create balconies and loggias,
- adaptability to changes in design and construction standards and regulations (requirements for thermal insulation, fire resistance, safety, etc.),
- adaptability to the different needs of users in terms of participation in the creation of facades, which will represent the individual expression of each user on part of their facade, which has so far been realized in rare cases when it comes to multi-story buildings.

On this occasion, attention will be paid to the first two parameters, considering that they are directly related to the development of new facade technologies, energy saving, and thus the reduction of environmental pollution.

2 Adaptability to annual and daily cycles

Facade concept and structure should be designed to provide satisfactory user comfort, so in order to achieve high living and working comfort, advanced facade technologies are being developed that allow adaptation to the changing external environment (Furundžić et al. 2018), specifically, the annual and daily changes.

Adaptive facades are characterized by changeable appearance as a result of adaptation/response to daily and annual changes in the environment. Depending on the technology, there are mechanical and dynamic/kinetic facades.

Dynamic/kinetic facades are usually incorporated in, i.e. built into the building structure, and consequently they have to be part of the design idea from the beginning. In terms of functioning, there are three types: facades with smart material, intelligent dynamic facades and responsive dynamic facades, and in the case of these concepts, people have no direct influence or contact with the elements from which the facades are made.

When it comes to wooden facade components, their use is observed in the case of mechanical adaptive facades. Mechanical adaptive facades contain elements that are being moved by human command and/or hand and thus adapt to the needs of the users. The concept is characteristic for adapting the facade to the function of protection from solar radiation. The design of mechanical adaptive facades differs depending on the orientation of the facade, and the types differ depending on the position/orientation of the elements, the shape/type of elements and the mechanism of actuation/movement in the function of adapting to changes in the environment (Figure 1).

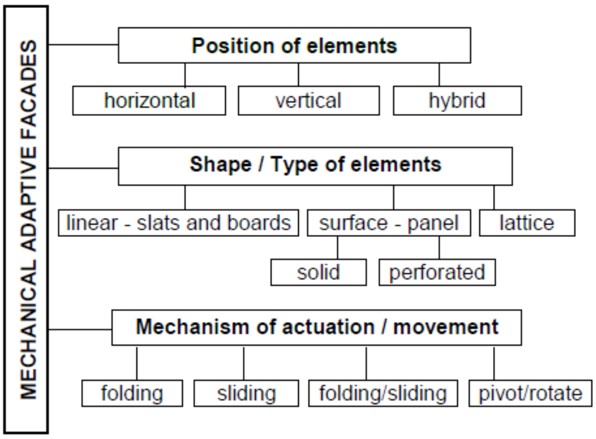

Figure 1. Design parameters of mechanical adaptive facades (image: A. Krstić-Furundžić)

Figure 2. Vertical folding/sliding wooden components of the adaptive facade of the housing block in Wroclaw, Poland (image: A. Krstić-Furundžić 2017)

Figure 3. The sliding wooden components of the adaptive facade of the housing block in Wroclaw, Poland (image: A.Krstić-Furundžić 2017)


Figure 4. Panels made of solid boards as wind protection (rotate along the vertical side axis), Trondheim, Norway. Left: the appearance of the building, right: facade detail (image: A. Krstić-Furundžić 2006)

Regarding the position/orientation of elements, horizontally and vertically oriented elements are distinguished. Horizontal ones are characteristic for the southern orientation of the facade, while vertical ones are used for the eastern and western orientation of the facade. Their combination is also possible - hybrid forms. Shape/type of elements can be linear – slats and boards, and surface – panels, while in terms of processing panels can be solid or perforated, which strongly affects the visual experience of the appearance of the facade and building. Panels constructed from a frame into which slats are inserted are often used, which provides protection from solar radiation, good daylighting of the interior space, as well as a view of the exterior space (Figures 2 and 3). The mobility of the slats contributes to a better response to changes in the environment. Panels formed from solid boards are usually used in windy areas when they serve as wind protection (Figure 4). Actuation/movement mechanisms are folding, sliding, folding/sliding, pivoting/rotating. Usually, the wooden elements are attached to the facade via a metal substructure and are located at an appropriate distance from the insulating layer of the facade. There are various systems for hanging wooden elements for the substructure, which can be visible to a greater or lesser extent, affecting the appearance of the facade. The fastening system of wooden elements must be designed in accordance with the types and intensity of loads that occur due to the weight of wooden elements, the effect of wind and thermal stresses, as well as occasional stresses due to fires or earthquakes.

The design of high-performance facades is unavoidable in contemporary architectural practice as a key trend in achieving environmentally responsible buildings, as well as buildings that enable the well-being of users. This approach is also noticeable when it comes to wooden facades and buildings. „The performance of building envelopes hugely relies on their response to their changing environment. More comprehensive understanding of the combination of forces affecting a building envelope requires designers to create more flexible and responsive solutions. These responsive solutions involving technologies such as microprocessors and actuators entail collaboration with other disciplines of mechanical and electrical engineering, computing, physical and social sciences. Therefore, design of high-performance building envelopes is a good example of interdisciplinary practice in architecture resulting in improved efficiency and performance in buildings“ (Tashakori 2014).

3 Adaptability to new technologies

In conditions of energy deficit and increasing energy prices, the need to use renewable energy sources and reduce environmental pollution, the building envelope is recognized as a position for locating devices with advanced technologies for energy production. The facade, as the component of the building that is most directly exposed to the sun and wind, is the most effective site for innovations in energy savings and alternative energy generation (Velikov and Thun 2012).

The integration of energy production technologies into wooden facade structures is the subject of many scientific researches and experiments. Different solutions are present in terms of developing technology and devices for the production of thermal and electrical energy. Solar thermal collectors (STCs) are devices for the production of thermal energy, while photovoltaic modules (PV modules) are devices for the production of electricity. In both cases, stand-off or add-on and building integrated devices are available, and the application of each of them has a different effect on the appearance of the building. Add-on are independent devices applied on roof or facade structure, while building-integrated are building components which can substitute conventional roof or facade cover materials (Krstic-Furundzic et al. 2017). Hybrid PV/T facade concepts are also available. The unique quality of prefabricated wooden facade wall panels with integrated solar thermal collectors (BISTC) and PV modules can be achieved by factory production. Assembly is easier and takes less time.

The wooden structure of the facade can be a substructure for carrying glass panels with integrated PV cells, i.e. PV modules, whereby the facade, in addition to the function of closing and protecting the interior space, also has the function of generating electricity and protecting against solar radiation, which makes this facade multifunctional (Figure 5).

The outer layer of STC and PV module is transparent and mostly made of glass plate. That is why the facade looks like a glass facade, which camouflages that it is a wooden structure of the facade. The appearance of solar thermal collector and PV module, as a building component, is determined by the material, surface texture, color and type of jointing. The color of solar thermal collector depends on absorber color or selective filter color, while the color of the PV module depends on the type of PV cells and/or the color of the antireflective layer.

Figure 5. Facade of wooden structure with integrated PV modules, The Academy of Mont Cenis, Herne, Germany. Left: the appearance of the building, right: facade detail (image: A. Krstić-Furundžić, 2019)

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SG Design for disassembly and reuse

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Designing timber buildings for disassembly and reuse

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Paola Leardini, The University of Queensland (Australia)

1 Introduction

Research, frameworks and experimental projects addressing building design that embraces Circular Economy (CE) principles have multiplied in the last few years (Munaro et al., 2020), including guidelines for ‘circular design’, a term clearly outlined in Cheshire’s *Building Revolutions* (Cheshire, 2017) and the *Circular Design Guide* by Ellen MacArthur Foundation (2018). Key to understanding circular building design is Brand’s concept of building as “shearing layers of change” (Figure 1), which acknowledges different lifespans of building components (Brand 1994; Nordby 2009). This supports a systemic approach to building design, where each component of the system is integrated and yet replaceable to accommodate functional and spatial changes of the building (and its users) over time. Conceiving and designing a building in layers combined with Design for Disassembly /Deconstruction (DfD) allows for maintenance and repair, as well as salvaging of building components at the end of life through disassembly and reuse in the same or a new context (relocation, adaptation, modification) (Akanbi et al., 2018; Nordby, 2009). While the focus of this report is on structural systems, assemblies, and components, many principles of disassembly and reuse can equally be applied to the building envelope, building services, and other non-structural elements (Finch et al., 2021; Michael, 2020; Stephan & Athanassiadis, 2018; Wasim et al., 2020).

2 Design for disassembly and reuse

DfD was introduced across many industries to facilitate maintenance and repair of products (Akanbi et al., 2019; Bogue, 2007; Boothroyd & Alting, 1992; Boothroyd & Girard, 1996a, 1996b; Desai & Mital, 2003; Smith et al., 2012, 2016). Boothroyd and Girard (1996b) propose DfD guidelines for the product structure (functional units, easily accessible and easy to (dis)-assemble) and materials (few identifiable and separable materials, non-harmful and recyclable). Bogue (2007) defines DfD rules for a product structure (modularity, standardisation, minimise components / variants), materials (mono materials, recyclable),

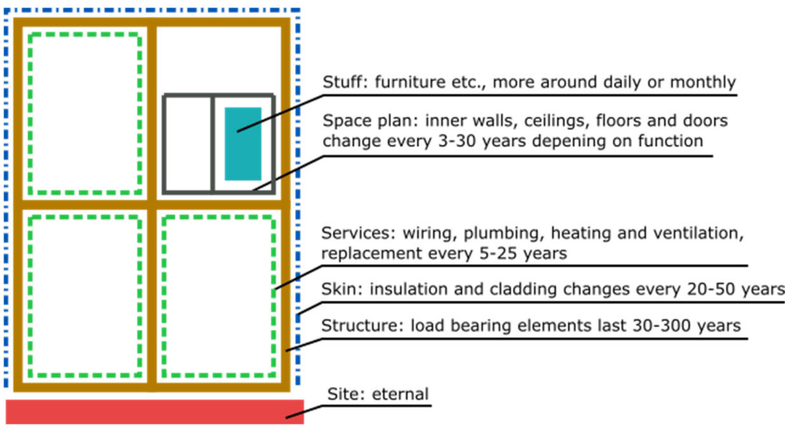

Figure 1. Shearing layers based on Brand (1994). Source: Ottenhaus (2022).

connections (minimise number of joints, accessible and visible joints, easy to disassemble, fasteners instead of adhesives), component characteristics (lightweight, robust / durable, non-hazardous), and disassembly conditions (automated, no specialised procedures or tools). Smith et al. (2012) provide further design rules for 'green products' that allow for selective disassembly of components for repair, reuse, recycling, or remanufacturing. The rules include easy disassembly, single-translation motions, removal of components and fasteners from a single direction, boundary components (layers) that can be easily removed and in the same direction as target components (i.e., those that frequently require maintenance), placing target components close to the boundary and close to each other. All these design rules can be applied to buildings as products.

In building construction, both terms Design for Deconstruction and Design for Disassembly are used interchangeably. DfD is often seen as a progression from Design for Manufacture and Assembly (DfMA), a well-known concept in modular offsite construction (Akanbi et al., 2018, 2019; Akinade et al., 2015, 2017). Crowther (1999) notes that DfMA and DfD have been used throughout history, e.g., in the design of kit homes of British colonies. Crowther also makes recommendations for a multitude of circular design strategies that are enabled by DfD, such as materials recycling (fewer materials, avoid hazardous and toxic materials, mono materials in inseparable sub-assemblies, avoid finishes and coatings, permanent material identification), component reprocessing and reuse (minimise number of components and wearing parts, use mechanical connections, open buildings, building in layers, ease of access, tolerances, standardised connectors, permanent component identification), and building relocation (standardisation, regular grid, lightweight material and components, DfD).

While Crowther (1999) sees DfD as an implicit enabler of material, component and building reuse, Nordby (2009) uses the term 'salvaging' to describe DfD with the purpose of reuse. Nordby also synthesises DfD literature for building construction: Berge (2007), who investigates design for assembly and disassembly principles, which are separation of layers, possibilities for disassembly within each layer, and use of standardised monomaterial components; Fletcher (2001), who introduces 27 DfD principles at system level (adaptable buildings), product level (refurbish, repair, replace), and material level (reuse, recycling, cascading / degradation); Thormark (2001), whose thesis focuses on "Recycling Potential and Design for Disassembly in Buildings"; Sassi's work on closing resource loops within circular economy frameworks (Sassi, 2002, 2004); Crowther (2003), who introduces 27 DfD principles for industrial design, architectural technology, buildability, maintenance, and research; Durmisevic (2006), who lists 37 DfD principles at building, system, and material levels; and Brand's shearing layer concept (Brand, 1994). Nordby also derives the following salvageability criteria:

- **Limited material selection**, i.e., minimise types of material, use mono-material components that allow for separation at end of life, reduce types of components and connectors, e.g., through standardisation, and avoid toxic or hazardous materials and secondary finishes, which, again, affect disassembly and end of life scenarios.
- **Durable design**, i.e., long-lasting components with adequate tolerances to withstand repeated dis- and re-assembly and reuse, thereby lasting several building lifecycles.
- **High generality / standardisation**, e.g., standardised dimensions, modular construction (prefabrication), and a standardised structural grid, combined with small(er) and lightweight components for easier handling, and reduction of complexity of components and assemblies such that common (standardised) tools and equipment can be used.

- **Flexible connections**, i.e., the use of accessible reversible connections for subassemblies, between components and between building parts, allowing for parallel disassembly and reassembly.
- **Suitable layering**, by designing structurally independent functional layers arranged according to their expected technical service life (Brand, 1994).
- **Accessible information**, that provides information about material and component types, provides updated as-built drawings, log of materials used and guidance for deconstruction, and identifies and provides access to connection points. Present day examples are digital twins (Qi et al., 2018) or material passports (Heinrich & Lang, 2019).

Sanchez et al. (2020) and Sanchez and Haas (2018) define further rules to plan (partial) disassembly of buildings. Durmisevic (2019) gives design strategies and technical solutions for reversible buildings as part of the Buildings as Material Banks (BAMB) project.

While DfD has been embraced as a key design strategy to enable circularity in the built environment (Akanbi et al., 2018, 2019; Akinade et al., 2015; Cruz Rios & Grau, 2020; Geldermans, 2016; Minunno et al., 2018; O'Grady et al., 2021; Walsh & Shotton, 2021), Akinade et al. (2017) highlight that non-technical factors, such as policy and legislation, and a change in design thinking need to be addressed to enable DfD.

3 Additional requirements for timber buildings

In timber buildings, DfD is often enabled by reversible connections (Akinade et al., 2015; Boyd et al., 2012; Klinge et al., 2019; Nordby, 2009; Sparandara et al., 2019; Yan et al., 2022). Ljunge & Silfverhjelm (2022) investigate the potential reuse of structural CLT panels with respect to inter-panel joints. They highlight issues related to reversible joints (i.e., lack of technical solutions), as well as technical challenges in the removal of CLT panels itself with respect to the motion and access required. Hence, design for disassembly and reuse requires careful consideration at early design stages to enable multiple reuse cycles (Forsythe, 2011; Kuiri & Leardini, 2022).

Direct reuse of timber components, such as beams, columns, or panels, is only possible if the components are intact, including parts of joints that are permanently attached (Nijgh & Veljkovic, 2019). This means the timber itself needs to be free from damages or decay that affect functionality, which can be challenging to assess for older reclaimed timber components (duration of load effects), thus requiring regrading (Crews, 2007; R. Falk et al., 1999; R. H. Falk & Green, 1999; Nakajima & Murakami, 2007). Alternatively, components should have only sustained an acceptable amount of damage that can be repaired or does not affect functionality (Celadyn, 2019). An example of reuse with lower functionality would be recycled timber that has been down-graded, whereas an example of reuse after acceptable damage would be timber elements with sacrificial joints (fuses) that can be replaced while the member itself remains intact, which is common practice in low-damage seismic design (Blomgren et al., 2018; Holden et al., 2012; Sarti et al., 2013). If reuse in a similar configuration or functionality is not possible, timber materials can be cascaded, i.e., cross from the technosphere into the biosphere, where they are reprocessed into engineered wood or fibre products, as shown in Figure 2.

Finally, some reuse scenarios may require a timber structure to retain its performance despite frequent reassembly cycles. Examples are temporary structures such as scaffolding or emergency housing. In those cases, it is crucial that timber joints retain their initial stiffness and tolerances, i.e., limit embedment deformation that creates slip (Reynolds et al., 2018).

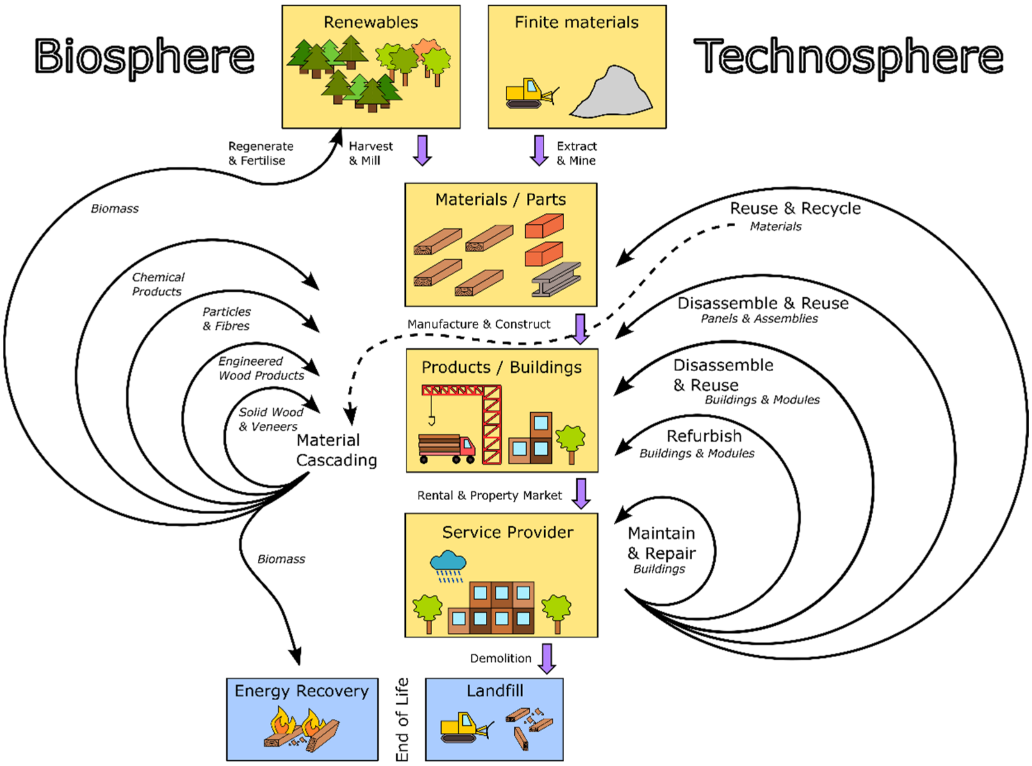

Figure 2. Butterfly diagram of circular timber buildings (Ottenhaus, 2022b). *Adapted from Ellen MacArthur Foundation's "Butterfly Diagram"* (Ellen Macarthur Foundation, 2019).

4 LCA of timber buildings designed for disassembly and reuse

Finally, it is worth assessing the lifecycle impact of reuse. Often, durability enhancing measures, such as chemical timber treatments, are associated with a higher environmental footprint but higher reuse potential. Buyle et al. (2019) undertook consequential Lifecycle Assessment (LCA) and Lifecycle Costing (LCC) for different internal wall assemblies to assess circularity potential. Seven wall assemblies were assessed over a period of 60 years, with a refurbishment every 15 year. Low lifecycle impact was achieved both for assemblies that are designed to be used again and have a higher initial impact, such as a plywood boarding connected reversibly to a demountable metal frame substructure, as well as for assemblies with no possibilities for direct reuse that have a low initial impact, such as a drywall system with a wooden substructure. Eberhardt et al. (2019) came to a similar conclusion after conducting a LCA case study on a Danish concrete building designed for disassembly. Their findings show that substituting concrete with conventional timber construction still leads to higher CO_2 emissions savings than a concrete building designed for disassembly and reuse. Nevertheless, Akinade et al. (2015) recommend that "[i]n the case of timber structures, not only the use of prefabricated assemblies and demountable connections must be considered, but also the durability of the wood. This is to enable the reusability of timber components because wood has more value in reuse than in recycling."

Buyle et al. (2019) found that key to incentivising reuse was shifting environmental burdens upstream, by taking environmental consequences of design decisions into account.

5 Summary

In summary, Design for Disassembly/Deconstruction (DfD) is essential to enable maintenance, repair, adaptation, and reuse of timber buildings. DfD is generally enabled by reversible connections and research is needed to further develop timber connections for repeated assembly and disassembly without loss of performance. Reuse of timber components has further requirements regarding timber durability, limited wear and tear, and reliable assessment of the remaining service life due to duration of load effects.

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Circular material flows for timber buildings

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1 Introduction

The greatest innovation potential to re-shape construction practice for a circular economy is at the design stage, through a paradigm shift in the way buildings are conceived: as long-lasting yet temporarily artefacts that can be easily reconfigured, for flexible use, or disassembled into reusable components and materials. Extending a building's service life and keeping its materials in use for longer are both key to designing out waste and reducing resource consumption. Timber stores carbon dioxide (CO_2) while in use; the average tree absorbs 10 kg of CO_2 per year for the first 20 years (Bernal et al., 2018), which presents a case for using responsibly harvested wood in timber building construction. Since both decomposition and incineration release the stored CO_2, extending the life of a timber building and its parts is an effective way to implement circular principles in construction. However, current end-of-life (EOL) options for timber buildings are usually considered from a biosphere perspective, with a focus on cascading or energy recovery - which releases the stored carbon (Campbell, 2018).

This paper explores literature that addresses design principles for implementing CE principles in timber building construction to maximise their sustainability potential through carbon sequestration and value retention across multiple use cycles. While the literature focuses on different typologies and scales, most principles are applicable to low-, mid-, and high-rise construction alike.

2 Designing timber buildings for circularity

The following section is a non-exhaustive state-of-the-art literature review of available frameworks and methods to establish circularity for timber buildings. The review is based on a literature study conducted in early 2020 using the keywords *circular** and *timber OR wood* in a Scopus query. It should be noted that circular building design includes many concepts such as *Building as Materials Banks* (BAMB)[1], material passports (MPs), urban mining, design for adaptability, disassembly and reuse, maintenance and repair, etc., but not all of them are discussed here. This review rather focuses on material flows for timber buildings.

2.1 Circular economy frameworks and the building industry

The Ellen MacArthur Foundation (EMF) "works to accelerate the transition to a circular economy" (EMF, 2022). In collaboration with partners, the EMF has released guidance and reports on CE principles in the built environment.

McKinsey (2015) introduces the ReSOLVE framework, which includes six actions for the implementation of CE principles:

- **Regenerate**, shifting to renewable energy and materials
- **Share**, thereby slowing product loops, design for durability and reuse
- **Optimise** performance and efficiency, reduce waste
- **Loop**, keeping components and materials in closed loops and minimise those loops

[1] Buildings as Material Banks (BAMB) is a circularity concept and the title of an EU Horizon 2020 research project.

- **Virtualise**, rather than making physical things
- **Exchange** by replacing old materials with new advanced materials and technologies

ARUP (2016) applies the ReSOLVE framework to the built environment and integrates it with other concepts such as Brand's shearing layers (Brand, 1994). The publication evaluates over 40 case studies using the ReSOLVE framework.

A later report by ARUP and Ellen MacArthur Foundation (2018) presents a roadmap towards a CE in building construction and use and identifies three key stakeholders to enable the transition: policymakers, investors, and construction clients. It is the first part of the *From Principles to Practices* collaborative project between ARUP and the EMF.

The second part of this collaborative project by ARUP and Ellen MacArthur Foundation (2020) introduces five new circular business models for real estate: **Flexible spaces** that allow for multi-use of the same space; **Adaptable assets** for alternative use case scenarios either due to changing market conditions and/or social expectations; **Relocatable buildings** that allow for temporary use at different sites using modular, deconstructable buildings; **Residual value**, where building materials retain value at deconstruction; and **Performance procurement**, i.e., product-as-a-service business model scaled up to whole building systems.

Geldermans (2016) highlights that CE and Cradle-to-Cradle frameworks imply radical changes for the construction sector and puts forward the concept of 'buildings as material banks', where high quality monomaterials are employed together in a system that anticipates their reuse and regeneration. Geldermans discusses 'design for adaptability' as a strategy for extending a building service life, and touches on EOL concepts such as 'design for disassembly' and 'design for recycling'. Geldermans also provides an example inventory matrix that captures building layers (shearing layers), material turnover rates (lifespans) and regeneration routes (reuse, recycling, reprocessing) for those layers in the technosphere or biosphere. Geldermans (2016) highlights the need to approach circularity not only from a technical viewpoint but to integrate environmental, societal, and economic factors.

2.2 Urban Mining and material cascading

Given the environmental credential of timber as a renewable material with carbon sequestration capability, EOL options for timber buildings and components are considered in practice mostly from a biosphere perspective. However, the literature reveals research focusing on its potential reuse and recycling.

Mair and Stern (2017) review and contrast circular economy (CE) and cascading utilisation (CU) of wood products in literature between 1990 and 2016. First, the two concepts hardly appear together in the same publication, which may be owed to the fact that CE and CU are used in different contexts as shown in Figure 1. While the CE includes considerations of many kinds of resources, publications on CU include a stronger focus on bio-based materials (such as timber). CU mostly refers to the use of resources from high- to low-value products, where the bio-resource is effectively down-cycled (cascaded). In contrast, the CE focuses on how to keep the resources in the system and minimise the use of primary resources. The paper concludes that CU addresses primarily resource management whereas the CE provides a more holistic approach. In consequence, CU should be considered a basic concept within a CE framework and particularly in the circular bio-economy (biosphere), in which investigations are performed on raw material efficiency performance over multiple-use phases.

Honic et al. (2019) present a proof of concept for material passports (MPs) for a residential building designed of either timber or concrete. In the study, the "MP acts as a design optimisation tool, as well as an inventory of all materials embedded in a building and displays the recycling potential and environmental impact of buildings". The study finds that while mass timber has a lower recycling potential than the concrete option, the concrete building generated more waste overall. Furthermore, lifecycle assessment showed that the timber option performed better than the concrete option. The paper recommends using a material with a long lifespan (durability) and high reuse potential. MPs can then facilitate urban mining "where existing stocks serve as a source of secondary raw materials" and be used as a decision-making tool in the whole value chain.

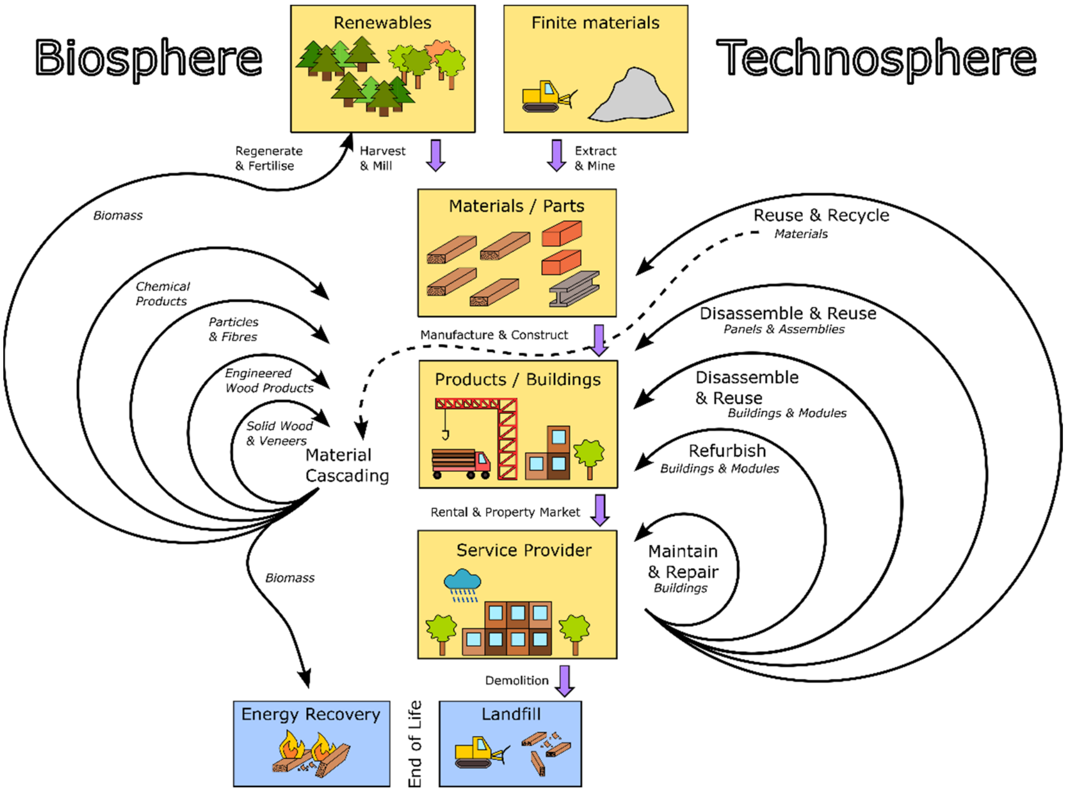

Figure 1. Timber material and component flows within the technosphere and biosphere (Source: Ottenhaus, 2022a).

Deetman et al. (2020) model construction (inflow) and demolition (outflow) of building floor space for both residential and service-related purposes as global annual demand for construction materials as well as an estimation of the availability of waste materials after building demolition. The paper projects that, by 2050, only 55% of construction-related demand for copper, timber, and steel could potentially be covered by salvaged building materials. This shows that urban mining alone cannot cover the growing demand for construction materials.

Romero Perez de Tudela et al. (2020) present a method to estimate the timber stock in residential buildings in London pre-1992 which is based on secondary data from external research bodies, national statistics, and a housing stock management database. The paper finds that, generally, there is more timber in floors and roofs, and in older buildings. The presented method is a valuable tool when BIM is not available and capable of contributing to the growing understand of existing buildings as material banks.

Höglmeier et al. (2013) explore wood waste cascading from demolition waste in 2011 in south-east Germany. They find that 45% of the recovered wood is potentially suitable to be cascaded in particle- or fibreboard production, 26% would be suited in a reuse scenario, and 27% could be channelled into other high-value secondary applications. However, challenges in certification for structural application are highlighted.

To ensure safe and reliable use of reclaimed materials, they might need to be regraded or reclassified (Crews, 2007; Nakajima & Murakami, 2007). This is especially important for materials salvaged from older buildings for which information about their original grade or quality is often missing (Forsythe, 2011). Reclaimed timber materials may also suffer from biological or environmental degradation, as well as duration of load effects (Hartnack & Rautenstrauch, 2005; Smith & Foliente, 2002).

Rasmussen et al. (2019) examine the feasibility of reusing construction materials and showcase a Scandinavian company offering three building products based on reused materials, windows, wood cladding, and concrete. The analysis shows that reuse is price competitive and leads to significant reductions in environmental impacts. Likewise, Klinge et al. (2019a, 2019b) and Roswag-Klinge et al. (2019) showcase how to reuse timber elements and materials from existing buildings, using waste wood as a resource.

Crowther (2003) and Nordby (2009) stipulate design criteria to increase reuse potential. To allow reuse of timber components, they need to be intact, including parts of joints that are permanently attached (Nijgh & Veljkovic, 2019). Alternatively, components should have only sustained an acceptable or repairable amount of damage, unless they can be reused in a way where the damage does not limit the functionality (Celadyn, 2019).

3 Opportunities for timber buildings in a CE

In the binary approach to material flow discussed above, either within the biosphere or the technosphere, timber buildings present, indeed, a challenge, as they sit at the interface of both spheres. When timber materials are only considered for cascading, processing cost in manufacture and construction are neglected, both monetary and in terms of emission and environmental impacts. Furthermore, cascading of waste timber can be impacted by durability measures, such as chemical treatment, and impurities, such as fastener remnants or paints (Faraca et al., 2019, Heräjärvi et al., 2020), which reduces the effectiveness of this approach.

Figure 2 illustrates how the CE not only offers opportunities in the biosphere through cascading or recycling of timber materials and fibre, but also in the technosphere through repair, maintenance, reconfiguration, adaptation, disassembly, and reuse of timber buildings, as well as their components and materials. Both spheres need to be considered holistically to maximise circularity potential and minimise product and resource loops (Jarre et al. 2020).

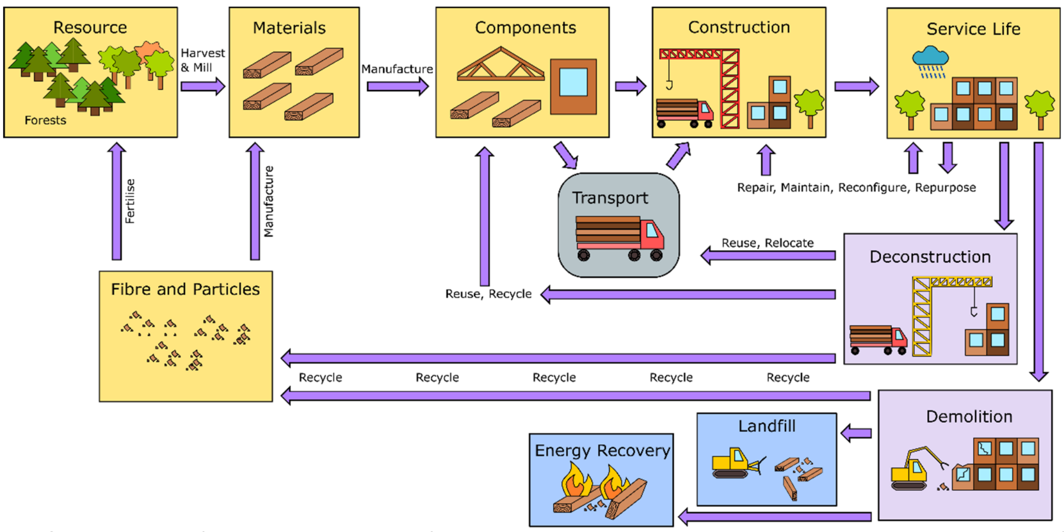

Figure 2: Opportunities for circular design of timber buildings in the biosphere and technosphere. (Source: Ottenhaus 2022b).

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Properties of salvaged structural timber components: How to account for long-term loading effects given unknown load histories?

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1 General remarks

In order to reuse salvaged timber for structural purposes it is necessary to establish the remaining mechanical properties for the next service life. Generally, timber members need to be regraded / recertified / reclassified according to a standardised procedure before they can be reused. This needs to be done irrespective of the intended reuse configuration or application; the certification has to apply whether the component is reused in its original shape, quality and dimension, or serves as raw material for the production of new structural timber products, e.g. by cutting boards from large-dimensional beams as base material for glulam or other products. Establishing such reclassification procedures appears even more challenging than grading of new timber as there are some additional unknowns. One of these unknowns is the origin of the source material which may play an important role in the grading process, e.g. with respect to grade or strength limits. Furthermore, the original species might be unknown and assigning the correct timber species difficult (Crews 2007; Falk et al. 2008).

2 Effect of damage and imperfections

Another unknown is the effect of mechanical damage on the mechanical properties. However, mechanical damage is very common in salvaged timber members, including holes, slots, milling pockets from joints, etc. as well as wear and tear, and accidental damage from assembly / dismantling (see e.g. Falk et al. 1999). Falk et al. (1999), report that damage affected the strength class in 30 % of the cases and led to downgrading by one class on average. Kenneth et al. (2001), Fridley et al. (2001) and Falk et al. (2001) analysed the effect of fastener holes on the bending capacity of reused timber members. They found that structural reliability is significantly affected by the hole location relative to the edge, similar to the grading criteria for knots. As fastener holes simply cut fibres, unlike knots where fibres nicely flow around, they affect the resistance approximately similarly as knots of twice the diameter.

Checks and cracks caused by moisture variations (primary drying) and possible part-time overloading might further limit the residual mechanical properties. Green et al. (2001) analysed the effect of heart checks on the bending properties of 6 inches by 8 inches Douglas-fir timbers. They found no influence on the Modulus of Elasticity (MOE) but a 15 % reduction of mean Modulus of Rupture (MOR). Their study did not address the effect sampling might have on the distribution of juvenile and mature timber which in turn would affect MOR and MOE.

Even earlier, Falk (1999) reported similar influences of checks on MOR and MOE. Nevertheless, checks and cracks are expected to have a significant influence on the tensile properties perpendicular to the grain as well as shear because of the reduced cross sections. Rammer (1999) and Falk et al. (2008) report high amounts of shear failures in their bending tests on reclaimed timber members. Specimens failing in shear showed significantly lower resistances than new timber (Rammer 1999); however, as will be discussed further below, the contributions from checks and cracks as well as duration of load (DoL) effects are not clear.

1 Effect of load history, moisture, and creep

Structural timber components might suffer from some biological degradation caused by insects and decay, as well as weathering. Before reusing structural timber for a specific project, conditioning to a common target moisture content (MC) might be necessary, as the components might come from different sites and might feature different MCs. Another important aspect are so-called long-term loading effects, which affect both the serviceability and ultimate limit states design and corresponding material properties. With increasing duration of loading, these effects lead to increasing deformations, i.e. creep, as well as reduced strength properties, i.e. duration of load (DoL) effect or static fatigue. In addition, the residual capacities to withstand cyclic loading (fatigue) may be of interest. In the current European timber design standard EN 1995-1-1 (2014; EC 5) these long-term loading effects are considered via the creep factor k_{def} and the modification factor k_{mod}; EN 1995-2 (2004) introduces the fatigue factor k_{fat}. For new timber products and constructions, the factors k_{def} and k_{mod} are tabulated depending on the service class, as a function of the expected MC, and the structural timber product. Yet, if and how these or similar factors are applicable to salvaged structural timber components is questionable. The main challenge is the unknown load history and consequently the degree of utilisation in serviceability and ultimate limit states for each individual piece of timber as precondition to reliably predict the residual mechanical capacity.

Recently, Cavalli et al. (2016) summarised past investigations on aged (small clear) wood and salvaged (structural) timber. With respect to the potential change in mechanical properties over time they differentiated between wood and timber degradation, the former being related to the state of conservation (durability), and latter describing the effects on mechanical properties due to long-term loading. According to their review, previous research found that the elastic properties (MOE in bending, tension, and compression parallel to the grain) are overall not significantly affected by long-term loading (Crews 2008; Crews & MacKenzie 2008; Falk et al. 2008; Nakajima & Murakami 2008; Falk et al. 1999; Rammer 1999).

In contrast, their findings regarding structural strength are much more diverse. This is in part owed to the fact that strength properties of reclaimed timber usually only be estimated as statistical values from past experience and present material properties. For structural timber, the MOR was found to decrease over time (see also Crews 2007, 2008; Crews & MacKenzie 2008; Falk et al. 2008; Nakajima & Murakami 2008; Falk et al. 1999; Rammer 1999). Based on their findings, Crews (2007) and Crews & MacKenzie (2008) outline the necessity to consider DoL effects in salvaged timber and proposed to reduce the MOR by 35 %, 50 % and 55 to 60 %, respectively, for members featuring load histories of short term / low magnitude loading, longer term / high magnitude loading, or unknown load history.

For compression parallel to the grain, the conclusions are less consistent; for example, Crews (2007) report on a comparable reduction in bending strength of members cut out from the compression and tension zone of larger beams. However, compression parallel to the grain is correlated with density which remains constant over time; see also Falk (1999) and Falk et al. (2000). There are also no clear results for the tensile strength parallel to the grain. With respect to the shear strength and in reference to Rammer (1999), the negative influence of splits and checks is highlighted; only half of the strength of new timber are reached. Yokoyama et al. (2009) conclude that well preserved wood remains safe under adequate conditions provided it is not loaded perpendicular to the grain. They also observed a significant embrittlement in old timber loaded in longitudinal or radial bending whereas MOE and MOR in longitudinal direction and MOE in radial direction remained constant but MOR in radial direction decreased.

The inconsistency of results in literature may be owed to underlying assumptions of the different studies. Generally, it is difficult to obtain good reference values for salvaged timber and comparable new timber of similar strength grades. In addition, the preparation of specimens from salvaged timber itself frequently involves machining of cross sections for structural testing. In consequence, only a limited or specific part of the original cross section is tested to failure. Furthermore, the number of destructive investigations on salvaged timber is rather small and often very specifically related to the object from which the material was salvaged. Cavalli et al. (2016) conclude for the effect of time on the mechanical properties that this is complex due to a number of interacting factors, such as (i) the state of conservation, (ii) the load history, (iii) the original grade / quality, and (iv) influences from damage.

To sum up, there are several experimental studies conducted on timber members reclaimed after being in service for years, decades or even centuries (e.g. Erhardt et al. 1996; Yokoyama et al. 2009). However, experimental findings vary with respect to elastic properties and significantly vary with respect to strength values when members were tested to failure in bending, tension, compression, and shear, both for small samples and samples in structural dimensions. With respect to strength, the outcomes indicate either a significant loss in magnitudes usually predicted from current DoL models (e.g. Rammer 1999; Crews 2008; Crews & MacKenzie 2008) or even slightly increasing capacities over time (e.g. Falk et al. 2000; Chini & Acquaye 2001). Fridley et al. (1996a,b, 1998) conducted extensive experimental, numerical and reliability based analyses. They conclude that the missing observation of DoL effects in their experiments is not the result of overdesigned structures but rather the effect of differences between real and modelled loading, i.e. the shape of load impulses. They recommend also to redirect experimental investigations on DoL from long-term low-stress testing to short-term high-stress testing.

2 Grading of recycled timber and design regulations

A remarkable development with respect to regulations for salvaged structural timber components is the Australian interim industry standard for recycled timber (Crews et al. 2008; with Crews & MacKenzie 2008 and Crews 2007 as background). This standard provides visual grading rules for salvaged hardwood components and guidelines for designers with respect to design properties, bolt holes and notches, connections as well as on DoL effects. In term of classification, the standard indicates that elastic properties of salvaged timber are similar to new timber whereas for strength properties a declassification by two grades is recommended. With respect to characteristic properties directly regulated for each grading class, this declassification corresponds to residual values of 60 to 65 % for bending strength, 50 to 65 % for tensile strength parallel to the grain, 60 to 65 % for compression strength parallel to the grain, and approximately 70 % for shear strength, depending on the grading class.

Overall, half to two-thirds of the characteristic strength properties assigned visually to new timber are considered for salvaged timber. Consequently, well-known relationships between strength and elastic properties are significantly different, i.e. shifted between new and salvaged timber components. In contrast to new timber, however, the long-term effects of loading on reused timber are reduced due to the unknown but successfully passed load history. This is done by assuming five months to 50 years of accumulated duration of loading. Based on the regressive relationship between load level and duration of loading, different load-duration modification factors are recommended as follows: $k_{mod} = 1.00$ for short-term loads

(< five days), k_{mod} = 0.98 for service loads up to five months, and k_{mod} = 0.90 for permanent loads with a duration of > five months.

This somewhat counteracts significantly reduced strength properties, since the Australian Timber Design Standard AS1720.1 (1997) recommends k_{mod} = 0.57 and EC 5 k_{mod} = 0.60 for permanent loads in service class one and two. For connections in salvaged timber the same k_{mod} factors are recommended together with 20 % lower strength properties of timber in conjunction with fasteners, e.g. withdrawal and embedment. This is justified by the fact that density remains unaffected by long-term loading effects, and density is the only timber property considered when describing the interaction between strength properties of fasteners and timber, i.e. embedment, withdrawal and head pull-through. However, it is not clear to the authors of this contribution why strength properties of fasteners should be less affected than all others in case of salvaged timber as the capacities of fasteners are a system property dominated by the local resistance of timber against compression, tensile and shear stresses in interaction with the fastener. This circumstance is also considered in the design of new timber structures where strength properties of the timber itself and those in interaction with fasteners are treated equally, i.e. the same k_{mod} factors apply. With respect to salvaged softwood timbers and in reference to Falk et al. (2008) similar regulations as for hardwood timber appear applicable.

3 Next steps

Currently, DoL effects for new timber are being discussed by the scientific as there is so far no consensus on the DoL models. Several physically based models are available; however, they still require calibration of input parameters based on test results which in turn are based on different test methods. It is also not completely clear to what extend current DoL models are able to represent the long-term behaviour of timber considering the high variability of timber properties with respect to the type and direction of loading. So far, there is also no consensus nor sufficient knowledge on the accumulation of load cycles in a static fatigue sense; analogies to dynamic, cyclic loading (fatigue) may provide a solution. Furthermore, the way test data are processed before DoL models are calibrated may have a significant influence on the outcome; methods like the equal-rank assumption need to be evaluated in more detail. Given that background, the aims of the envisaged study with focus on long-term loading effects on the mechanical properties of timber are to:

- expand and summarise the literature and re-evaluate existing data sets with respect to potential counteracting effects from partly deviating timber qualities in reference values compared to that of reclaimed timber;
- deepen and expand the knowledge on long-term loading effects on timber and joints in timber as preparation of a sound basis for possible regulations for salvaged timber;
- additionally, and exemplarily analyse long-term loading effects by means of reliability methods;
- develop proposals on how to regulate long-term loading effects for salvaged timber considering the following unknowns: load history and the number and duration of past service lives.

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Quantification and classification of salvaged timber components via Bayes updating

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1 Introduction

In order to ensure that salvaged structural timber (products and components) will be used widely again for structural, load bearing purposes a sufficient evaluation procedure is essential. Within such procedures, for example, it has to be ensured that timber with environmental degradation, or at least the degraded parts of the components, are excluded. Furthermore, the mechanical properties need to be quantified and classified accordingly. In principle every kind of available information, such as load history, various non-destructive and semi-destructive inspection methods, could be considered for such an evaluation. Therefore, the development and establishment of widely applicable standardized procedures are crucial.

Depending on the amount of the available material, its dimensions and the type of engineered wood product different procedures might be suitable. Considering e.g. the reuse of individual timber boards (or squared timber components) a detailed evaluation of the load history as well as time (and cost) intensive inspection methods might be disproportional to the economic gain. This needs to be considered although their general reuse potential might be high as such members may be reused directly for similar purposes in original or slightly reduced dimensions or serve as base material for structural timber products such as glued laminated timber (glulam; GLT) or cross laminated timber (CLT). In contrast, the reuse of the main structural components from a larger timber hall that will be demolished may be associated with sufficient value so that a detailed investigation becomes efficient, also from an economic perspective.

Missing regulations for the evaluation and reuse of load-bearing timber construction products according to their original purpose or as a base material for, for example, glulam and CLT, together with the conflict between the social mandate to use resources sustainably (and in the sense of a circular economy) and the constraints of economic considerations are seen as the main obstacles for the establishment of appropriate frameworks and possibilities. The aim of this contribution is to present a framework which is formulated on a mathematical sound basis, capable to handle in principle all possible types of information and an essential part in future regulations handling the reuse of salvaged timber.

2 Framework to estimate the mechanical properties of timber elements

The information for estimating mechanical properties of timber elements can be of very different nature; for example, it can origin from various building phases (e.g. the planned conditions) and different hierarchical levels of data collection, (e.g. (partly) known load history; results of various non-destructive and semi-destructive inspection methods (see e.g. Dietsch and Köhler 2010 for an overview of different inspection methods). Dependent on the investigation, however, different types of information are collected. They can be grouped as direct and indirect information, and as equality type and inequality type information (see Köhler 2006). For examples, see also Table 1.

A framework to consider different types of information is Bayes updating. For the procedure a prior information that can be quantified needs to be available. Such a prior information can be e.g. the planned conditions (if available) or an expert opinion; obviously the prior information is associated to uncertainties (see e.g. Rackwitz 1983 or Köhler 2006 for more information). Depending on the type of information different updating procedures are available, see e.g. Rackwitz (1983), Faber et al. (2000), Faber (2012), Fink and Kohler (2014). In Fink and Kohler (2015) a framework for the estimation of the strength properties of existing timber structures using Bayes updating is presented. Although the selected investigation methods might be different, the general principles are also valid for the estimation of mechanical properties of timber elements for the purpose of reuse.

3 Showcase – reusing glulam beams

There are several possibilities to reuse (or recycle) large-dimensional glulam beams. The ideal case might be reusing without any further processing. Obviously, the options to reuse large-dimensional timber components are limited because they are usually designed for specific structures and use. Considering smaller geometrical adoptions (planning, end cutting, etc.), the scope of possible applications will increase, however it might be still limited. Anyhow, from a structural engineering perspective, a reliable estimation of the mechanical properties would be needed. Table 1 shows a compilation of information from non-destructive inspections and evaluations, classified according to the type of information for the estimation of the strength properties.

Table 1. Examples of different types of information for the estimation of the strength properties of glulam beams based on non-destructive inspections and evaluations.

Direct & equality type information
- Destructive testing is the only possibility to get direct and equality type information. For the quantification of an individual structural component this is not possible (as the component is damaged after testing). However, for the estimation of the strength properties of a set of glulam beams (assuming they belong e.g. to the same strength class, fabricated by the same producer, etc.) destructive tests performed on selected samples could be used to estimate the strength properties of the entire sample.
Direct & inequality type information
- Load history: the bending strength of the beam in the past was at least as high as the bending stresses caused by loadings at that time; because of duration of load (static fatigue) effects in timber and possible additional damage in conjunction with high loading meanwhile the bending strength might be lower. At the same time, the information of survival together with the duration of load effects can also be used to exclude low realizations of the basic population (Kohler 2014). - Proof loading: the bending strength of the beam is at least equal to the bending stresses from proof loading. As before also here possible damage needs to be considered.
Indirect & equality type information
- Stress waves or ultrasonic runtime: e.g. estimation of the strength properties based on the dynamic modules of elasticity using correlation models. - Deformation measurement: e.g. estimation of the strength properties based on the static modules of elasticity back calculated from deformation measurements from well-defined static systems and loads by means of correlation models.
Indirect & inequality type information
- Status inspections (e.g. visual inspection, environmental conditions, moisture content, cracks, endoscopy); please note: such inspections can be very useful for the identification of environmental degradation, however, for the purpose of a quantitative assessment they are of minor importance and thus not further considered here.

It should be noted that for reusing entire glulam beams several aspects, besides the estimation of the mechanical properties, need to be considered. Examples are CE marking and material storage. An alternative approach could be the further processing into smaller components (e.g. glued solid timber elements with standardized dimensions) or components with common cross sections that are acting as base material for glued products such as glulam and CLT for which thin resawn products of such glulam members might be used as single layers. The potential to reuse small-dimensional components without changing their original cross sections might be easier in particular when the cross-sectional dimensions are somehow standardized. This is in particular true for glulam beams featuring a homogeneous layup whereas the possibilities are limited in cases of heterogeneously built up glulam beams. Regarding the quantitative assessment the same NDT methods as presented in Table 1 are suitable, however, especially regarding the destructive tests a significantly larger sample might be possible. Furthermore, existing strength grading methods (both visual and machine grading) can be applied, and the results can be used to enhance the estimation.

4 Conclusion and outlook

Reusing salvaged timber elements can result in environmental and economic benefits. For example, addressing global warming, extending the life-time of structural timber products directly impacts the carbon storage capacity of timber and opens up possibilities to use new timber for others than structural purposes. One challenge therefore is the quantification of the mechanical properties, in particular of strength values. In this note the estimation of the mechanical properties by using Bayes updating is shortly introduced. In principle the same approach can be also extended for the evaluation of timber connections or even entire structural systems. This could also be potentially used for the evaluation of existing buildings, for example for the sake of adoptions or renovations.

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Design for disassembly - learning from traditional and contemporary building techniques - case studies

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1 Introduction

The concept of performing a design process while taking into consideration the future disassembly and the possibility of further using the structural elements after the end of usage of the building is a up-to-date research topic due to the fact that contemporary constructions are responsible for a high use of various materials and a significant amount of the generated waste. Still, the concept of designing a building while thinking about a future disassembly is not a new concept. It is a principle that has been common since neolithic times, especially in the case of timber structures (Crowther, 1999). Tents or other similar shelters were built using timber structural elements, simple joints, and perishable exterior materials, which made their disassembly easy. The same can be observed later on, in the case of roof structures where timber elements were reused from one building to another (Keller, 2020). This was only possible due to the use of traditionally crafted timber joints, with steel of timber pegs, which allowed easy disassembly and reassembly in the new place.

2 Principles and practices

The concept is defined by a set of principles which make the whole process of repair, reuse, upgrade, and even disassembly of a building during various interventions or after its end of life, while still highly complex, easier to follow (Bertin et al., 2022; Crowther, 2018; Tleuken et al., 2022). The main principles are as follows:

- The use of materials that can be reused, in a different context, or recycled makes wood a suitable material for buildings that are designed while also considering future disassembly
- Use of joints that are visible and easy to reach so that proper maintenance is possible and disassembly can be performed without affecting the structural elements.
- The use of connections that can be easily disassembled. In the case of timber structures, traditionally crafted joints using timber or steel fasteners have proven to be efficient over time.
- The use of few/similar types of connections, structural elements and modules in order to make the assembly and disassembly of the building easy and less time consuming
- Designing structural elements that can easily be transported on site, or from one site to another

3 Traditional building techniques

To better understand the concept of circular economy and the principles of design for assembly as a first step, the knowledge of design and construction during major historic periods was analysed. The construction history shows that the Dfd principles, which are now a up-to-date research topic, were already used for most of the historic timber structures (Crowther, 1999). An interest towards following principles was observed:

- Use of timber elements with dimensions which can make them easy to be handled and development of connection joints which allow the increase of their length

- Clear assembly rules that make disassembly easy
- Clearly numbered timber elements to identify their position during the assembly, and to be able to further reuse the components after the end of life of the structure.
- Clear design rules using a small number of timber element cross sections and repetitive joints, in order to encourage a future reuse of the structural components
- Possibility of replacing certain components of the structure if they suffer damages due to the use of traditionally crafted timber joints with wooden and steel fasteners

These principles were also observed during comprehensive studies conducted on historic timber roof structures in Europe(Keller & Mosoarca, 2017; Mosoarca & Keller, 2018). Roof structures represent one of the most complex databases concerning traditional building techniques and detailing, a database that can be used as inspiration for contemporary timber buildings, since the construction techniques have proven their efficiency over time. The study has shown that these structures were designed and built with respect to a series of strict geometric principles defining the cross section of the timber elements and their position. The structures have a repetitive pattern, being altered only to comply with certain architectural/aesthetical requirements. More than this, up until the beginning of the 20th century the structures were marked with a carpenter mark, in order to be able to identify the craftsman involved in the construction process, and numbering signs, placed on each timber element, used to identify matching structural elements and be able to join them in the correct place.

The connection between the linear timber elements was made using a great variety of joints, which can be divided into four main categories: tenon and mortise joints, notch joints, lap joints, and scarf joints. All these joints were additionally connected by using wooden pegs or later on in the twentieth century by steel pegs.

The reuse of timber roof structures can sometimes be observed in the case of buildings that suffered damage or changes. In most cases a series of mortise cavities or signs of previous joints can be observed in the area of the main structural elements, which is a clear proof that the structures were disassembled and adapted to a new context and comply with the new structural requirements (Keller & Mosoarca, 2017).

The same was observed in the case of traditional log buildings, both religious and residential (Isopescu & Stoian, 2019) throughout the world, which were built taking into account future necessary interventions/repairs or changes and are therefore already designed for disassembly. The joints used were also made to facilitate the disassembly of the building and its reconstruction in a new place if necessary.

Both cases highlight not only the possibility of reusing timber structural elements, but also the need to clearly understand the dependency between elements, both structural and nonstructural, and how each layer of the building can be adapted or reused without affecting the others. Only in this way, all the components, load-bearing and nonload-bearing materials of a building can be disassembled while preserving the service and aesthetic qualities with minimal alterations.

4 Contemporary building techniques

A series of studies have also been performed on the potential of using the design principles for disassembly in new timber structures. All of them show that the concept has to be considered from the early design phases of a building, significantly influencing not only the architectural layout of a building and its load bearing structure but also all the other professionals involved in the design process. Still, they highlight that despite the effort, this type of approach can be a real alternative to current demolition practices (Rios et al., 2015).

One of the most recent studies on this topic (Piccardo & Hughes, 2022) consists of a comprehensive study on a series of case studies. Case studies, identified in a list of reviewed articles, were designed considering the reuse of timber elements, some after the end of the building's useful life, and other by reusing salvaged structural elements. During the study, all case studies were analyzed on the basis of a series of criteria.

- Joint configuration and its ability to be disassembled after the end of life of the building
- Relation dependency refers to the effect the disassembly of certain elements will have on the integrity of other structural and nonstructural elements. This feature greatly influences the service life of reused structural elements (Galle et al., 2017; Vandervaeren et al., 2022)
- Level of prefabrication referring to structural components or modular elements that were designed and manufactured without considering their subsequent disassembly
- Recovery of salvaged wood and adaptable building layout, depending both on the considered construction system and its ability to also include salvaged timber elements.

Studies highlight that if the Design for Disassembly concept is taken into consideration, important decisions have to be taken from the first design phases, so that the structural or nonstructural elements are manufactured taking all these principles into consideration so they can be adapted over time.

Therefore, starting from these principles and all the principles characteristic for the Design for Disassembly concept, a series of additional case studies (Table 1, Table 2) in order to bring forward how the concept is approached by different professionals.

Case studies in the field of design for future disassembly are surprisingly few taking into consideration the history of timber structures and their adaptability and even fewer that use only timber. Still, a special interest was observed for demountable structures in the case of the modular structures developed for the Solar Decathlon competition (EFdeN, 2022; Roofkit, 2022), where all the DfD principles are identifiable since the developed structures have to be easy to build, transport, and most of all easy assembled and disassembled, while taking into consideration current standards and norms like energy efficiency or acoustics. More than this, many of the developed structures are modular, offering the possibility of adapting the building during its use. They represent therefore an important base for future studies concerning DfD.

Table 1: Case study analysis – basic data

Case study	Country	Year of construction	Function	Height	Structural system	Structural material
Woodcube (ArchDaily, 2013)	Germany	2013	Residential	5 stories	Reinforced concrete core Solid cross-layered panels	Timber and Concrete
Nest We Grow (ArchDaily, 2015)	Japan	2014	Public	4 stories	Rammed-earth walls and timber column beam	Earth and Composite Timber
VATRA Prototype(EFdeN, 2022)	Romania	Concept (2021-2022)	Residential	up to 6 stories;	Panels + timber columns	Timber
RoofKIT(Roofkit, 2022)	Germany	Concept (2021-2022)	Residential	Up to 3 stories	Beam and column	Timber

Table 2: Case study analysis – DfD related principles

Case Study	Joint Type / Material	Joint dissasembly	Possibility of considering a circular system	Dependency between elements	Prefabrication	Dimension of elements
Woodcube (ArchDaily, 2013)	Wood plugs	yes	yes	no	Yes, pre-fabricated walls and slab panels	medium
Nest We Grow (ArchDaily, 2015)	Traditional inspired + Steel	yes	yes	no	yes	small - linear elements
VATRA prototype (EFdeN, 2022)	Steel	yes	yes	no	yes - modular	small - panels
RoofKIT(Roofkit, 2022)	Reversible - No glue or sealants	yes	yes	no	Yes – prefabricated structural units	

5 Conclusions

This paper comprises the main design principles identified after the analysis of the literature on DfD. The study focuses on historic timber structures that were built using traditional building techniques and reversible joints and have therefore become suitable for disassembling after the end of life of the building but also on contemporary buildings, already designed considering their future disassembly. Based on the analysed paper and identified case studies, it can be observed that the topic is currently insufficiently approach despite the EU recommendations.

At the same time, despite the suggested design guidelines, the principles are insufficiently defined and leave room for future interpretation, standards and norms are not suitable to encourage the use and reuse of structural and nonstructural elements. This can be observed in all the analysed case studies which still highlight the struggle of identifying suitable solutions. Therefore, it is of utmost importance, by focusing on circular strategies for timber structures, to further develop DfD principles and include them in contemporary design standards. This has to be done through the involvement of all types of professionals from the early design stages to be able to coordinate decisions and find proper solutions while respecting the Dfd principles.

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Barriers to design for disassembly and reuse of timber and lifecycle potential of service time expansion

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1 Obstacles to Design for Disassembly and Reuse (DfDR) of Timber

Although not extensive, the literature on the design for disassembly and reuse (DfDR) of timber increased quickly in the last couple of decades (Thormark, 2001; Crowther, 2005; Gorgolewski, 2008; Hradil, 2014; Diyamandoglu & Fortuna, 2015; Huuhka, 2018; Cristescu et al., 2021; Sandin et al., 2022; Piccardo & Hughes, 2022). Nevertheless, despite the increasing body of research on the subject, Cristescu et al. (2021) point out that for the established knowledge to become valid and guide decision-making in practice, a more detailed set of principles is lacking, linking appropriate strategies to each stage of design or construction.

In that regard, Cristescu et al. (2021) identified three main obstacles hindering a more widespread DfDR of structural timber. (1) Building regulations present the first hindrance, as the same procedure for grading new timber should be employed to assess the strength of reclaimed components. Without this step, even perfectly reusable and high-added-value load-bearing components must be downgraded and applied for non-structural purposes (Hradil et al. 2014). (2) The second challenge refers to building demolition processes and has a fundamental and evident role in the recovery of quality material for reuse. Yet, demolition methods are rarely considered in the design phases and construction of buildings, often driven by economics and time constraints. That, in turn, leads to demolition practices that rely on heavy equipment, damaging otherwise good material, and thus hindering its reuse or recycling (Chiara and Hughes, 2022). As an example of the importance of demolition methods, Diyamandogly (2015) studied the potential for the reuse of light wood framing systems and stated that around 25% of wood-based materials could be reused but only when soft-stripped. (3) Finally, architectural obstacles provide the third barrier to timber DfDR in construction. Beyond the hindrance of grading and demolition methods above, the simply high variability of pieces in terms of length, section, and looks creates a substantial challenge related to dimensional coordination, thus generating a higher design burden. Hence, designers sometimes perceive DfDR as if they are taking increased risks by specifying components with less predictable characteristics (Gorgolewski, 2018). Moreover, the second obstacle of demolition is also defined during the design process, leading Hradil et al. (2014) to conclude the greatest impact on a building material re-usability derives from its design stage.

Likewise, after developing a qualitative case study of five buildings, Sandin et al. (2022) found design aspects such as reversibility of connections, easy access to components, and standardization of parts to be essential principles for an increased DfDR of timber. Similarly, a recent case study research by Chiara and Hughes (2022) corroborates the idea that designers play a substantial role in enhancing the reuse of wood. They concluded that end-of-life management is often not part of the design process, frequently resulting in fixings and joints that are difficult to disassemble. The authors then propose dividing DfR strategies into upstream and downstream groups of activities to tackle the full scope of DfR strategies (Chiara and Hughes, 2022). Upstream activities are developed in the design phase to facilitate future timber reuse, especially in the maintenance and end-of-life phases. Downstream activities concern the salvaging of wood from buildings during renovation, deconstruction, or demolition, followed by their (re)use in a new building.

However, Chiara and Hughes (2022) warn that both upstream and downstream strategies implementation are more complex than conventional wood use as it entails specific expertise concerning the material-efficiency design of buildings. As the implementation of strategies to recirculate wood in constructions is relatively recent, expertise is still lacking, and standard procedures are fragmented. (Chiara and Hughes, 2022). In a study evaluating the significance of architectural design for reclaimed timber reuse, Huuhka (2018) found the inherent material properties to affect the whole spectrum of architectural design. Due to the lack of realized projects reusing timber in a downstream direction, Huuhka (2018) developed a theoretical design exercise with students leading to 10 relevant practical design guidelines. The study by Huuhka (2018) is cited in the recent literature, thus achieving a real impact in the field and portraying one path where educational activities can contribute to improvements in real-life practice.

2 Lifecyle benefits of DfDR and DfA (Design for Adaptability)

The literature on the environmental impact of the construction sector consistently favors wood-based building materials as a means to reduce GHG emissions due to the biogenic carbon content in wood (Gustavsson & Sathre, 2006; Robertson et al., 2012). However, studies also showed the uncertainty of biogenic carbon benefits as it varies depending on a specific time scale and adequate end-of-life (EoL) scenario for wood-based products (Börjesson & Gustavsson, 2000; Gustavsson & Sathre, 2006). Hence, a considerable number of more recent studies on the LCA of taller timber buildings also started to tackle the time dimension and its influence on environmental performance (Pittau, 2018) (Head, 2020) (Zieger, 2020) (Morris, 2021) (Resch, 2021) (Göswein, 2021) (Robati, 2022). The dynamic LCA studies quantify the extended effects of biogenic carbon storage in fiber-based materials aiming for more accurate assessments of its impacts on buildings and materials. Those studies conclude that considering an expanded time horizon, sometimes up to 500 years (Zieger, 2020), is beneficial to fiber-based products (Zieger, 2020) (Resch, 2021). The results also show that when the timing is considered, the faster the growth rate of fiber-based materials, the more beneficial it is in the short term, which gives an advantage to straw, hemp, and cork over wood (Pittau, 2018), although the differences between fast- and slow-growing biomaterials level out in the long-term (200 years horizon) (Göswein, 2021). In the same line, recent papers started to stress the relevance of the end-of-life scenario and further potential for mitigation of extending the lifespan of buildings and materials through strategies such as design for adaptability, disassembly, and reuse to increase the time-related benefits of wood-based materials (Morris, 2021) (Resch, 2021) (Kröhnert, 2022) (Robati, 2002). Likewise, Passarelli (Passarelli, 2018; Passarelli, 2019) reiterated the critical role of EoL and demonstrated we can improve the environmental benefits of wood construction by reclaiming and reusing wood-based materials instead of combusting or composting them. Nevertheless, the former study uncovered two critical unforeseen practical challenges of reuse. Designing from reclaimed materials led to an increased design burden and high material loss from remanufacturing as elements were not optimized for reuse. The results of the LCA review, therefore, reinforce the findings about the main barrier for a more widespread implementation of DfDR.

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SG Repairability and maintenance

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Repairability and maintenance of timber buildings – need for future timber buildings

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1 Introduction

The topics of circularity, adaptability, repairability, and maintenance are currently broadly discussed in architectural and structural research and also in the focus of this COST Action. All of them aim at reducing the sustainability impact of buildings.

Maintaining the existing building stock for its planned service life and beyond is the most efficient way to preserve the materials' grey energy within the building stock and prevent unnecessary consumption of new resources and energy for their replacement. In addition, maintenance of existing timber buildings ensures continuous carbon storage, which contributes to the transition to resource-efficient buildings to meet the climate challenge and achieve a sustainable society.

However, the relevant international standards lack effective design guidance to quantify and verify the performance of existing timber structures. Design guidance and recommendations for structure maintenance, assessment, and repair need to be developed and disseminated to practice. That way the sustainable use of the resources in buildings will be ensured.

Repair and maintenance of timber structures has been in the focus of many research projects and programs in the past. Within this COST Action CA20139 the focus is set on modern taller timber buildings, in contrast to much previous research on historic buildings (such as (ICOMOS 2008)).

2 Terminology

2.1 Maintenance

According to (BSI 1984) "Maintenance is the combination of the technical and associated administrative actions intended to retain an item or system in, or restore it to, the state in which it can perform its required function".

2.2 Repair and Reinforcement

An inspection, structural analysis, and verification may conclude that repair is necessary to restore the damaged or deteriorated structure to its original condition.

Reinforcement is according to (SIA 2011) a measure to improve the load-bearing resistance and serviceability of a structure or component. (Branco et al. 2021) gives a recent overview of different reinforcement methods.

3 Demands for maintenance and repair

Examples of aspects that may require the need for adaptability of structures can be summarised as follows:

- Changing user demands on a building and structure
- Changing structural demands

- Repair of damages
- Upgrading due to increased regulatory demands (e.g. energy saving requirements)

Addressing these aspects already during the design stages of a building will strengthen the confidence in timber buildings and support the wider use of timber in buildings. In a research project carried out in Sweden in 2019 (Jockwer et al. 2020), a high interest of building stakeholders & insurance companies was identified in interviews regarding solutions to mitigate the effects of fire and water damages. Property owners showed a high interest in maintaining the value of their property through repair and maintenance.

4 Examples of need for repairability and maintenance

4.1 Critical details

Due to its natural composition wood can show biological decay when exposed to unfairoable environmental conditions over longer time. Maintaining and ensuring the optimal environmental conditions for the wooden members can enable a maximum service life of a structure. Some examples of critical details that may require repair are:

- Problems with details at e.g. balconies etc
- Water damage on a floor due to leakage
- Damage of an interior wall due to leakage of a kitchen pipes
- Moisture damage behind a shower unit due to crack in the sealing
- General problem with flat roofs
- Local fire damage in parts of a building

4.2 Challenges regarding repairability

The need for repair of damages often raises a variety of challenges:

- How can damaged elements be repaired?
- How can elements be disassembled and re-connected
- Conflicts with different users in a larger timber building
    - Exchange of walls or floors affects multiple parties
- Large elements
    - How to exchange an entire floor or wall?
    - How do you get an entire floor or wall in place (e.g. center of a building)

Robustness is most often referred to in the context of avoiding disproportional collapse of structures. However, more general robustness should limit the extent of disproportional consequences of an event. Hence, robustness frameworks can also be applied to non-structural events and damages that might for example cause disproportional costs or impacts. Having this in mind the possibility for an easy repair should be considered already in the planning phase of the building. Easy detailing, which allows for disconnection, exchange, and replacement can facilitate the repairability of a structure considerably. This includes also the separation of members with different function in a structures, such as envelope elements in the façade and the main loadbearing structure.

5 Importance of enhanced maintenance

General

- Implementation of NDT and updating in the maintenance and repair process
- Risk based maintenance and repair for optimisation of intervals and actions

Some specific aspects

- Central and accessible installations
- Monitoring of structural details (e.g. post-tensioning)
- Accessibility of neuralgic members and details (e.g. major joints, structural systems, post-tensioning)
- Areal moisture monitoring

6 Repair and maintenance in previous research programs, projects, and existing guidelines

6.1 COST Action FP1101

COST Action FP1101 “Assessment, reinforcement and monitoring of timber structures” had the objective to increase the acceptance of timber in the design of new structures and in the repair of existing structures by developing and disseminating methods to assess, reinforce and monitor them (Harte and Dietsch 2015).

The COST Action was structured into three working groups: Working Group 1: Assessment of timber structures, Working Group 2: Reinforcement of timber structures, Working Group 3: Monitoring of timber structures.

6.2 Guidelines

6.2.1 Standard SIA 269

The Swiss Standard series SIA 269 covers the basis for examination and interventions for existing structures and the subsequent series covers specific rules for actions on existing structures and for the different building materials with timber being covered in Standard SIA 269/5. An introduction into the standard series is given by (Brühwiler et al. 2012). It is pointed out that interventions (operational and/or constructional) need to be optimised and the issue of proportionality of an intervention needs to be addressed in this context. Some aspects related to the maintenance and rehabilitation of timber structures are pointed out by (Steiger 2010).

6.2.2 CEN/TS 17440

CEN/TS 17440 (CEN 2020) is a technical specification documents by CEN on “Assessment and retrofitting of existing structures” that was published in 2020. Similar to Standard SIA 269 it covers the basis of design. It is specified in its introduction that the rules in the Eurocodes (EN 1990 and following) are primarily intended for the design of new structures. CEN/TS 17440 is intended to supply additional or amended provisions in order to apply the principles of EN 1990 also to existing structures. More specific application rules focussing on timber structures are still missing on European level.

7 Implementation and need for further development

Considering the repair of a building holistically a strategy against unforeseen events and consequences already in the design will help to ensure the long-lasting performance, efficiency, and sustainability of timber buildings.

In order to facilitate repairability and maintenance of buildings in practice it is necessary to work towards specific education of engineers and architects, authorities, other stakeholders such as insurance companies and develop adequate guidance documents. In addition, robust details need to be developed in collaboration with practitioners and manufactures and established in the market and industry.

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(P)Re-paring taller wooden buildings: Building enclosure detailing importance in durability of non-transparent envelope

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Timber structures are prone to damage due to nature of the wood as an orthotropic material with properties different in different sides of the element (timber is strong along the fibres, but very weak across them), also, it creeps with time, which can be critical in heavily loaded structures like tall timber building (Voulpiotis at al. 2021). Complex phisical and structural properties in timber structures leads to neccessity to design these structures through details by taking into consideration durability, maintainability, fire safety regulations, building physics and indoor air quality parameters. Besides that separate parts in the building play different roles, the composition and interaction between these is even more important.

This paper aims to show how the adequate design of details, layers, joints, and other elements affects the need for restoration and repairs. Inadequate approach to the selection of materials, poor joints or penetration between different elements are the primary factors influencing later problems in the use of buildings, thus necessity for the repairs. They can lead to envelope disassemble, appearance of moisture, mould growth, discoloration, falling out of segments or connecting elements from the envelope etc. A special reflection will also be made on the relationship of well-resolved details (mainly non-structural) to internal comfort in terms of the thermal characteristics of the space as well as the quality of the living space in general.

Indoor Environmental Quality (IEQ) of buildings include aspects of the built environment that affect occupant health and well-being, and commonly includes factors such as indoor air quality, thermal comfort, visual comfort and acoustic comfort (Arif et al. 2016). All these parameters are affected by the building envelope performance as a boundary between the indoor space, and user behaviour and the external influences of the environment.

For tall timber structures, the design of the building envelope damage due to long-term exposure to water and short-term and long-term shrinkage that can occur as a result of structural loads or changes in moisture content (Green and Taggart 2017) since timber is hygroscopic material which degrades significantly when it remains wet for a long time (Voulpiotis at al. 2021).

1 Building envelope components overview with specific role in physical performance of the envelope

According to Voulpiotis et al. (2021) wood is shown as a material with numerous benefits, however, it also comes with great challenges that need to be taken in consideration such as: sensitivity to moisture, light weight, othotrophic properties, low stiffness, brittleness, system, size and time efects that influence on overall perormance of timber structures. The above properties make the design of a timber building everything but straightforward, particularly at larger scales. The most complex part of the building in terms of building physics is certainly the envelope, which affects both physical properties and quality of life of the tenants.

In order to design structure which is both structurally robust and cost-optimal, integral design principles include thermal specialists which track suitable conditions under environmental changes, building physicists which are researching material mutual behaviour within complex envelope structures such as moisture control and thermal conductivity, architects capable for managing complex details and detailed designs, HVAC engineers, structural engineers and contractors, shall be involved in the panels' design phase (Gajić et al. 2020).

It is necessary to look at what makes up one envelope, after which the combinations of materials and the places where conflicts occur should be examined in order to provide high quality details that will eliminate the need for major renovation projects. According to (Green and Taggart 2017) main envelope components are listed below:

- **Thermal insulation** is only one of many components that make up the building envelope, although is the most important in terms of energy conservation and thermal comfort. Certain thermal insulations have high fire resistance (rock wool), high level of water vapor diffusion resistance (vacuum insulation panels), humidity control and noise reduction. All insulation materials have their own strengths and weakness, and these should be evaluated primarily against the design, durability, cost-effectiveness, and environmental impact criteria.
- **Vapor barriers** are used to control the diffusion of water vapor through the building envelope and prevent vapor from condensing on colder surfaces as it migrates through the assembly. Vapor barriers are most important in cold climates in which the need for heating predominates, as well as in the buildings with different heat zones where heat flows are significant (Čvoro and Peulić 2019). Barriers are installed on the interior side of the insulation in most wall and roof assemblies, and typically consist of a coating, a membrane, boards or other rigid materials. In both thermal insulation and vapour barriers some other influential parameters can disrupt these orders, etc. buildings under protections, when some contemporary materials and details need to be consulted; in either way these materials need to have as low coefficient of thermal conductance, high level of fire resistance, and ability for vapour diffusion conduction. (Gajic et Al. 2019)
- **Air barriers** can be used anywhere in a building envelope assembly to stop the movement of air into or out the conditioned space and control heat losses or gains and moisture transfer. Air barriers can be in form of wraps, self-adhered membranes, spray-applied materials, rigid sheets, or any other layer that prevents the passage of air. The key concern is that it must be continuous with lapped joints if it is film or membrane, sealed joints if it is of panel construction – and all penetrations (pipes, ducts, windows and doors) must also be sealed.
- **Finishing layer, or sometimes called water-resistive barrier,** is the one mostly exposed to the environment. It is most prone to damage both from the inside and outside. In case of wooden structures most often it is about light materials that can be easily replaced. Mostly, this is about mechanical types of connections, although the use of construction adhesives is not uncommon either, which only apparently accelerates construction, but in fact are dependent on the temperature and humidity on the construction site, which cannot be controlled. It is positioned within the wall assembly to protect vulnerable components from damage caused by water penetrating the assembly from the outside. The first line of defence is often a rainscreen cladding system, in which the cladding is fastened to vertical battens mounted on the exterior face of the wall assembly. Aging of materials, especially wood, should be seen as a natural feature and the details should be adapted to that feature. Here, the most important features are actually the type of wood, the way it is processed, as well as the

layers that occur in the background, considering that the biggest problem can be caused by simultaneous atmospheric influences from the outside and water vapor from the inside.

Besides above mentioned, there is additional one which can contribute to overall durability:

- **Installation systems** – Although they do not belong to the envelope layers, the installations are located within the walls, both internal and external. Therefore, it is necessary to classify them as potential elements of conflict that lead to the destruction of the internal structure of the wall and actually represent one of the most common problems of the appearance of moisture, mould, material deformation, and therefore the need to, very often, replace the entire wall. Here, special attention should be paid to water and sewage pipes, which, in addition to damaging the integrity of the wall, conduct matter in a liquid state and at different temperatures, whose leakage can damage severely integrity of the layers, walls or even whole building in case of late detection and untimely reaction.

2 Thermal performance and moisture flows treatment

In order to be durable and to avoid necessity for often repairs a building detailing has to be made right. It is necessary to ensure several things while making detail designs and follow these on construction sites. Firstly, it is necessary to control that presence of moisture in building materials is on adequate level during transportation, installation and usage phase. The moisture content of the wood components should not exceed 19%. As the enclosure consists from multiple layers with specific roles in building physics properties, problems can occur on the joints, overlaps, gaps and penetrations. Thus, it is crucial to ensure air-tightness of the building – thus install details with membrane overlaps and correct array of the layers and avoid thermal bridges on connections. Thermal performance of a building depends not only on the continuity of the air barrier, but on the integrity of the insulation. In the solid portions of walls or roofs, thermally conductive components should not penetrate the full depth of insulation as they will create thermal bridges, where heat loss or condensation will occur. Predict continuous thermal insulation on opaque part of the envelope including balconies, overhangs etc. Occasionally, penetrations are unavoidable, so each has to be designed carefully to ensure continuity of other materials. Common practice is that balcony structures do not penetrate buildings' envelope - they are independent structures suspended by rods that are attached directly to the external wall structure (but do not penetrate the insulation). Windows and door frames that penetrate the full depth of the exterior wall assembly must be thermally broken with insulating material separating the various parts of the frame or constructed from non-conductive material such as wood or fiberglass. Predict installation shafts for ease of maintenance and ensure that sewage and water pipes are reachable and well-connected during installation.

3 Problems detection

Non-destructive methods make it possible to see the problem without revealing the structure. This significantly reduces the time it takes to find defects and reduces the amount of waste generated as a result of renovation. Thermal imaging can show different wall temperatures, which can be associated with the appearance of moisture as well as cracked pipes or dew on metal pipes. Micro cameras allow detailed inspection of the pipes, so the cracks can found precisely and later logistics can be developed on which part of pipe needs to be replaced. There are many sources of building moisture, including humidity, condensation, pipe leaks, rain and snow, and even people and animals breathing. A thermal imaging camera cannot "see" moisture in walls, but it can detect subtle temperature differences and patterns that reveal the existence of water. (Flir 2019)

4 Conclusion

The work presented physical properties of the envelope with overview on specific role of each material in the ensemble. The complexity of the design including numerous actors need to provide an integral thinking on timber structures in order to reduce the demand for the repairs and avoid collisions and material decay. Further work can go with analysis of good case study examples with focus on three points: layering of the facade, installation systems inside the wall and protective coverings.

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Horizontal topics

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Computational methods supporting design for robustness, reuse and repair

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1 Introduction

Addressing robustness, adaptability, disassembly, reuse and repairability in the design of taller timber buildings as strategies towards more sustainable buildings requires the integration of a large number of divers, interacting and often contradicting design parameters into the design process of buildings and their construction elements. Complex design is driven by a variety of relevant performance parameters creating a solution space beyond the regular expectable design space. Solutions where the various design aspects accumulate to an effective, efficient construction will be rare peaks in large and cliffy solution spaces characterised by a high level of customisation and differentiation. Specialised and differentiated construction elements require customised fabrication methods with a high level of precision. Computational processes from design to fabrication and robotic production provide an efficient and seamless materialisation of highly customised construction members. Robotic assembly complete the digitised and computational workflow from early design stages to the actual erection of the building.

Replacement or relocation of elements require robust information about the element and its properties. Digital models of the element and the respective constructive environment are indispensable to enable competent decisions on potential reuse of parts.

Numerical simulations based on digital models are essential to evaluate the quality of a design solution. Combining simulations with parametric models and optimisation engines provides a design environment where form could be found on a data informed basis aspiring to fulfil relevant objectified design goals.

Robustness, reusability and repairability are major contributors to sustainability not only but also for taller timber buildings. Computational methods are concerned with the robotic or digitalised fabrication of constructions and its elements, the assembly of discrete elements, with the topological and geometrical description of construction elements and their relations as well as with the description and integration of material properties into these processes.

This is a collection of contemporary techniques, methods, case studies and concepts within the realm of computational methods which are directly or indirectly addressing robustness, reusability or repairability. The report investigates the pathways of academic research and the contemporary application thereof in practice.

2 Computational Design

2.1 Multi objective optimisation

The design of sustainable taller timber buildings is a challenging task demanding multiple design parameters to be considered within the solutions. The integration of material or fabrication related aspects into the design process culminate into a complex design process. Considering the robustness of these buildings and their elements, their repairability or their potential reuse after the end of the building's life, add to the complexity.

Multi-objective optimisation methods provide simulation-based results to inform design decisions in complex design scenarios to address building performance and other design criteria. Transformation of the abstract design goals into parametric description of the geometry and comparable evaluation is key to successful optimisation algorithms. Evolutionary genetic algorithms are robust and therefore generally suitable for design problems. (Spaeth, 2016) Due to contradicting and overlapping design criteria optimisation procedures typically provide a multitude of comparably good solutions in a pareto front rather than a single optimal solution.

The adoption of computational tools is highly dependent on their accessibility which correlates directly with the necessary expert knowledge and level of necessary computational accomplishment. Visual user interfaces and graphical illustration of results increase the acceptance of such tools as within i.e. Rhino Grasshopper and respective plugins. (D'Agostino et al., 2021) (Joyner et al., 2022).

2.2 Generative evolutionary algorithms

Simulations used as evaluation systems in evolutionary design systems demonstrate the robustness of the evolutionary algorithm in ill-defined design environments and the ability to generate form on the basis of given output criteria. Generating form with target design parameter is viable as a proposed design system generating form on the basis of acoustic and geometric target criteria proved in concept. (Spaeth, 2016) Although demonstrated on acoustics and geometric criteria as design drivers the complexity and nature of simulations could be potentially transposed into the realm of timber constructions.

2.3 Neuronal Networks

Neuronal Networks (NN) a section within in the realm of Artificial intelligence (AI) artificially remodels the communicative system of the neuronal activity in brains. Neuronal Networks can be trained to make informed decisions on specified problems. NNs can be trained with data from simulations which they learn from. After training the NNs are capable of applying their acquired knowledge onto new, unknown situations. Training data of parameterised school buildings in correlation with simulated daylight metrics enable the NN to predict daylight situation for new constellations within the school building without the need of time-consuming simulations. (Lorenz et al., 2018) The implementation of design solutions proposed by a Neuronal Network on a parameterised geometry model considering complex daylight predictions, indicates a potential use in a design environment for timber constructions.

3 Computational Fabrication

3.1 Robotic fabrication

A digitalised workflow with digitalised planning models, to an explicit digitalised representation of construction elements enable the direct and seamless robotic fabrication of the respective elements. Robotic fabrication enables individualised mass customisation within differentiated design solutions at reasonable costs. The robotic customised fabrication of the differentiated joint design provides an alternative to conventional steel-timber or timber-adhesive joint solutions. The high level of precision and the ability to articulate every single joint according to its structural and geometric need is achievable through the digital process and the robotic fabrication. (Robeller & Weinand, 2015)

3.2 Reuse of elements

Combinatory algorithms allow to efficiently rearrange elements. If the properties of the elements are sufficiently described the elements could be used in different buildings at suitable positions. As demonstrated with the parametrisation, individual adaption and the joint of gross tree trunks, the potential of this technique to be adapted for the reuse of elements within the timber construction of taller timber buildings appears viable. (Geno et al., 2022). Elements are often designed for a specific use, due to efficiency reasons. Therefore, the reuse of elements could be limited since they may only fit the exact position and situation they are design for. However, with a detailed and exact parametrisation a suitable reuse or a consecutive adaption might be possible.

3.3 Robotic assembly

Robotic assembly of timber elements is not yet implemented into construction practice but it is subject to academic research. Timber members are connected either in a construction site scenario, where the robots operate on site or a prefabrication scenario where the robotic fabrication occurs in an industrial workshop. Industrialised prefabrication is common practice in other industries but still underdeveloped in most parts of the construction industry. However, timber construction is already ahead in terms of prefabrication where construction members are prefabricated with CNC machinery but the actual assembly of elements is mostly manual work. Practical applications of autonomous robotic assemblers for taller timber buildings are obvious and desirable since a higher level of automatization and industrialisation potentially reduces costs and dependencies on weather or other site conditions. Basic research (Leder et al., 2019) demonstrates that the concept of autonomous robots crawling the construction while building it up is viable. Robots, consisting of rotational gripper heads use one side to hold itself and the other to place a new member into the construction.

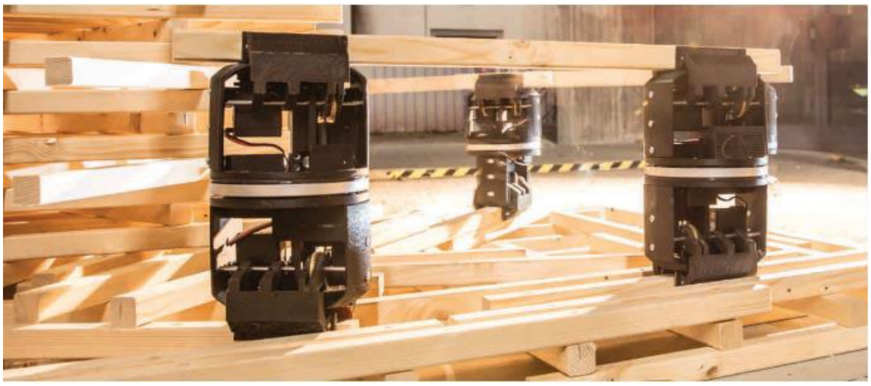

Figure 1: Distributed Robotic Timber Construction (Leder et al., 2019, S. 510), with permission by ICD Uni Stuttgart©.

Apparently, this is early stage research, where the material supply, fixing of elements and the larger distance movement are to yet to be solved. However, it provides a prove of a general viable concept.

Prefabrication of timber constructions as an adaption of already know by conveyor band production in other industries differs by the need of individual elements, since buildings are not produced as a recurring mass product but as individual solutions for specific design problems. While elements within one building recur in small series a highly adaptable and individualised production line is required. Even timber-only joints with rather complex geometry and assembly conditions can be handled with high precision and reliability. (Helmreich et al., 2022).

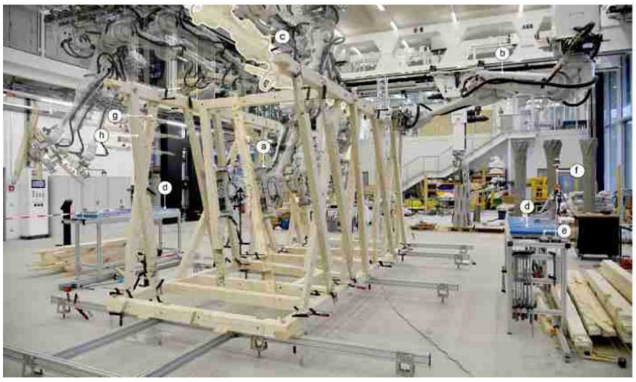

Figure 2: Robotic assembly system (Helmreich et al., 2022), with permission by Gramazio Kohler, ETH Zürich ©.

Robotic handling of the construction and its elements require full digital models since members and their individual positions need to be identified unequivocally. Industrialised and automated production of elements allows for high precision and individualised design of elements which increases robustness, repairability and reusability. Digital models and the corresponding industrial production allow for identical reproduction of elements if needed for repair.

4 Conclusion

Although the timber construction industry appears to be at the fore front of computational design and fabrication methods the construction industry as a large seems to be slow in adopting innovative methods into their processes. While the design often is already accomplished digitally the production is predominantly manually and on site, with low levels of industrialisation compared to other industries like for example the automotive industries. Academic research demonstrates already the general potential of an applied digital process including design, construction, fabrication and erection. The mentioned projects demonstrate that the computational methods and the integrated a digitised design-fabrication process are at the fringes to be adopted into practice.

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