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Citation for the original published paper (version of record):
Jockwer, R., Goto, Y., Scharn, E. et al (2020). Design for adaption - Making timber buildings ready for circular use and extended service life. IOP Conference Series: Earth and Environmental Science, 588(5). http://dx.doi.org/10.1088/1755-1315/588/5/052025

IOP Conf. Series: Earth and Environmental Science **588** (2020) 052025 doi:10.1088/1755-1315/588/5/052025

Design for adaption – making timber buildings ready for circular use and extended service life

R Jockwer[1], Y Goto[2], E Scharn[3], K Crona[3]

[1]Division of Structural Engineering, [2]Division of Building Technology, Department of Architecture and Civil Engineering (ACE), Chalmers University of Technology
[3]Sweco Architects AB, Gothenburg, Sweden

[1]robert.jockwer@chalmers.se

Abstract. The construction sector has a significant share of Green House Gas emission and raw material consumption globally. Among common construction materials, timber has a long tradition of numerous applications as a renewable material. The implementation of the concept of circularity in the process of the construction of timber buildings has a high potential sustainability impact. The concept of design for adaption is to extend the service life of timber building to the maximum in several life cycles. In this paper the demand regarding circularity is analysed from interviews with different stakeholders and their economic, social and environmental incentive. The possibility to assess the sustainability impact of design for adaption are evaluated. Different examples of existing practices and potential solutions for design for deconstruction and adaption are summarized.

1. Introduction

1.1. Climate impact from the construction sector

The construction sector has a significant share of Green House Gas emissions and raw material consumption globally [e.g. 1]. The shift of the construction sector towards a circular economy is crucial in order to realize a more sustainable society. The three most effective ways to ensure the sustainable benefit of the circularity in the construction sector can be seen as:

(1) Maintain the service life of structures and buildings materials as long as possible to avoid unnecessary emissions and costs for demolition and reconstruction.
(2) Conserve the quality of materials as long as possible to avoid unnecessary emissions and costs for the replacement and processing of new materials.
(3) Recycle and repurpose only the parts and materials which cannot function any more for technical and/or socio-cultural reasons.

Among common construction materials, timber has a long tradition of numerous applications as a renewable material, the implementation of the concept of circularity in the process of the construction of timber buildings therefore has a high potential sustainability impact when the timbers are sourced from sustainable managed forests.

1.2. Challenges and possibilities with circularity in timber buildings

The existing concepts regarding the material circularity in the built environment focus mainly on the reuse and recycling of the building products and building materials in different applications. This approach has not yet successfully established for timber buildings, amongst others, due to the following drawbacks:

- Timber is a relatively cheap material with a negative carbon footprint, hence, there is no economic initiative for recycling this cheap and environmentally friendly material. Instead, the wood material suffers from down-cycling and is e.g. often burned after primary use.
- Buildings are highly individualistic structures, and thus the reuse of building parts and products is hard to achieve.
- Buildings are being built to last long times, and thus disassembly, reuse and exchange of parts is currently not foreseen.
- No established method yet exists in order to evaluate the performance of the building parts for reuse.

When considering the recycle and reuse of wooden building elements, it is also important to consider the different approaches according to the types of engineered wood (such as glulam, LVL, CLT etc.) due to different relative mass of adhesives contained in each product.

1.3. The new approach: design for adaption

In order to overcome the challenges of the conventional concept for circularity, the research project present in this paper proposes a new approach: the circularity is imposed not merely by reusing the renewable material (amongst others due to the drawbacks as described above) but rather by extending the service life of the structure from a minimum of roughly 50 years to the maximum in several life cycles spanning 100 years or more. This approach, to extend the service life to the maximum, requires the possibility of the structure to be adaptable to different demands over time. The change of the demands may arise from technical problems such as damages to load bearing elements of the structure and/or socio-cultural issues such as the change of the functional requirements of the building. This approach goes beyond the conventional repair and renovation approach, in which only the non-load bearing components such as partition walls or façade elements are refurbished.

1.4. Terminology

The following terminology can be defined: **Adaption / Adaptation**: the act of changing to suit new conditions. **Adaptability** in the context of this research focuses on 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. **Design for adaption** considers the adaptability of the structure already in the planning and design process. **Deconstruction** of buildings is the selective dismantlement of building components, specifically for reuse, repurposing, recycling, and waste management. In addition to giving materials a new life cycle, deconstruction has the benefits of minimising landfill waste and to help to lower the need for virgin resources. The assumption in this research is that an adaptable building is likely also easier to deconstruct which is regarded as a positive feature.

2. Demands for DfA

2.1. General

The idea of DfA (Design for Adaption) is to enable future changes – demands **-** by considering a timber structure´s possibility to adapt or respond already in the design phase. Following the concept of adaptability in the design of a building may ensure more lifecycles with regard to a variety of different aspects, amongst others:

- Change of use or changing demands could mean increased loads and the load bearing structure may be adapted e.g. strengthened.
- Durability and the possibility to repair damaged load-bearing components meaning that parts of the structure can be easily restored or exchanged e.g. in case of water leakage, compartment fire, etc.
- With changing requirements regarding energy consumption, insolation etc. the relevant parts such as e.g. facades can be replaced and adapted.
- The users of the building can adjust the building to their demands, both in a short-term perspective or for long term use.

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2.2. Literature survey on damages in buildings

The Swedish government assigned Boverket (The Swedish National Board of Housing, Building and Planning) in 2009 with the directive to make a thorough survey and inventory of the Swedish building stock [2]. The purpose was to obtain background data in order to support new objectives regarding moisture, mold and other factors that are of importance for a good indoor climate. Part of Boverket´s assignment was also to estimate the need for actions and the costs for any damages and defects.

The inventory showed that approximately 40% of the apartment buildings have some kind of damage, however most were not of a serious kind. Of the noted damages, about 45% were moisture related. Known problematic constructions, such as furnished basements, insulation on the ground floor and crawl space, are prominent in the damage reports. Apart from these, most damages were observed in the protective layer; outer walls, windows and doors, roofs and foundations, but also in wet rooms and in installations [2].

The report "Vattenskadeundersökning" ("Water damage survey") [3] compiles statistic for the most common reasons for water damages in houses and multi-story buildings. The conclusion is that corrosion and freezing in water pipes causes damages to the pipe system, and mechanical connections causes more damages than soldered ones. An important factor is the state of the installations and older ones from the 60ths and 70ths dominates in terms of damages. The waterproofing layer´s connection to the bathroom well causes the most damages in wet rooms.

For new buildings Boverket [2] sees a danger in the fact that untested and not properly evaluated construction solutions fast can be in production at large-scale. Such as the solution with undrained, plaster over wood stud wall facades, which became a popular solution during the millennium and later has proven to be a very risky construction in terms of moisture.

In Sweden it was prohibited up until 1994 to build more than two story high buildings with timber frame. Typical damages or risky constructions for this kind of structures is therefore little known due to a limited amount of buildings and the fact that they are still relatively new. However, since the listed damages mainly relate to execution, maintenance and age rather than structural system, they are likely to be of a point for consideration also in a timber building.

In terms of worries for damages in multi-story timber buildings there seem to be two reoccurring topics; fire and water/moisture. What is often referred to as a risk is the extinguishing water, or rather the amount of water used when firefighting. The fire brigade uses several thousands of liters of water per minute when putting out a fire. For a timber building, being exposed to this massive amount of water, can be devastating if the water penetrates the structure. Increased moisture content in the structure can cause excessive deformations or even decay in the load bearing elements. The cost to fix water damages caused by extinguishing water can be as high as those for the damages from the actual fire [4]. The routines for extinguishing fires in timber buildings are probably different from that of a concrete one, hence the fire brigades working methods is seen as something with potential for development. Another solution that has been suggested is to create "watertight" zones at every third level or so in order to limit the worst-case water damage scenarios to three floors [5].

Apart from the water, there is the fire itself. Timber shows a slow and predictable burning and charring creates a protective layer which slows down the progress of fire. Nevertheless, there is a need to study new types of timber buildings made from e.g. CLT (cross laminated timber) in terms of fires.

Insurance companies are often critical to the fact that the fire safety rules, although they save lives, are too weak in terms of protection of property. Since damaged property constitutes great costs for them, they would like to see stricter regulations. In the case of a fire, in their experience the damage is likely to be more severe and extensive if the building is a timber building rather than a concrete building [6].

Norén and Just [7] concluded that there is a prominent need to evolve standardised test methods to verify details in constructions with combustible materials. The test methods used today are produced for non-flammable materials such as concrete and cannot be said to give representative results for combustible ones. The risk of smouldering e.g should be part of the criteria. The design of details has a big impact for the fireproof at large and for individual building elements. The execution of details is therefore important and small changes in materials and components can be crucial for how a building performs in the case of a fire [e.g. 8].

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2.3. Interviews with stakeholders on demand for DfA

A questionnaire has been developed at Chalmers in collaboration with Sweco Architects AB in order to evaluate the demands regarding adaptability in interviews with various stakeholders in Sweden.

The questionnaire consists of a variety of questions from the following topics: General question about field of industry/stakeholder and experience in timber, Building permit and regulations, Challenges regarding fire, Building installation, Moisture and insulation, Costs, Availability of material & components, Influences by the users, Life cycle of the building, Materials and products, Damages, Attraction of the concept of adaptability.

Part of the research has been to interview stakeholders in order to gather their view on how adaptable design could be beneficial for timber buildings. By identifying common problem areas and needs a bases of demands can be derived. Different interviews with the following groups of stakeholders have been performed: Developers, Property owners, Insurance company, Contractors.

All interviewees but one had a positive attitude to timber buildings. Positive environmental aspects and easiness to adjust things on the building site and inside the apartments were considered as major benefits. In addition, the atmosphere and living condition a timber building creates for the tenant/occupant was considered as positive. One company which was not motivated on timber buildings was a property owner for rental apartments. They considered timber buildings are more costly and it does not create an incentive to build a more expensive building for rental apartments. One interviewee had a critical view on the fire regulation and insurance which reflects the concern on the damage in case of fire in [5]. Meanwhile, construction companies with solid experience with timber buildings do not see the fire issue as a major problem. After all, all interviewees considered design for adaption to be an interesting strategy to switch out parts easily throughout a building´s lifespan.

2.4. Summary of the demand analysis

Both the literature survey and the interviews highlight the gap in knowledge and interest between the construction industry and the insurance companies. There seems to be an insufficient understanding of how the risks with fire and water can become a future problem with insurance. The insurance companies are sceptical to cover buildings that are difficult to rebuild after a fire. This is a potential problem that could arise in the near future while the timber market keeps growing. DfA approach itself cannot solve the issues with fire safety but it could mean a way to mitigate the local damages from fire and water.

There seems to be an interest of the concept DfA mainly for property owners who maintain their properties. Based on the fact that the most common damages occur in kitchens and bathrooms, if the slab/floor construction was designed with adaption in mind making it easier to repair, protect and switch out, the costs for repairs could be greatly decreased. This could also influence the amount of actions needed postfire. The slabs construction and connection to surrounding walls, together with the structure of the layers on top, as pointed out in the interviews, are something that would need to be solved differently if DfA is to be successful.

3. Sustainability assessment for DfA

3.1. Life Cycle Assessment (LCA)

Different design and adaption measures have different environmental, economic and social impacts. In order to give incentives to stakeholders to practice DfA, it would be beneficial to quantitatively evaluate the sustainability impacts of DfA application in each building project.

Generally, sustainability impact assessment is carried out as a comparative study with several scenarios, for example a comparison between one scenario with no DfA measures and another with as many DfA measures as possible. Typically, Life Cycle Assessment (LCA) is a common method to carry out a sustainability impact assessment. The impacts need to be characterized by appropriate sustainability indicators. The selection of the indicators needs to well reflect what sustainability performance changes would be observed among the different scenarios. For example, one typical environmental indicator is global warming potential for general LCA studies of energy performance of buildings.

Another important point in LCA is system boundary. Typical system boundaries are so-called "cradle to gate" and "cradle to grave" in terms of the lifetime of a product. The boundary of material flow of the product also needs to be defined (for example, either it analyses tracks for all or selected biproducts or it focuses solely on the primary product). An adequate system boundary needs to be defined in each of the sustainability impact analysis cases.

Boverket plans to make LCA in the planning of multi-story residential buildings mandatory from 2022 in Sweden. The LCA methodology in the building permit procedure is supposed to follow the general framework of the relevant international standards such as ISO 14040 – ISO 14043. While there is a common agreement on the fundamental methodology of LCA and there are commercially available and widely accepted LCA tools such as SimaPro (https://simapro.com/) and Gabi (http://www.gabi-software.com/), there is no common LCA tool for the sustainability impact assessment of buildings under the Swedish building regulation. As of January 2020, it seems likely that the LCA in the building permission process would only require the conformity with the common standards, and it would be up to the building owners´ decision on which LCA tool is used.

3.2. Other Sustainability impact assessment schemes

In addition to the LCA approach, there are several voluntary building certificate schemes which quantify the sustainability performance of buildings. Among numbers of building certificates, the most common ones in the Swedish construction industry are; Miljöbyggnad (https://www.sgbc.se/certifiering/miljobyggnad/), LEED (https://new.usgbc.org/leed) and BREEAM (https://www.breeam.com/). While LEED and BREEAM have been developed outside Sweden , Miljöbyggnad was developed in Sweden and has been applied in practice since 2010. As of January 2020, all of these (and other) building certifications are recognized and utilized in the Swedish market.

In terms of material circularity and life cycle perspective which are emphasized in the DfA approach, Miljöbyggnad does not have a directly relevant indicator in its 15 sustainability performance indicators (energy purchase, heating demand, solar gain, primary energy mix, noise protection, radon content, ventilation, N2O, moisture safety, thermal comfort in winter, thermal comfort in summer, daylight, legionella, documentations of materials and hazardous materials). In moisture safety, although the moisture safety of connections in the design and construction phase is considered, the ease of replacement of damaged parts is not taken into account in the evaluation. Therefore, the DfA approach will not increase the incentive to achieve a higher grading in this regard.

While current version of Miljöbyggnad lacks the relevance to DfA, LEED and BREEAM have considerations which are relevant to lifetime performance and material circularity to some extent. BREEAM introduced "circularity" as a new indicator in October 2019. The circularity indicator "relates to the efficient use of physical resources in the building through careful design, construction efficiencies and durability/maintainability" (https://www.breeam.com/news/new-breeam-indicators-to-be-added-to-breeam/). This perspective is well relevant to the DfA approach and thus BREEAM shall give some certain incentive to building owners to consider DfA for a higher grading.

There is another environmental certificate for products in the Nordic nations; Nordic Swan Ecolabel (http://www.nordic-ecolabel.org/). This certificate has been applied to various types of consumable products since its launch in 1989. In 2012, the labelling added construction products in its range of the product categories. The number of the certified builders and buildings has been gradually increasing in the recent years (36 apartment projects and 14 companies have been certified/licensed as of Feb 2020). In order to incentivize the end users to purchase the certified property, banks also have introduced "green mortgage". In terms of the potential evaluation of DfA, the certification acknowledges extra points in "recycling of building waste" and "Green initiatives", which should give benefits for the building owner to consider the application of DfA.

3.3. Indicators

There are numbers of indictors to characterize environmental, economic and social sustainability performances of a building. There has been little research which focused on the selection of indicators which are suitable for DfA approaches. Therefore, in order to specify the most relevant indicators, it is necessary to review the indicators of the existing sustainability assessment schemes.

Regarding environmental indicators, as it is discussed above, the most common one is global warming potential when the energy consumption is concerned. As for DfA approaches, the energy consumption is actually of less relevance unless energy renovation is to be facilitated through DfA approaches. ISO 21931-1 "Sustainability in building construction – Framework for methods of assessment of the environmental performance of construction works - Part 1: Buildings" further specifies the methodologies which are tailored for the construction sector. In this ISO, a list of 34 environmental and 12 environmental-social indicators are given. Among those, "process quality of maintenance", "waste production and disposal", "reuse, recycling, recovery of materials" and "repair, conservation, replacement of products used in the building" are the primary ones for the DfA approach.
Regarding economic indicators, there are numbers of cost factors which can be relevant to DfA approaches. According to Wood and Hertwich [9], the following is a list of indicators as absolute measures for an economic LCA; components of value added, capital, labour, profit, tax and imports. They additionally list indicators as relative measures such as novelty, capital and labour to characterize productivity, linkages and industry distribution.
Regarding social indicators, although this is the least studied area in sustainability of built environment, Larsen and Jensen [10] reviewed the social indicators in DGNB (https://www.dgnb-system.de/en/) and compared them to the SDGs by the UN. Among those indicators, the ones which are more relevant to DfA approaches are; design for all and plan layout.

3.4. Summary of sustainability assessment of DfA
In order to promote the application of DfA concept, it is essential to establish a scientific methodology to analyze and quantify the sustainability impact of DfA measures. In the review of existing methodologies, number of environmental, economic and social indicators were collected to characterize the DfA concept. Although those applicable indicators and their definition exist already, there is no single tool to systematically assess the sustainability benefit of DfA concept.
Therefore, there are two alternatives to follow to achieve the sustainability assessment of DfA. One is to develop a specialized tool to carry out the analysis in a most holistic way by considering numbers of (ideally all of) indicators. The development of such a tool shall consider the simple design of it for the industrial application in the later stage. The other way is to collaborate with existing sustainability assessment schemes such as Miljöbyggnad and Nordic Swan Ecolabel.

4. Overview of examples of technical solutions
Adaptability can be applied to all elements and levels of scale in a building as discussed above. Within the scope of this project it was focused on the adaptability of on level of the structural elements. Different structural elements can be distinguished within a building, most commonly wall elements, floor elements, columns and beams. These elements can be either linear or planar elements and they can be arranged horizontally or vertically. Depending of the construction type and method these elements may be arranged in different way. Different construction methods are frame structure, post-and-beam, CLT elements, and prefabricated modular systems.

4.1. Development from historical timber buildings to modern constructions
Traditionally, building with timber elements has been characterized by prefabrication (pre-cutting) and modularity [11]. Starting from log houses and developing towards half-timbered houses, there exists a variety of examples in which single elements of the structure were exchanged or reused, or in which entire buildings were relocated or adapted. These houses had a built-in adaptability, they could be upgraded or renovated easily without it affecting the functionality of the building at large and the waste was kept to a minimum due to local actions.
Current conventional construction, however, is mainly characterized by massive and highly complex techniques, in which the single elements cannot be exchanged anymore due to irresolvable connection, layered compositions and the general lack in considering adaptability in design.
In modern timber construction, the concept of modularity is very widespread. Volume elements forming single or multiple rooms are combined into an entire building, which could be disassembled and

relocated to other places. However, only the entire building or entire volume parts can be removed, which complicates the adaption towards individual demands or makes it impossible.
An example of a building in which single load-bearing elements could be replaced is “House of Natural Resources” at ETH in Zurich, Switzerland [12]. In this building, the connections between the timber elements are established by posttensioning forces, which could be released in order to replace elements. However, this construction system is not optimized with regard to adaptability but rather seismic resistance. Obstacle for a broader application in practice for this system are currently low economic incentives and lack of international regulations.

4.2. Enabling adaptability in a structure
For a long time, the limitation of connection technology was one of the biggest obstacles in the development of more advanced structures. The ongoing technological progress leads to the development of new connection systems, able to carry higher loads. The role of connections, therefore, becomes crucial for global structural behaviour. The challenge and complexity of the connection design can be seen e.g. at the connections of the timber members of Mjörstornet, which is currently the tallest timber building in the world [13]. In order to allow for an efficient transfer of forces, the connections are made with a large number of steel dowels and several steel plates. Such complex connections do not allow for any possibility of disassembly or adjustment of members.
In order to build high-performance structures and to make efficient use of the material resource, connections with high efficiency are needed. A high degree of utilisation of the timber cross-section can be achieved by applying high-performance connections [14,15]. An efficient building process has been achieved for examples for structures made of prefabricated timber members with connector elements, that are embedded in the timber by means of glued-in rods or self-tapping screws. The assembly on site is realised by connecting the special connector elements. Special care has to be taken to avoid any kind of brittle failure modes in the timber members in the surrounding of the connection.
There are different examples of connections that might be seen as a first step towards the direction of adaptable timber connection system: screwed- in or bonded-in steel rods allow for a direct transfer of tensile stresses along the grain direction of the timber [16,17]. By placing rods at different inclination into the timber, brittle failure in the timber in tension perpendicular to the grain can be prevented [18] and the connection can resist a variety of loading directions. By combining the rods with adequate connector elements into one system it is possible to prefabricate, assemble and disassemble timber components [19]. All these types of connections show very promising behaviour but have to be further developed towards predictability of behaviour, universality in application, reusability and efficiency.

4.3. Summary of technical solutions
Adaptability can be applied to all elements and levels of scale in a building. Within the scope of the project it was focused on the adaptability of on the level of the structural elements. Crucial for the successful application of adaptability in a structure is the shaping and detailing of the connections between the elements of the building. The adaptability applies to all these connections and details. Different technical solutions can be found in practice, that enable the removal and opening of connections, and hence the adaption of elements and members in a structure. These solutions can be integrated into the concept of DfA but have to be developed further and optimized for the particular application in a building. There are similarities between the concepts DfA and design for deconstruction (DfD), in the way that they are both concepts for how a building could be taken apart into its consisting components, although focusing on different events of a building’s lifespan. Some design strategies of DfD could therefore also be of use when designing for adaption.
Maximizing the simplicity and clarity of the construction and the design is the first step in implement DfA. The next consideration is to minimize the number of different materials used on the project. This way the number and the different types of connections required are minimized. Using mechanical connections as opposed to chemical ones (adhesives) will enable components to be separated more easily; the connections should also be simplified wherever possible.

5. Conclusions

The paper describes the strategies towards a more sustainable built environment by making buildings adaptable to the changes of demands and requirements to building functions and thus leading to an extended use of buildings in several life cycles.

In a life cycle perspective, there are many advantages with DfA, both for users and property owners but the benefit extends further even to the society. A building that can transform during its lifetime to adapt to different needs is a building with less carbon footprint. The most sustainable building is the building that is not torn down (though some say that the most sustainable building is the one that isn't built). The second most sustainable building is the one that can be deconstructed and reused.

The research provided an overview of the challenges and opportunities for timber constructions with DfA and have shown several demand areas that needs to be addressed in future research. Most salient is the fire, leakage, maintenance aspect and a commonly applicable sustainability impact assessment method. And innovations in the joint system of building elements are also needed to make the DfA applicable in practice.

Acknowledgments

The work presented in the paper was financially supported by Vinnova in Project number 2019-02423.

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