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DESIGN FOR THE FUTURE – VERSATILE, RELOCATED AND VERTICALLY EXTENDED TIMBER BUILDINGS FOR A CIRCULAR ECONOMY

Karin Sandberg[1*], Frida Görman[2], Janina Östling[3], Alar Just[4], and Ylva Sandin[4]

[1] RISE Research Institutes of Sweden, WoodTech

[2]IVL Swedish Environmental Research Institute

[3] IsoTimber Holding AB

[4] RISE Research Institutes of Sweden

*Corresponding Author: karin.sandberg@ri.se

ABSTRACT

Background and aim. Developing timber buildings suitable for deconstruction, reuse, and adaptability in practice is challenging and complex. The project "Design for the Future - Reuse of Timber Buildings in a Circular Economy" developed two concept buildings to be reused with preserved functionality. Focus was on environmental benefits and was obtained through collaboration within the circular value chain and according to real estate developers' requirements. One building featured industrially manufactured volumes designed to be relocated and rebuilt. The other was an adaptable building with planar elements, designed to be flexible, relocated and vertically extended with two added floors.

Methods and Data. The concept method, a co-creation process, was used that involved possible scenarios, construction, deconstruction, reconstruction, waste management and estimation of reusability. The method SimFORCE, Simulation for Future Oriented Reuse and Circular Economy, was developed. Evaluation of reusability and preserved functionality was conducted in cooperation with expert groups. The climate reduction potential of reuse was analysed using Life Cycle Assessments.

Findings. SimFORCE helps identify whether structures are designed for deconstruction or need improvement. Further, the results were useful in preparing and writing deconstruction and reconstruction guides. Climate calculations show a significant reduction in environmental impact when buildings are reused.

Theoretical/Practical/Societal Implications. With SimFORCE, two timber buildings were demonstrated as possibly being reusable with preserved functionality (structural, acoustics, fire resistance, etc.) with a considerably reduced climate impact. Assessments were based on profound knowledge and experiences of the building systems, deconstruction and testing. The actual buildings have not been deconstructed and rebuilt.

KEYWORDS: Adaptability, Co-creation, Design for deconstruction, Reconstruction, Reuse

1 INTRODUCTION

Global consumption of materials is expected to double in the next forty years (CEAP, 2020). The Circularity Gap Report (CGR, 2024) shows that the share of secondary materials is barely 7.2% in 2023, steadily declining since 2018. It also mentions that construction and demolition processes drive nearly one-third of all material consumption. Therefore, the total amount of materials consumed by the global economy is expected to increase, out of which most extracted materials entering the economy are primary. It can be concluded that there will be a material shortage if we do not leave the linear economy and make more use of the earth's resources. We also need to reduce emissions of greenhouse gases due to the climate impact. The built environment, including

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housing and commercial buildings, is essential for our quality of life. About 40% of global greenhouse gas emissions can be attributed to buildings' construction, use and demolition (CGR, 2024). The European Commission adopted the new circular economy action plan (CEAP, 2020), one of the main building blocks of the European Green Deal, Europe's new agenda for sustainable growth. The EU's transition to a circular economy will reduce pressure on natural resources and create sustainable growth and jobs. It is also a prerequisite to achieving the EU's 2050 climate neutrality target. Building with wood has, therefore, become more critical since it is a renewable building material. However, it must be used efficiently and in accordance with the waste hierarchy and should be used as long as possible as a building material. A considerable amount of wood from the building stock can be available for cascading and second use (Nasiri et al., 2021) and recovered wood from the building stock could potentially be substituted into products (Höglmeier, 2013). Achieving this requires meticulous deconstruction of buildings and careful handling of materials. Research and development in recent years have increasingly transferred from a linear to a circular economy. The European project InFutUReWood investigated, for example, how we should build today to be able to circulate tomorrow and compiled findings on design as well as material (Sandberg et al., 2022). Several publications supporting the development of design for adaptability have been published (Ottenhaus et al., 2023) and constructions in circular economy (Çimen, 2021). Still, it is highly complex to manage the development of a fully circular building. It is used over a long period of time and consists of thousands of components. Sandin et al. (2023) support designers and industries applying Design for Deconstruction and Reuse and Adaptability (DfDR/A) to interpret ISO 20887:2020 by providing practical examples from case studies. Jockwer et al. (2020) mention the lack of existing methods to evaluate the performance of the dismantled elements before reuse as one of the reasons that the circularity concepts are not yet effectively established in timber buildings. This can also be due to considering buildings long-lasting and not anticipating disassembly and reuse of their elements.

1.1 AIM OF THE STUDY

The aim was to contribute to a deeper knowledge of how to build today to simplify future reuse and preserve the earth's resources, by developing concept buildings demonstrating reusable timber structures with preserved functionality. The intention was to create timber buildings adapted for increased circularity through Design for Deconstruction, Reconstruction and Reuse (DfDR&R). Environmental benefits and collaboration in the circular value chain were in focus. This was to be done by theoretical simulations to obtain more reusable designs in a process that relied on qualified estimates and calculations based on today´s knowledge and experience.

2 METHODS AND DATA

The work was part of the project "Design for the Future - Reuse of Timber Buildings in a Circular Economy" and two concepts with the following scenarios were investigated:

- The Modular Building: a timber building with industrially manufactured volumes designed to be relocated and reconstructed (elastic).
- The Adaptable Building: a timber building with planar elements, designed to be flexible and versatile, relocated and vertically extended with two added floors (elastic).

The concept method is described in section 2.1-2.6 and is illustrated in Figure 2. A workgroup conducted the concept studies in a co-creation process with the following assumptions and limitations. Anticipated scenarios and developed concept buildings are based on the knowledge of the project participants, and the processes are based on current industrial off-site timber-building techniques in Sweden. This involved reviewing technical solutions, theoretical and practical studies of building processes, testing and calculations, transport, storage and business models through work meetings, drawings and document studies, and building regulations and standards reviews. Requirements of real estate developers were included.

Definitions were used according to EN-17680:2023.

- Adaptability, is the ability of the object of assessment or part to be changed or modified to make it suitable for a particular use. Adaptability can be subdivided into functions of flexibility, versatility and elasticity of the building, part of or group of buildings.
- Flexibility is related to changing space distribution within the existing building unit.
- Versatility is related to changing the use of the building.
- Elasticity is related to changing the volume of the building space either outside the existing building unit or addition of a new building(s) within the site.
- Reuse is an operation by which products or components that are not waste are used again for the same purpose for which they were conceived or used for other equivalent purposes without reprocessing but including preparation for reuse.

2.1 CO-CREATION IN THE CIRCULAR VALUE CHAIN – THE TEAM

An essential part of the project was to engage the circular value chain for residential buildings, from procurement and planning and manufacturing to building and waste management, in a co-creation process to understand and cover the whole process of a building's life. More than 30 persons have participated to varying extents in the "Value -Chain-Team". The two concept buildings are based on the needs of the project participants in the role of clients, property developers, owners and managers, and the municipality as an authority. Implementation and assessment of the structure's functions are based on

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existing knowledge of multistore timber buildings, off-site manufacturing methods, building at the construction site, component suppliers and transportation. Co-creation and a common goal were created through regular documented meetings with presentations and discussions and several workshops using visual work platforms (i.e. Mural) with a digital whiteboard.

2.2 SCENARIOS AND REQUIREMENTS

The results depend on the anticipated scenario. The assumed life cycle impacts the reusability of the building or the building component suited for its purpose. The project discussed what to reuse, the entire building or a structural part of it, and for how many times. The building's functional performance, required by the client, a user, or by regulations, also affects the outcome. Therefore, the anticipated scenario must be described for the building and the client's requirements (procurement) must be documented. Moreover, an execution plan for the simulation process and competence requirements for the evaluation process and the Expert Team (see section 2.3) are needed. Additionally, the boundaries and system limits that apply in the LCA must be specified. Scenarios in this project were determined through several workshops. The scenarios for the buildings were summarized in PowerPoints, presented and discussed at meetings, and thereafter reviewed in Word and Excel.
Questions that the Value-Chain-Team arose in the process were for example:

- How should we design for reusability, to maintain value and functional qualities for optimal reuse, deconstruction, and reconstruction to accommodate reapplication for the same purpose or adaptability?

2.3 SIMULATED DECONSTRUCTION, RECONSTRUCTION AND ADAPTABILITY

The project developed a method for a theoretical simulation of the possible reuse of a building, i.e. SimFORCE - Simulation for Future Oriented Reuse and Circular Economy. The method is based on today's knowledge and consists of several steps as described in section 2.3.1. The simulation method assumes an initial building design (Design 1) to be assessed and developed into an improved building design (Design 2) optimizing the initial building (Phase 1) for deconstruction and reconstruction (Phase 2). To help structure the complex and iterative work answering the questions and scenario while developing Design 2, the SimFORCE method was used. With the purpose of finding an improved structure adapted for deconstruction, the method is based on the already existing 'case study method' (Sandin et al., 2022). Within this project, the 'case study method' was complemented with a functional analysis (i.e. assessment of preserved functionality) to predict the outcome of deconstruction, relocation and reconstruction at a new site, but also an assessment of possible adaptability.

The method is based on the collective assessment of reusability and functionality by an Expert Team with diverse competencies and extensive experiences about the building system to be evaluated. In this project a profound knowledge in timber buildings were present, with experience from construction, deconstruction and reconstruction. The members were Quality and Product Engineers, R&D Managers, Designers, Structural Engineers, Constructors, Production Managers (including building planners), Sustainability Managers and Research Engineers in Wood Technology. Simulations were done for the two concept buildings, with different Expert Teams of 4-7 participants per session. Verifying new, improved solutions may require practical tests and lab experiments if functional performances are unknown and difficult to estimate. The estimates of material consumption, energy consumption, etc, have been used in the LCA calculations.

2.3.1 Simulation by the SimFORCE method

To make the work logical, Excel sheets could be used that are prepared by a process leader experienced in building techniques, leading the work and asking supplementary questions to the Expert Team. The Excel should consider topics such as those specified in Figure 1.

2.4 ENVIRONMENTAL EVALUATION

To evaluate the potential from circular construction and reuse a life cycle assessment was carried out for each of the concept studies in this project. The assessment was conducted to gain knowledge of potential benefits as well as to identify climate driving factors.
The climate calculation using LCA-methodology was based on the chosen scenarios and collection of data formed in mentioned process conducted by suppliers, manufacturers and architects. The life cycle stages assessed are cradle to gate (A1-A5) as well as energy use for deconstruction (C1). The assessment includes the entire building from the foundation to its insulation. The LCA were based on the following standards: EN 15978:2011 for buildings and EN 15804:2019 for building products. The calculation was performed using the Building Sector's Environmental Calculation Tool (BM 3.0). The tool contains a database with generic LCA data representative of the Swedish construction market, as well as generic data for waste and transport.
The result is reported in global warming potential (GWP), measured in kilograms of carbon dioxide equivalents (kg CO_2e), and includes the greenhouse gases carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). Scenarios for reuse and reconstruction assumed to occur in the future was calculated based on current knowledge. This means, for example, that future scenarios for the climate impact of building materials have not been applied.

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Step 1. Scenario and background.	
Define the background and the scenarios to anticipate the clients' brief/requirements and demand levels, whether to investigate on a system level or element level.	
Step 2. Suggestion of initial design suitable for customer requirements (Design 1) for the first life cycle (Phase 1).	
Describe the building system, how it is assembled (drawings) with text describing crucial components such as junctions, wall elements and other technical details that are important for Design 1 for the first life cycle (Phase 1).	
Step 3. Simulation of deconstruction.	
Identify (based on the structure in Step 2) and select possible areas to improve for an efficient deconstruction.	
Column:	**Activity**
1	**The assessment starts from top of the building**, going downwards the structure (material, component, structural) one Excel row for each part to be analysed.
2	**Comments.**
3	**Tools and vehicles needed.**
4	**Handling.** What happens to the part? Damage that occurs to components and materials from handling during deconstruction and reconstruction.
5	**Need for reconditioning, repairs and inspections.**
6	**Foreseeable problems with transportation or intermediate storage.**
7	**Predict material loss and waste.**
8	**Personal risk assessment**.
9	**Environmental risk assessment**.
Add columns for "Measuring performances" depending on scenario/client, for example from ISO 20887:2020. Describe the process, building, structure, how to deconstruct for reuse. Identify areas to improve. Necessary prework to perform before deconstruction etc.	
Step 4. Improved design solution (Design 2).	
The same layout and context as in Step 3, but with the modified and improved building/structure and solutions implemented (Design 2).	

Step 5. Assessing preserved functionality of Design 2 for the second life cycle (Phase 2).	
The initial building (Phase 1) has now theoretically been deconstructed, relocated and reconstructed. Based on previous work (Steps 2-4), now estimate, calculate, test the preserved functionality required for reuse. Describe how the functionalities are achieved and verified, or how to restore them, for Phase 2.	
Column:	**Activity**
1	**Functionalities.** List those identified as crucial, such as Airtightness, Stability, Acoustics, Fire resistance for structures etc
2	**Requirements.** List those related to the specific functionality.
3	**Class.** Specify if relevant.
4	**(A) Experiences.** Indicate facts/knowledge based on previous experience, competence, test
5	**(B) Evaluations/Calculations.** Estimate and/or calculate preserved functionality required for reuse based on standards etc.
6	**(C) Required lab tests.** Identify whether lab tests are required to ensure the functionality in Phase 2.
7	**Measures to consider.** Specify foreseen measures to be taken at the deconstruction and/or reconstruction to preserve or restore the functionality. Repair or replacement of components might be necessary.
8	**Assessment of functionality**. The Expert Team concludes whether the functionality can be preserved or restored (explain how in such case).
Step 6. Summary.	
Summarize the improved building design (Design 2).	

Figure 1: The structure of the SimFORCE method.

2.5 GUIDE FOR ADAPTABILITY, DECONSTRUCTION AND RECONSTUCTION

Crucial information obtained by the Expert Team in the simulation process (SimFORCE) was transferred to a guide for adaptability, deconstruction and reconstruction.

2.6 BUILDING DESIGNED FOR REUSE

The process of the concept method continued iteratively until conformity was reached within the Value-Chain-Team and the goals were complied. The documentation should be consistent in accordance with stated requirements. Any deviations from the requirements should be described in the documentation with clarifying explanations of why.

3 RESULTS AND FINDINGS

The main result was a concept method (3.1) to be used when designing new buildings. It was applied to two concept buildings (3.2, 3.3) and demonstrated useful for deconstruction and reuse scenarios. Theoretical studies were carried out for two Swedish industrially manufactured building systems based on the project members' requirements. It included determining possible scenarios, processes, and logistics, evaluating improved solutions, possible service life, waste management, simplified structures/components and material efficiency.

3.1 CONCEPT METHOD

The development of the concept took place interactively in loops during the project period and many companies have been involved in the process, see Figure 2. The focus was on reusability and to cause as little damage as possible during the deconstruction, relocation and reconstruction of the load bearing structure. Also, to keep functionality from the first life cycle (Phase 1) to the second life cycle (Phase 2). The analysis steps and loops enhanced an increased understanding of whether the technical functionalities were preserved or how they could be restored.

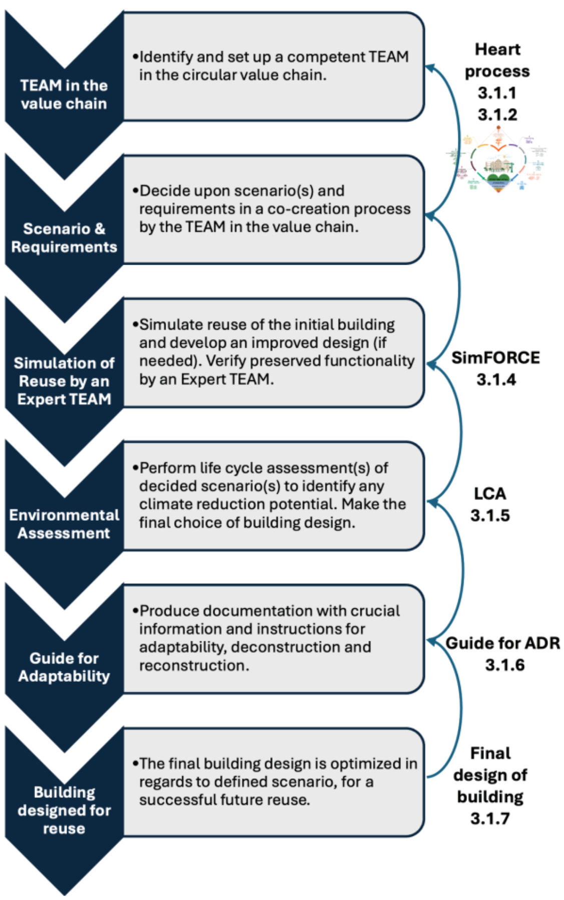

Figure 2: Method developed for the concept study in a co-creation process.

Industrial timber building process in Sweden

There are several ways to build in Sweden. The most common are frame structures of timber studs and/or lightweight beams (e.g. I-joists). Solid timber structures can be cross-laminated timber (CLT) or a post-and-beam structure made of glulam or laminated veneer lumber (LVL). IsoTimber is a semi-massive timber structure with a combined load bearing and insulating function. The building systems can be delivered to the building site as planar elements (panels), usually as walls and floor panels, or as 3D volumes (modules), which form entire rooms or apartments. Transport is usually conveyed by trucks. The industrially produced panels are assembled at the building site by contractors and completed to a building at a system level with plans for installations etc. The modules are built in the factory under the manufacturer's name and delivered to the building site, where the manufacturer's builders complete them (see Figure 3).

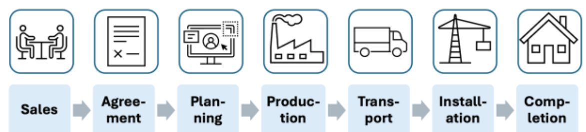

Figure 3: Industrially manufactured buildings in a schematic process of today.

3.1.1 Business in the Future Circular Value Cycle

The process for the first life cycle is known, but how will the deconstruction, relocation, and reconstruction of a building be managed in the future? The Value-Chain-Team identified that the process can be illustrated for a truly circular and sustainable building as in Figure 4. The complex process of finding a resource-efficient use of a building in its built environment, including its material use at any time, is explained in stages 1-10. Several new actors will be involved; for example, digital trading platforms and digital data management systems are under development. Therefore, the emergence of new actors will continue to enable the circular process.

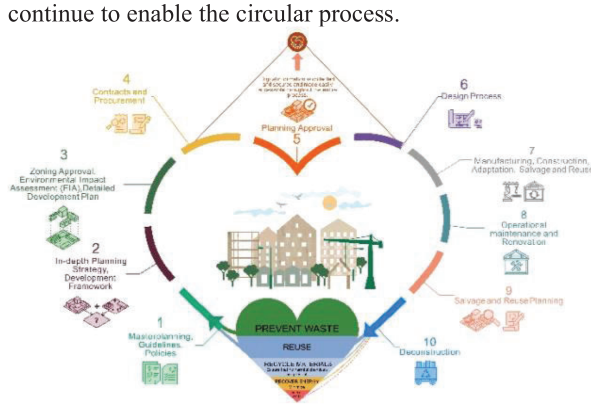

Figure 4: Circular value cycle process (the heart process) in 10 stages before the decision in the small heart: Prevent waste, Reuse, Recycle materials, Recover energy, and lastly Dispose.

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3.1.2 Identify the Value-Chain-Team and prepare for the concept study

The concept study was based on co-creation by a team in the value chain. It was important to identify members in the value chain who understood the challenge and the tasks. Relevant topics to discuss were, for example as listed below. The discussions led to agreeing on scenarios, client and general requirements, see examples in Figure 5.

- Contribution to circularity: Reusability was a priority, and the elements should be able to be reused after deconstruction. However, in some cases, it was preferable to repair or refurbish parts of the component after a relocation but before reconstructing the building so that it would last for many more years. An example of this was the sealing tape at element joints.
- The level of assessment, material, component or the entire building: The reuse was primarily on element and volume levels. Therefore, the focus was on element connections and identifying and finding important structural intersections to address in the guide for deconstruction.
- Management of the building foundation: Should it be relocated or not? Both options were explored.
- Relevant regulations and standards, both current and upcoming, and how to handle them in the simulations: The concept buildings are expected to perform with the same functionality after reconstruction as they do today, and the requirements are expected to be the same.
- Environmental and building requirements for new construction versus requirements for renovation/relocating the building and adaptation to new users.
- Verification of functional requirements: Since the Expert Team had a lot of experience in constructing timber buildings, but also deconstruction of buildings, transportation, etc, the requirements are based on existing knowledge, tests and calculation methods.
- Verification of the technical lifespan of materials: Systems are based on current communication and guarantees. Hence, if possible, environmentally friendly materials with a long technical lifespan, preferably more than 50 years, were chosen.
- The extent of documentation required, but also what kind of information should be saved for the future and who is responsible for archiving the information: Documentation as constructions and building documents, drawings, operational and maintenance instructions, material specifications, and structural documents.
- Content in a guide for adaptability, deconstruction and reconstruction of the building.

FUNCTIONALITIES TO CONSIDER

CATEGORY OF FUNCTIONALITIES	
	Structural capacities, such as vertical and foundations load bearing capacity etc.
	Healthy indoor environment, such as acoustics, emissions, temperature etc.
	Climate impact and other **environmental** impact, such as energy consumption etc.
	Certifications, such as today´s Miljöbyggnad silver, Svanen etc.
	Regulations by law, national, municipal and other local **recommendations**, such as and EKS and BBR in Sweden, and municipal strategies etc.
	Market requirements, such as an aestethic architecture etc.
	And many more functionalities and requirements that the TEAM in the value chain finds are important for the specific building to be analysed.

Figure 5: Other categories of requirements.

3.1.3 SCENARIO AND REQUIREMENT

The Value-Chain-Team defined and agreed upon clear scenarios and which requirements should apply. Scenario and requirements depend on each specific concept study. See section 3.2.1 for The Modular Building and section 3.3.1 for The Adaptable Building.

3.1.4 SIMULATION OF REUSE AND FUNCTIONALITY ASSESSMENT

Technical functionality requirements are very important to verify when reusing a building, and therefore, Expert Teams have worked with this task. The method is based on the collective assessment of reusability and functionality by this Expert Team with diverse competencies and extensive experience with the building system to be evaluated; see section 2.3 for the Expert Team in this project.

The development and evaluation process in the two concept studies followed the SimFORCE method described in section 2.3. Each study ending with an improved building design (Design 2) assessed its' preserved functionality to predict the outcome of deconstruction and reconstruction at a new site, but also an assessment of possible adaptability. See Figure 6 for a schematic overview of the functionality and fire safety assessed in the project.

Which functionalities should be assessed depends on the defined scenario and requirements; see sections 3.1.2 and 3.1.3. Each functionality should be assessed and documented according to the steps in the SimFORCE method. Three methods were considered: A: Experiences, B: Evaluation/Calculation and C: Lab test required. The Expert Teams decide which method to use or a combination of methods. However, the verification must be documented and clearly indicated in the final statement of the functionality assessment, along with any presumptions being made.

The project focused on reusability. Therefore, were minor damages and preserving the functionality from the first life cycle (Phase 1) to the second life cycle (Phase 2) assessed as the most favourable outcome. The standard ISO 20887:2020 provides examples of assessment criteria, see Annex C – Measuring performance, where C.5 "Ease of access to components and services" with a relative rating scale and C.9 "Supporting reuse (circular economy) business models" are valid for the evaluation.

EXAMPLE OF FUNCTIONALITY ASSESSED:
FIRE SAFETY

REQUIREMENTS	Sufficient fire resistance (REI30, 60, 90) according to EKS.
STANDARD/ CLASS	EN 13501-2
	EN 1995-1-2
A:EXPERIENCES	Personal: Participating in fire tests and analysing building parts.
	Facts: Fire stops can loose their functionality.
B: EVALUATION/ CALCULATION	Fire resistance calculations according to listed standards.
C: LAB TEST REQUIRED	EN 1363
	EN 1364
	EN 1365
MEASURES TO CONSIDER AT THE TIME OF REUSE	Evaluate protective boards (gypsum, plaster, wooden boards) – is there any presence of cracks, is the board thickness not valid or is there a presence of fasteners? If so, exhange the board.
	Check all fire stops, are they tightly fit to the joints? If not, replace the fire stop.
	Load bearing timber studs, are they of sufficient dimensions according to fire specifications? If not, strengthen the specific load bearing structural part.
ASSESSMENT OF FUNCTION 2:ND USE	The Expert TEAM assess that the building design will fulfill specified functionality at a future reuse. The assessment is based on A and B above, see (references) and presumes that indicated measures above are performed.

Figure 6: Examples of one functionality assessment, fire safety.

3.1.5 ENVIRONMENTAL ASSESSMENT

The environmental assessment findings are described under respective concept building; see sections 3.2.3 and 3.3.3.

3.1.6 GUIDE FOR ADAPTABILITY, DECONSTRUCTION AND RECONSTRUCTION

Valuable information is extracted using the SimFORCE method, as described in Figure 1. The information could be used to develop guides to facilitate the deconstruction and reuse of modules and panels, see Figure 7. Describing step by step, from securing walls and floors to fire safety and structural integrity throughout the deconstruction process to detailed descriptions of how to disassemble and remove installations, joints, elevators, balconies, stairs, access balconies, access balconies, roofs, facades, and finally lifting off the roof and then the volumes or planar elements for transport and storage. The deconstruction guide could also be complemented with a guide for reconstruction based on the functionality assessment. See the example in Figure 6.

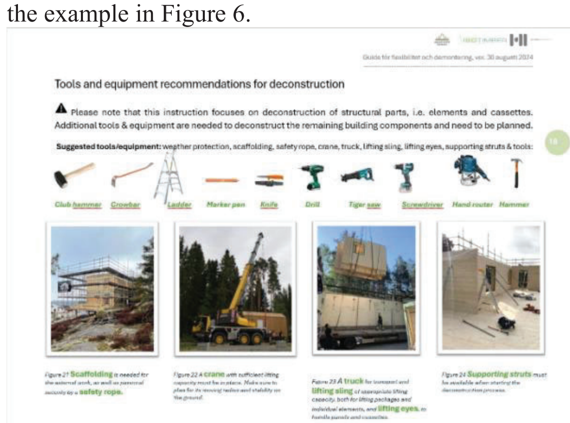

Figure 7: A guide for adaptability, deconstruction and reconstruction was developed for the Adaptability building.

Understanding the deconstruction process requires insight into the various steps outlined in Figure 3. During the initial building phase, there is a multitude of information about the building, including planning documents, drawings, and assembly instructions at the building site. However, this knowledge is often held by different people or departments. To learn more, meetings and discussions were conducted with individuals experienced in planning, industrial manufacturing, transport, and assembly at the building site, as well as the deconstruction of modules and planar elements. The assembly of the different parts and elements is planned during the initial design phase. Still, the deconstruction can be affected by the mounting and assembly at the building site and subsequent renovations and should be documented.

3.1.7 FINAL DESIGN OF BUILDING

The process, as described according to Figure 2, was completed. With quite an intense iterative looping, the project agreed upon two concept buildings that fulfilled the scenarios and requirements decided; see section 3.2 Concept - The Modular Building and section 3.3 Concept - The Adaptable Building.

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3.2 CONCEPT - THE MODULAR BUILDING

The Modular Building is based on the real estate developer Folkhem's planned five-storey high buildings at Klockelund in Farsta, Stockholm, Sweden, see Figure 8. The buildings should be certified according to the Nordic Swan Ecolabel Buildings. The requirements promote resource efficiency, reduced climate impact, circular economy and conservation of biodiversity.

Figure 8: Folkhem's proposal of a modular building in Klockelund in Farsta. Illustration by In Praise of Shadows.

3.2.1 Scenario, requirements and boundaries

The building should be manufactured with a frame structure of timber studs as 3D volumes, fully equipped with a kitchen and bathrooms delivered from the factory, assembled and completed at the building site with installations, roof and elevator shaft. The Value-Chain-Team concluded that The Modular Building was developed with the reuse scenario. That results in two phases:

- Phase 1 - Initial building, five-storey.
- Phase 2 - Deconstruction and relocation of the building to a new site (reuse). The foundation of the building is not relocated.

3.2.2 Simulation of deconstruction and reconstruction by SimFORCE

The building system is based on existing building systems from manufacturers of multistorey modular timber buildings in Sweden, Lindbäcks Bygg, Derome and OBOS. They agreed on one joint building design. Studies on design for reuse, separation, sorting, and handling of reclaimed timber were conducted in collaboration with personnel knowledgeable about the issues from various companies in the project. This was made in many sessions dedicated to the overall concept study process, as described in Figure 2. Two sessions were performed with Expert Teams in the SimFORCE process, see Figure 1, to develop improvements and evaluate functionalities. The manufacturers have deep knowledge and experience of their building systems and have the competence to assess improvements and functionality.

Findings of improvements of the building structure

Identified improvements were, for example, prefabricated roof cassettes. The reuse process and transport are more efficient if the roof structure is constructed in sections. Improved connections between volumes were developed for easier deconstruction and reconstruction. It is important to balance the 3D volumes precisely when lifting them at reuse, and a device was identified to get hold of and place the lifting slings easily.

3.2.3 Climate calculation and collection of data

The chosen scenario for the life cycle assessment considers the two phases of the modular building, which are considered two separate life cycles. The activities included in the two phases are:

- Phase 1: Initial construction. The assessment includes using primary materials and energy for transport to the construction site and the construction.
- Phase 2: Change of location (100 km) includes reuse of materials from Phase 1, energy use for deconstruction, transport and reconstruction and new materials used for parts that need to be replaced.

Material used for the foundation, frame structure, façade, roof and frame completion were determined and quantified through the project planning document. For interior surfaces and room completion, as well as installations (Technical installations (not solar cells) of timber building apartments), standard values were used (Malmqvist et al., 2021). Data on waste quantities and additional materials, as well as estimates of waste and energy consumption, have been provided by all three suppliers based on their building systems. However, when the building is reused in the second phase, the foundation, installations and technical equipment are assumed not to be reused. The interior surfaces and room completion are also assumed to have to be remade. These choices were made since the foundation cannot be removed and reused and not to overestimate the potential of what can be reused. The results from the climate calculation for Phase 1 and Phase 2 are shown in Figure 9. A considerable climate benefit, more than 50%, can be obtained in the product stage (A1-A3) by reusing materials from the initial building at a change of location.

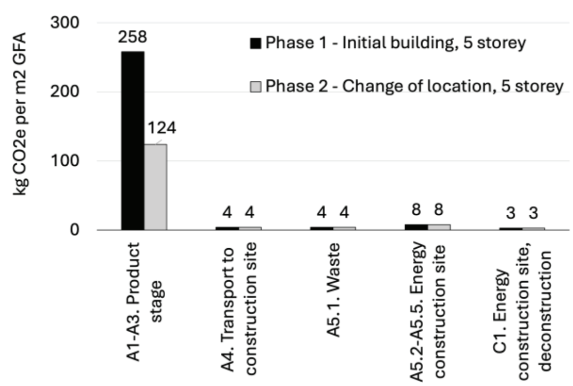

Figure 9: Climate calculations (kg CO2e per m2 Gross Floor Area (GFA)) for the initial building (Phase 1) and the relocated building (Phase 2), of the Modular Building.

3.3 CONCEPT - THE ADAPTABLE BUILDING

The Adaptable Building was developed based on the indicated needs of Skellefteå Municipality and Kiruna Bostäder AB (owned by Kiruna Municipality). They own buildings and rental apartments. Skellefteå Municipality is also an authority for building and demolition permits. They are in an expanding region in the north of Sweden and urgently need housing for entrepreneurs. However, it was identified that the property owner's needs will most likely change. In this case, from entrepreneur housing to student housing, or tourist accommodation. IsoTimber (supplier of external wall elements), Masonite Beams (supplier of floor/roof elements), and ETTELVA Architects jointly developed the new concept building. Figure 10 shows an illustration of The Adaptable Building.

Figure 10: The Adaptable Building was studied for different phases during its lifetime, from a new initial building to changes in layout (flexible and versatile), relocation and adding two floors (elasticity). Illustration by ETTELVA Architects.

3.3.1 Scenario, requirements and boundaries

Design for Adaptability (DfA) means both a flexible change, as in changing the space (layout) within the existing building, and versatility, i.e. changing the function or the use of the building, from larger apartments to tourist accommodation, for example. Further, the building can be adapted by adding new floors vertically (elasticity). The Adaptable Building should enrich its surroundings. Therefore, it was assumed that the building's layout and function change could be implemented in 20 years. A deconstruction and relocation of the building, for example, due to changes in infrastructure and new roads, is more likely to occur in a longer perspective, e.g. in 50 years. Hence, the building should also be designed for deconstruction, reconstruction and reuse (DfDR&R), with a foundation that can be relocated and reused. Based on these assumptions, the Value-Chain-Team concluded that the concept for The Adaptable Building should be developed regarding a scenario with four different life cycles (phases):

- Phase 1: The initial building, two-storey.
- Phase 2: Change of function and layout (flexibility and versatility).
- Phase 3: Deconstruction and relocation (100 km) of the building to a new site (reuse).
- Phase 4: Extension, from two to four-storey building (elasticity).

3.3.2 Simulation of deconstruction and reconstruction by SimFORCE

As mentioned earlier, general studies and co-operative learning occurred in the project, as described in Figure 2. Dedicated sessions with Expert Teams in the SimFORCE process, see Figure 1, took place 6 times for this concept building. Improvements were developed, and the Expert Teams assessed preserved functionalities.

Architectural design with flexibility in mind

The first life cycle (Phase 1) is planned as a two-storey multi-family house, with 2-room and 4-room apartments, that can be used as shared contractor accommodations. Design features included to maximize flexibility:

- Kitchens and bathrooms are concentrated around a combined shaft in the building's core to free up floor and facade space for varying rooms requiring daylight.
- The facade is well planned with generous, general, and repetitive window placements to divide rooms or move walls in a maximum number of different positions as needs change.
- Load bearing interior walls are not required as the flexible building systems from Masonite Beams and IsoTimber handle the spans through load bearing in the floor elements and outer walls.

At a later stage, if a change in layout is needed due to a change in functional requirements (Phase 2), the building can be adapted. This is possible by opening and partially removing the apartment-separating wall between the units while maintaining shafts and wet rooms, stabilising the building, and facades/windows in the same positions. According to the decided scenarios, the building should be able to be relocated (Phase 3) and extended with two floors (Phase 4). The building's climate shell and load bearing structure were specified, while the interior and technical installations were not specified or quantified and were included in the climate calculations by standard values.

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Findings of improvements of the building structure

The main improvement developed was a new connection detail at the junction between the external wall made of IsoTimber and the floor element built with I-joists of Masonite Beams. A consulting company assessed the acoustic performance of the new solution, and the fire safety performance was calculated and assessed as sufficient by members of the Expert Team.

It was identified that roof cassettes would minimize the need to remove the under-roof sheathing and parts of the roof and, therefore, would be preferable. The elements are easier to lift down, transport, and reuse. The lifting slings are left in place to indicate where to lift, but it is recommended to replace them if they are old.

The joints between elements are screwed, and that is a well-tried procedure and tested function. A problem might be finding the screw's right positions and uncovering them. There are different solutions depending on the joints. They can be covered with wear-layer or tape removed at deconstruction and replaced at reconstruction. It was suggested that panel joints can be clearly marked with a colour that is easy to find. The choice of screws can also be of importance, dimensions of screw-head and or replaced by wood screws. However, the performance needs to be tested and calculated before use.

3.3.3 Climate calculation and collection of data

The chosen scenario for the life cycle assessment considers the four different phases of The Adaptable Building which are considered for separate life cycles. The activities included in the four phases are:

- Phase 1: Initial construction. The assessment includes the use of primary materials and energy for transport to the construction site and the construction.
- Phase 3-4: Includes reuse of materials from Phase 1, energy use for deconstruction, transport, and reconstruction, as well as new materials used for parts that need to be replaced.

Material use for new materials for each phase was determined from the architectural drawings made by ETTELVA Architects, where amounts for the foundation, frame structure, façade, roof and frame completion were quantified. For interior surfaces and room completion, as well as installations (Technical installations (not solar cells) of timber building apartments), standard values were used (Malmqvist et al., 2021).

Data on waste quantities and additional materials and estimates of waste and energy consumption are the same as for The Modular Building.

When the building is relocated in Phase 3, installations and technical equipment are assumed not to be reused. The interior surfaces and room completion are also assumed to have to be remade. These choices were made not to overestimate the potential of what can be reused. However, the foundation can be reused compared to The Modular Building.

The results from the climate calculation for Phase 1 to Phase 4 are shown in Figure 11.

A considerable climate benefit, more than 50%, can be obtained in the product stage (A1-A3) for all scenarios (change of layout, change of location and extension).

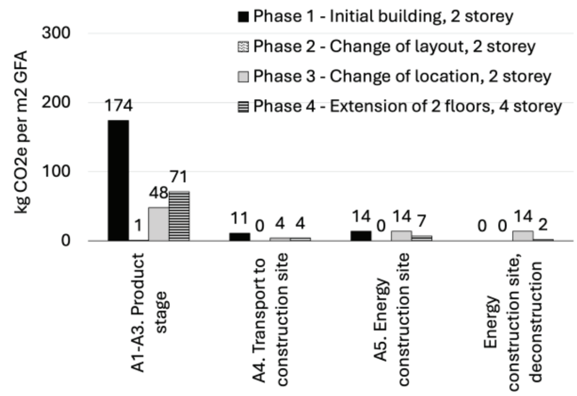

Figure 11: Climate impact (kg CO2e per m2 Gross Floor Area (GFA)) per respectively life cycle, i.e. Phase 1-4, for the Adaptable Building with planar elements, designed to be flexible, relocated and vertically extended with added floors.

4 DISCUSSIONS

Regarding results obtained by using SimFORCE, see 3.1.4 (Simulation of reuse and functionality assessment), the Expert Team must make sure to transfer any measures identified to be advantageous during reuse. The assumedly preserved functionality might be ruined if identified measures are not practically performed at reuse. For example, if the planar elements or volumes are not deconstructed carefully or connections are not exchanged as indicated, they might risk diminishing load capacity. The project identified the guide for adaptability, deconstruction and reconstruction as the best place to keep this kind of information today. Digital product passports are under development and might be a place to save information in the future.

To understand the complexity, the study identified that the SimFORCE method for a specific building with its defined scenario, covers mainly the right side of the circular value cycle process (heart process), see Figure 4. However, the scenario for the building also depends on the left side of the heart, for example procurement and building permits, but also the lower part (the small inner heart) as waste management and demolition plans. The circularity depends on the possibilities to implement the circular strategic 10 R's (Potting, 2017) and the cascading hierarchy.

Construction and assembly details and their practical implementation on the building site must be verified during renovation and deconstruction. The wear and tear of different parts after 50 years of use depends on the components' quality and position. Therefore, the deconstruction plan must vary depending on the building's structure and describe in chronological order what should be done, potential risks and tools needed. For deconstruction and future reuse, the components of the building must be thoroughly documented before construction. Describing elements, components, materials, weight, dimension, connection position, type of connections etc. The documentation should be digital as well as physically marked on the building elements. This is standard procedure in the prefabrication process used by current suppliers of panels and roof cassettes today.

The findings of this work indicate very positive outcomes of reusing timber buildings designed for deconstruction and reconstruction. Looking at the climate evaluations for the two concept buildings, it was clear that the largest climate benefits can be made by reusing the materials of the initial building in a second building. The climate impact in the product stage, according to A1-A3 in standard EN-15978:2011, could be reduced by 50% or more in CO2e/m2 GFA.

New building regulations are expected in Sweden in the coming years. Those will set limits for the CO2 emissions to be declared in climate declarations for the structural and building envelope. The results from the concept buildings are below today's anticipation of the coming limit values. For the Modular Building the assumed scenario was a change of location. As mentioned, the largest climate benefit is obtained by reusing material, see Figure 9. The impact from construction, reconstruction, transport, and deconstruction is less significant than the material impact. Regarding the Adaptable Building, four scenarios were considered. See Figure 11. It was clear that the largest climate benefits can be made by reusing planar elements and other large building parts to save material. Phase 2 (change of layout) and Phase 4 (extension) apply most reuse, even though Phase 2 shows the lowest values since very little material is added combined with low energy use. Phase 4, on the other hand, has added new material for two more floors which is why the impact is much higher than in Phase 2. Both Phase 1 and Phase 4 add material equal to two floors. However, Phase 4 shows less than half the impact from material use. This since both the foundation and the roof can be reused in Phase 4, while this is considered new material in Phase 1. Phase 3 shows less impact than Phase 4 but with a higher impact from energy use. It is also shown that the impact from construction, reconstruction, transport, and deconstruction is less significant when compared to the material impact. The lowest contribution is from the transportation of new and reused materials.

5 THEORETICAL/PRACTICAL/ SOCIETAL IMPLICATIONS

The concept method can be a strategic help to guide the process of defining which scenario(s) to aim for in practical cases when developing new circular buildings. This would encourage the industry to produce more buildings adapted for more efficient future reuse while making well-advised choices to keep the climate impact low. In the same way the method could guide buyers, such as real estate developers or municipalities, to assess which scenario(s) would best suit their situation and future.

The development of the concept buildings was based on the requirements of clients in the project and done by a team representing the value chain. Evaluation of preserved functionality for a second life cycle was based on the Expert Team's experiences of the building systems, building deconstructions, testing and modelling of structural engineering, fire safety and acoustics. The concept buildings have not been deconstructed, rebuilt, or tested in a laboratory. Even so, the method of simulating reuse, SimFORCE, was a valuable tool when developing buildings and a positive implication for society.

SimFORCE provides valuable understandings of the context and results useful when writing guides for DfDR&R&A, see Figure 7, which is practically useful for future building reuse.

A building consists of many different products and components with varying lifespans. The performance of reused building elements depends on components, the usage phase length, the construction type and load cases. Maintenance and renovation can also affect the performance. Potential damages depend on deconstruction or demolition, but also storage and transport. This affects the outcome, such as quality and maintained value. SimFORCE and the heart process (Figure 4) help to structure evaluation of the functional requirements for deconstructed, relocated and reused structures that need to be defined according to regulations and standards.

Choosing a suitable building system according to procurement and the business model is important. Consulting with industrial structural suppliers and contractors at an early stage can save time, materials, and costs, as they know their building systems' capabilities.

6 CONCLUSIONS

For nature and the public good, it is crucial to respect a building and its materials, retaining functionality and reuse. This must be the focus of the design process of new buildings today. The concept method is a practical tool in steps to obtain more circular timber buildings:

- Collaboration by co-creation in the building's value chain and sharing of the team's knowledge were essential for successful development.
- The circular value cycle process (the heart process) provides an understanding of the context and results affecting circular buildings.
- Defining scenarios and requirements of the building to be designed and assessed regarding its potential climate impact reduction.
- The method SimFORCE (Simulation of Future-Oriented Reuse for a Circular Economy). It was valuable for improving designs and assessing preserved functionality in circular buildings, although the actual buildings have not been deconstructed, reconstructed or tested in a laboratory. A competent Expert Team is required for the assessment.

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- It gives information to guide documents for adaptability, deconstruction and reconstruction.

The concept method was applied to two concept buildings, designed to be adaptable and reusable with preserved functionality with environmental benefits:
- The Modular Building: a timber building with industrially manufactured volumes designed to be relocated and reconstructed (elastic).
- The Adaptable Building: a timber building with planar elements, designed to be flexible and versatile, relocated and extended with two added floors (elastic).

Environmental evaluations compared the first life cycle (initial building) to the second life cycle of the respective building. In all scenarios, the reuse of timber buildings shows a substantial potential to reduce the climate impact, in the order of 50%, in the product stage (A1-A3).

The results demonstrate that various scenarios can be considered to adapt to future needs. The concept method can be used to define strategies for clients and authorities. The results of the concept of buildings demonstrate that buildings can be designed for adaptability while keeping the climate impact low of the initial building. Guides for adaptability, deconstruction and reconstruction were formed to assist this future building transformation. This is valuable for real estate developers.

Future work is to continue the development of the SimFORCE method and interpret the complex process of designing buildings following the circular value cycle.

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